Current status and future plan on radiation pressure experiment

Middle report 2018 @ Ando-lab
Kentaro Komori

Abstract

- Our goal is to observe radiation pressure fluctuation acting on a massive mechanical oscillator.

- We use a bar-shaped mirror as a torsion pendulum. Two optical cavities are constructed on both edges.

- We succeed in locking two cavities simultaneously with high power. Higher power by a few and better sensitivity by two orders are needed towards the goal.

Motivation

Observation of quantum radiation pressure fluctuation

R&D for GW detectors

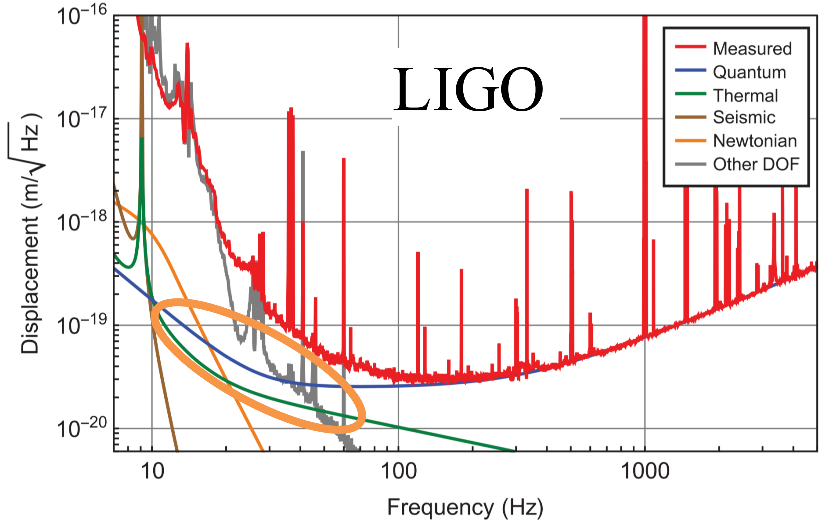
Macroscopic quantum mechanics

R&D for GW detectors

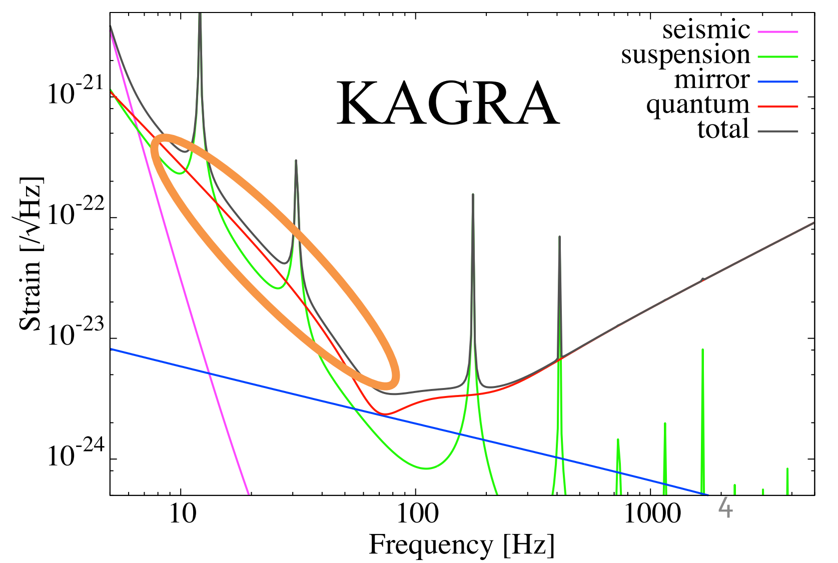
- Frequency region around 10-100 Hz is the most important for inspiral range.
- Sensitivities will be limited by radiation pressure noise.

⇓

- It is important to observe and reduce radiation pressure noise.



Abbott+ (2016)



Macroscopic quantum mechanics

- Optomechanics: A massive oscillator coupled with laser light.
- Superposition states for positions of macroscopic objects.

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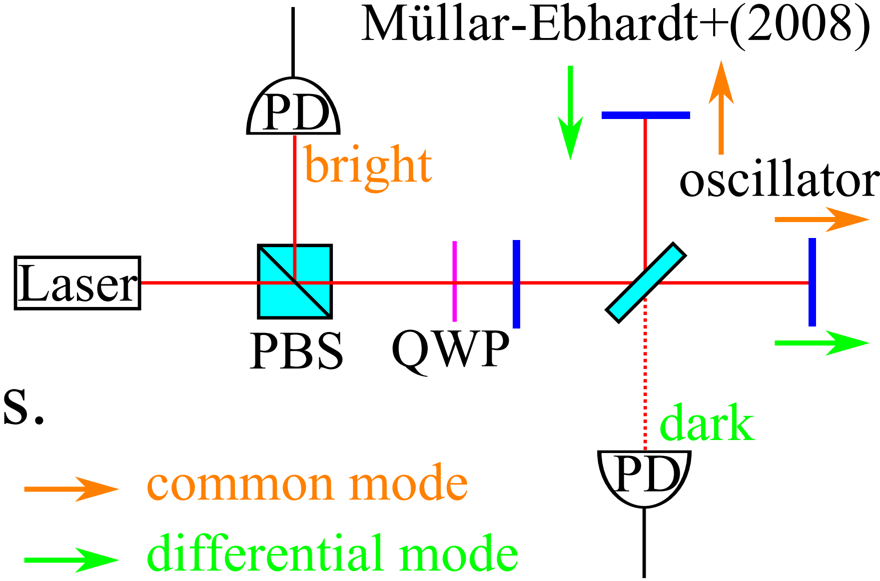
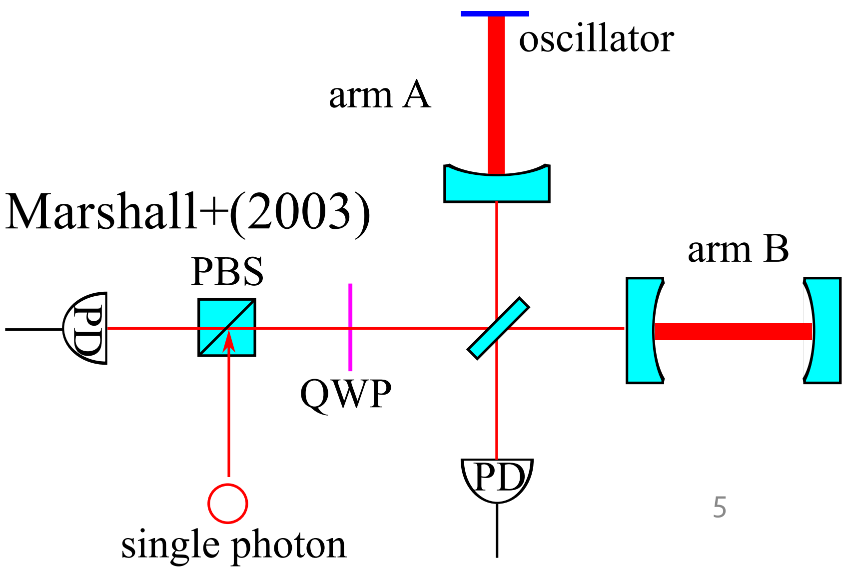
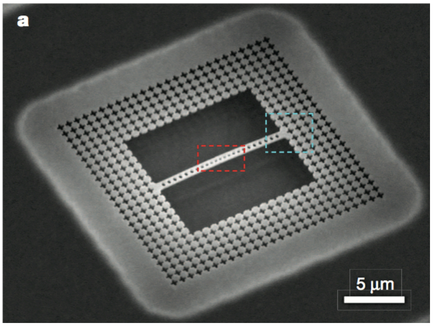
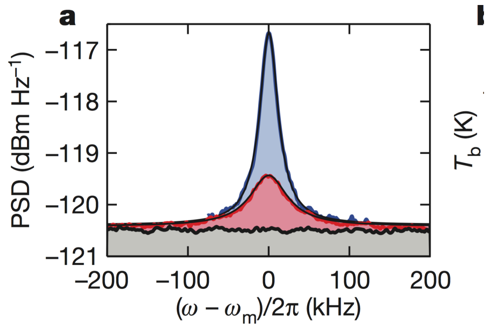
- Necessary condition is ground state cooling and observing radiation pressure noise.



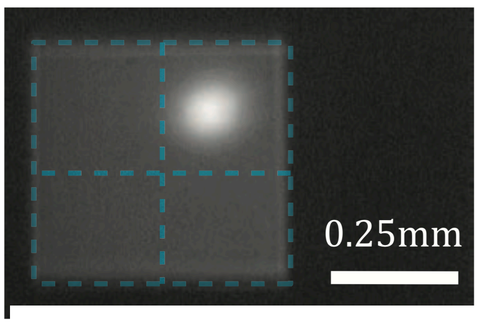


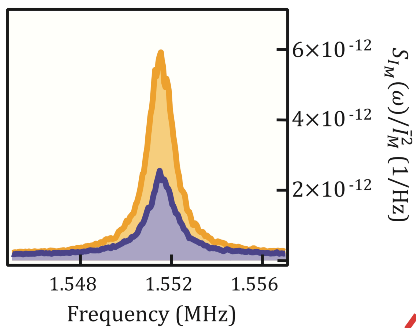
Previous works



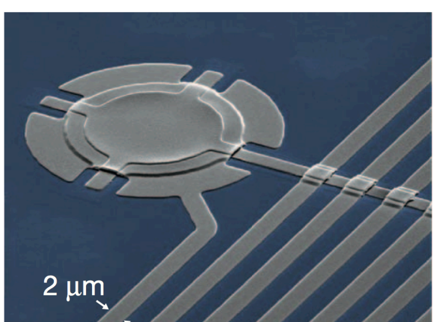


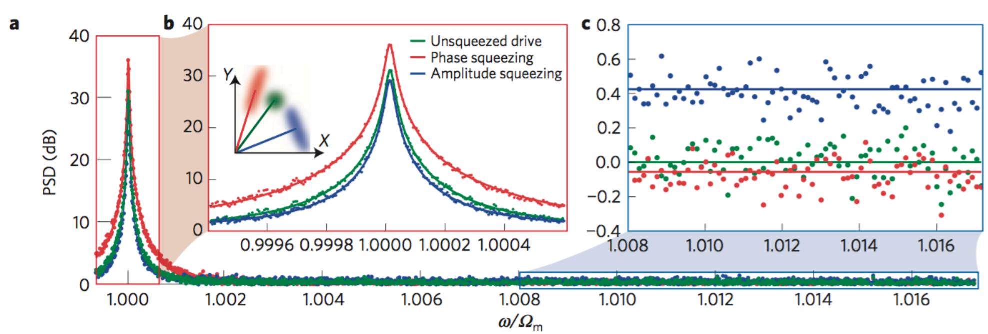
Chan+ (2011), m = 311 fg, f = 3.68 GHz





Purdy+ (2013), m = 7 ng, f = 1.55 MHz

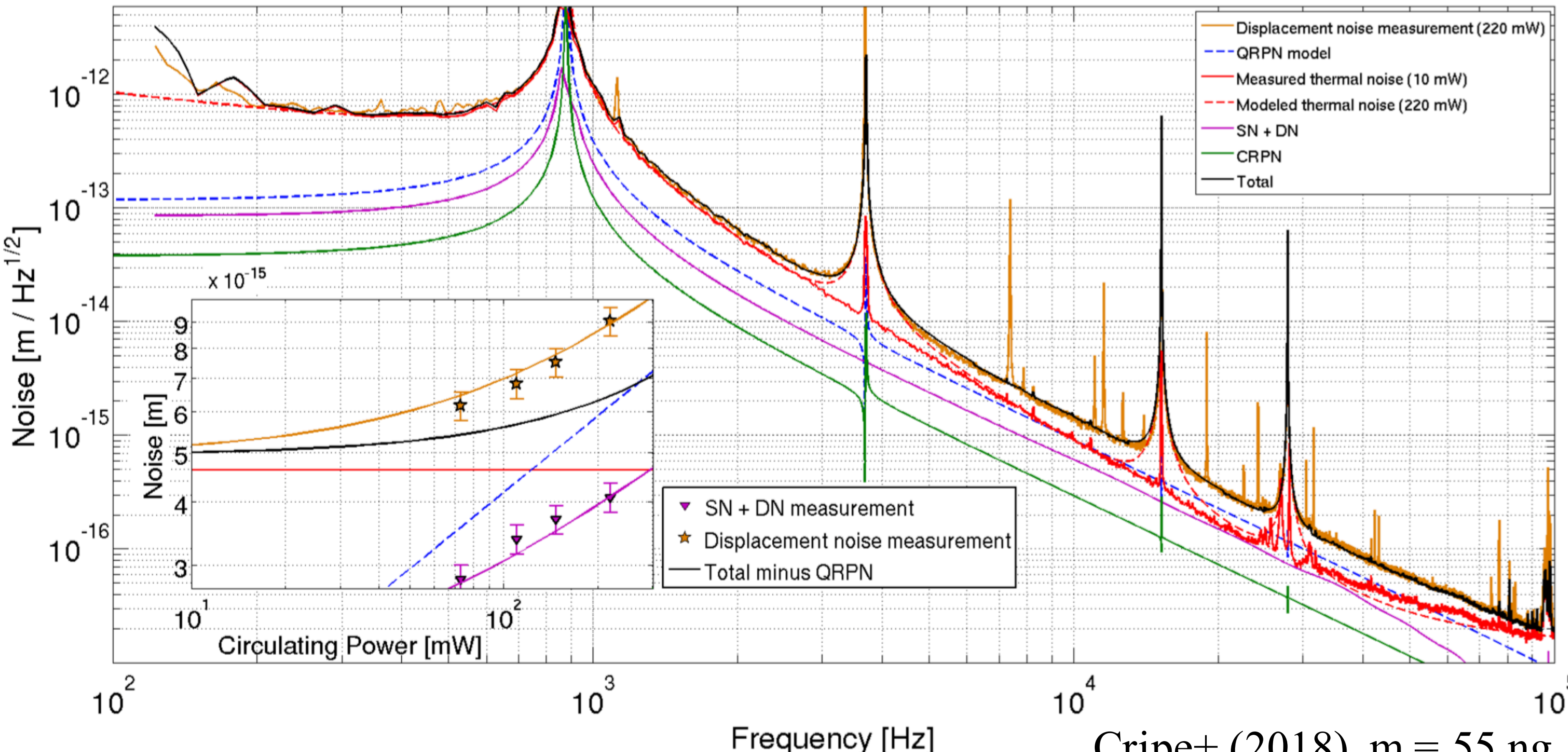




Teufel+ (2011,2016), m = 48 pg, f = 10.56 MHz

- ➢ Some oscillators has been driven by radiation pressure noise and even reached its quantum ground state.

Previous works



Cripe+ (2018), m = 55 ng,
f = 10 ~ 100 kHz

- Finally broad-band measurement has been realized!
- Observation below the resonant frequency.

Remaining challenges

- Over GW-detector band 10 ~ 1 kHz
- With a heavier oscillator
- In free mass range, which is especially needed for reaching SQL and ground state

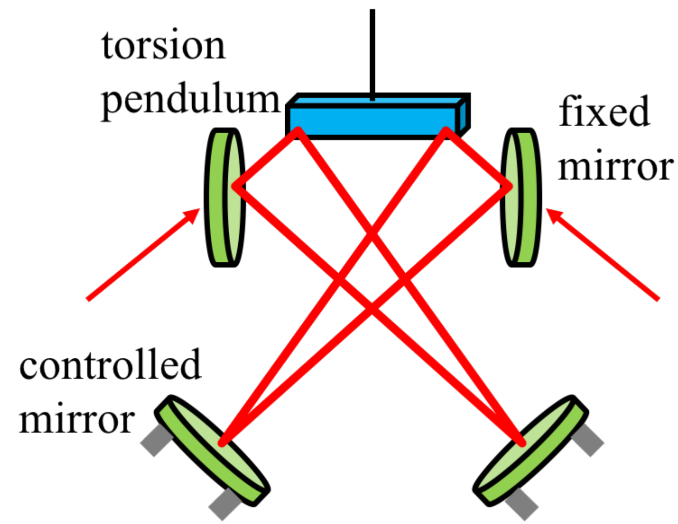
Method

✓ A bar-shaped tiny mirror as a torsion pendulum with two cavities at the both edges

✓ Measuring rotational mode by subtracting displacement of two cavity length

➢ Advantages

- Low suspension thermal noise due to low mechanical resonant frequency
- Common mode rejection of classical noise
- Light effective mass



Advantages

- Low suspension thermal noise due to low mechanical resonant frequency

➢ Thermal noise in force

$$S_{th} = \sqrt{\frac{4k_B T_{th} m \omega_m^2 \phi}{\omega}}$$

structure: $1/f$ e.g., suspension

$$S_{th} = \sqrt{4k_B T_{th} m \omega_m^2 \phi}$$

viscous: flat e.g., residual gas

loss angle ϕ: 1st order

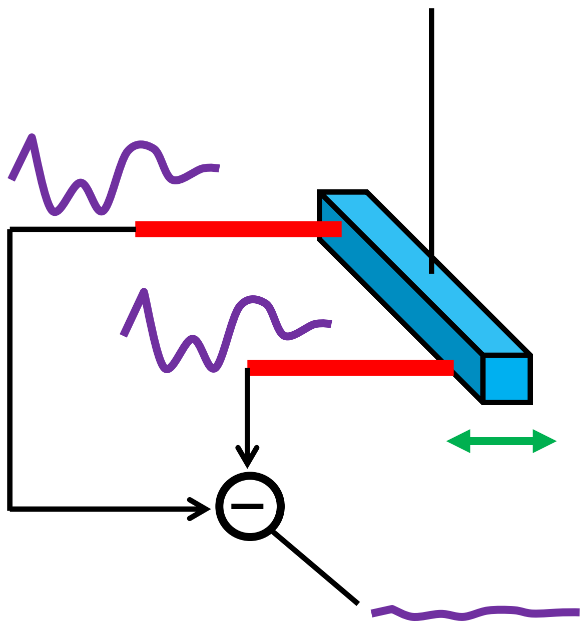
res. freq. ω_m: 2nd order

➢ Low res. freq. is better even at the cost of Q-value.

⇒ Torsion pendulum

Advantages

- Common mode rejection of classical noise
- Light effective mass

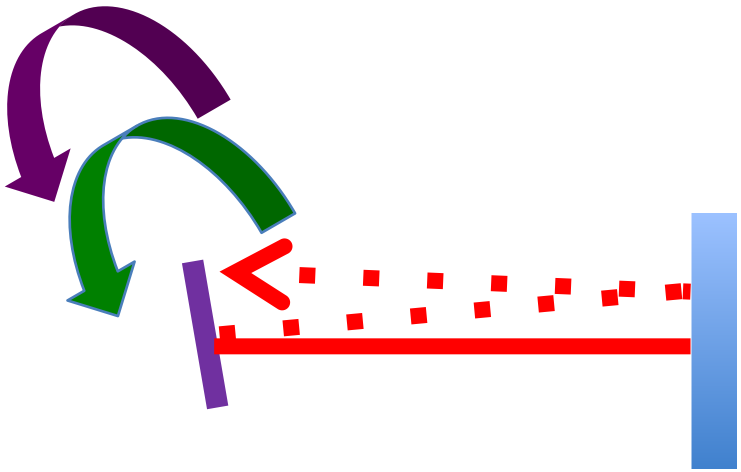


Laser frequency, intensity noise, vibration noise, etc.

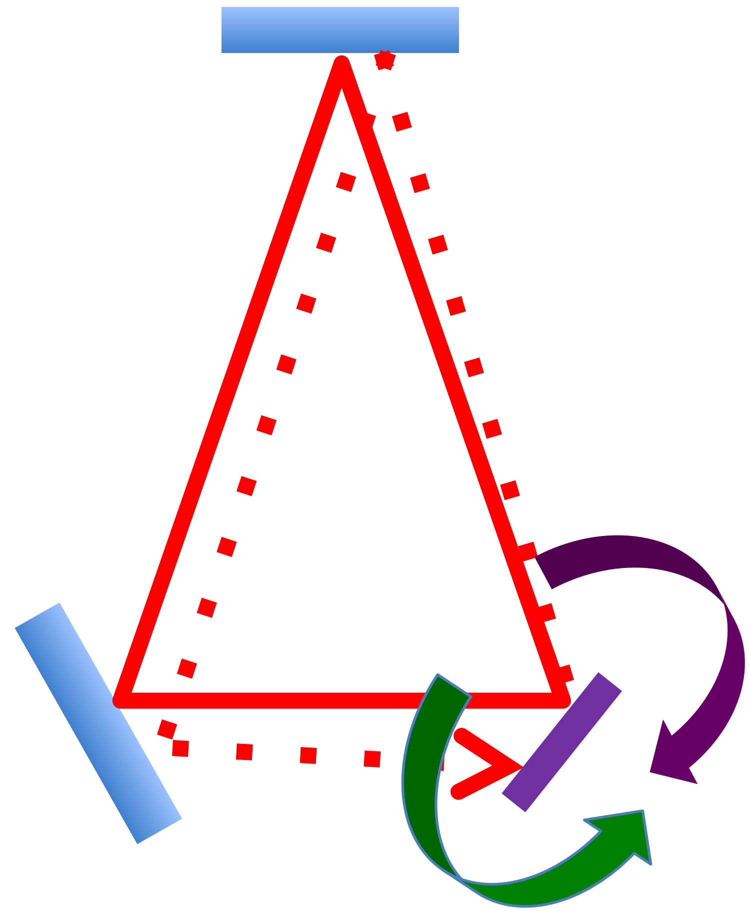
- ➢ All translational noises are reduced by subtracting signals from two cavities.
- ➢ Only quantum radiation pressure noise contributes to the subtracting (rotational) signal.

Moment of inertia: $I = \frac{1}{12} M L^2$ → Effective mass is divided by a factor of 12.

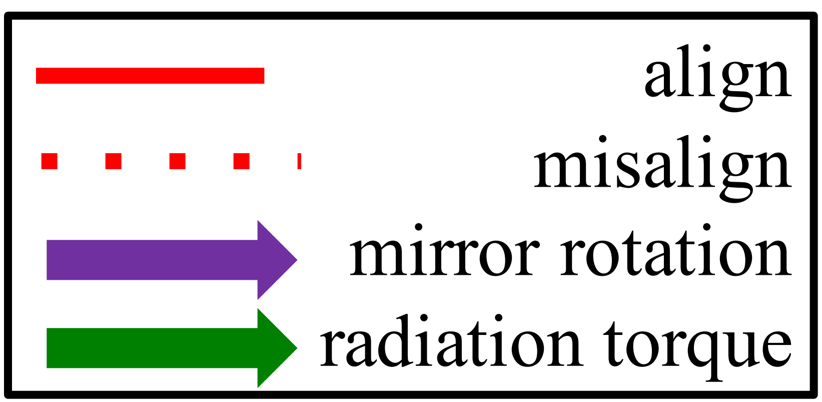
Triangle cavity



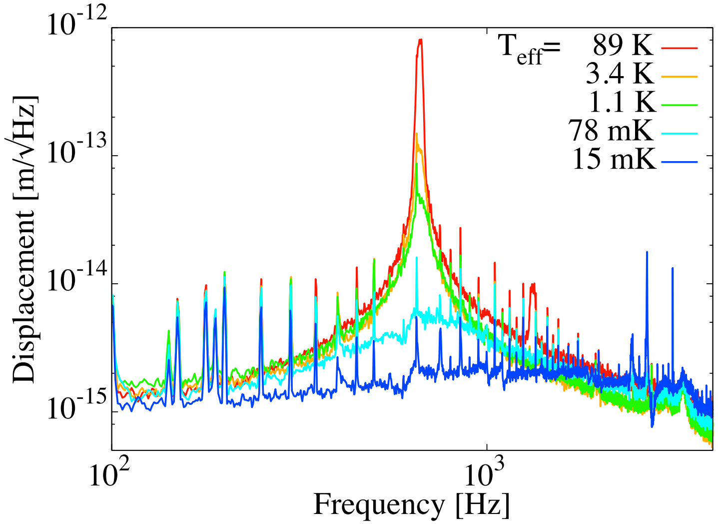
linear: Sidles-Sigg instability



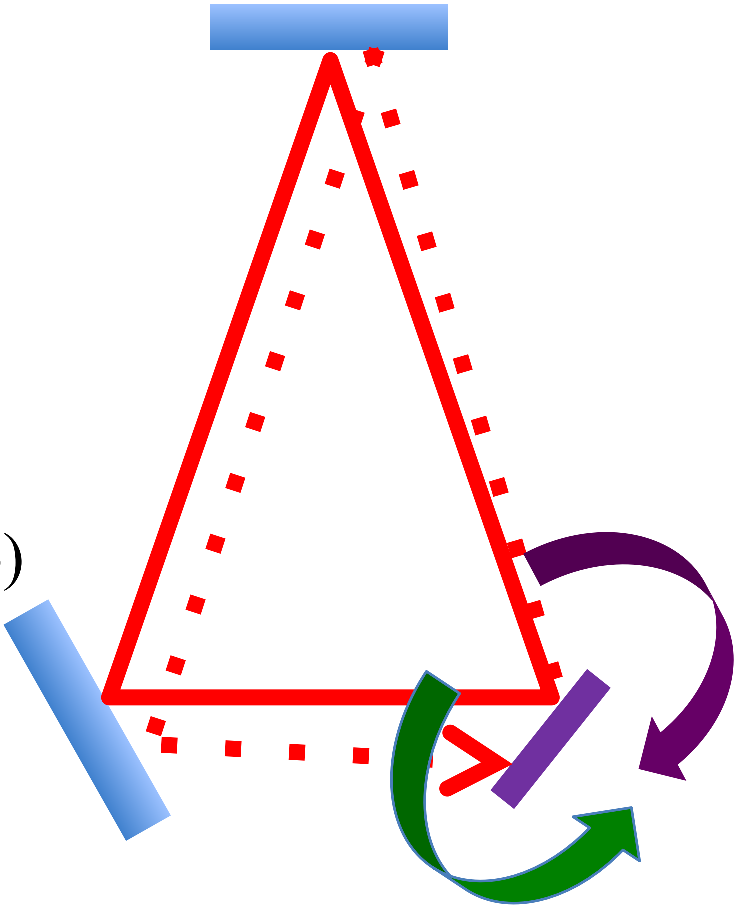
triangle: stable!



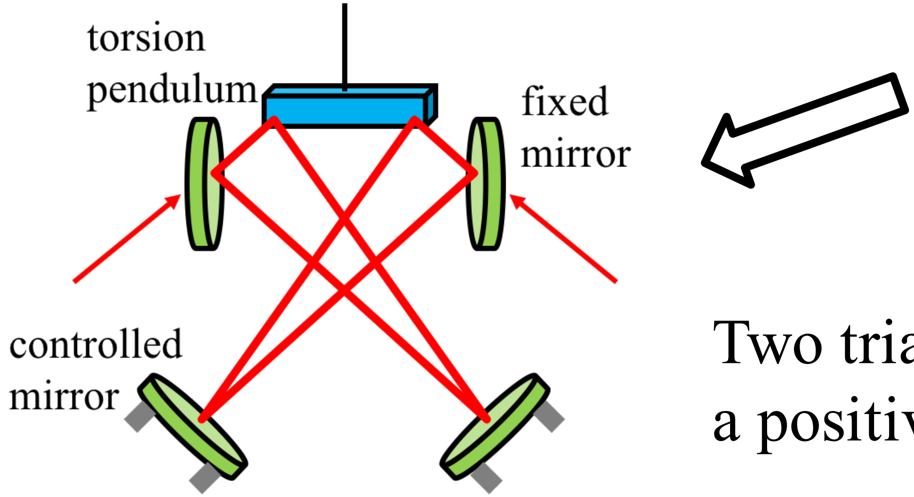
Triangle cavity



5 mg



Our group: Matsumoto, Komori+ (2016)

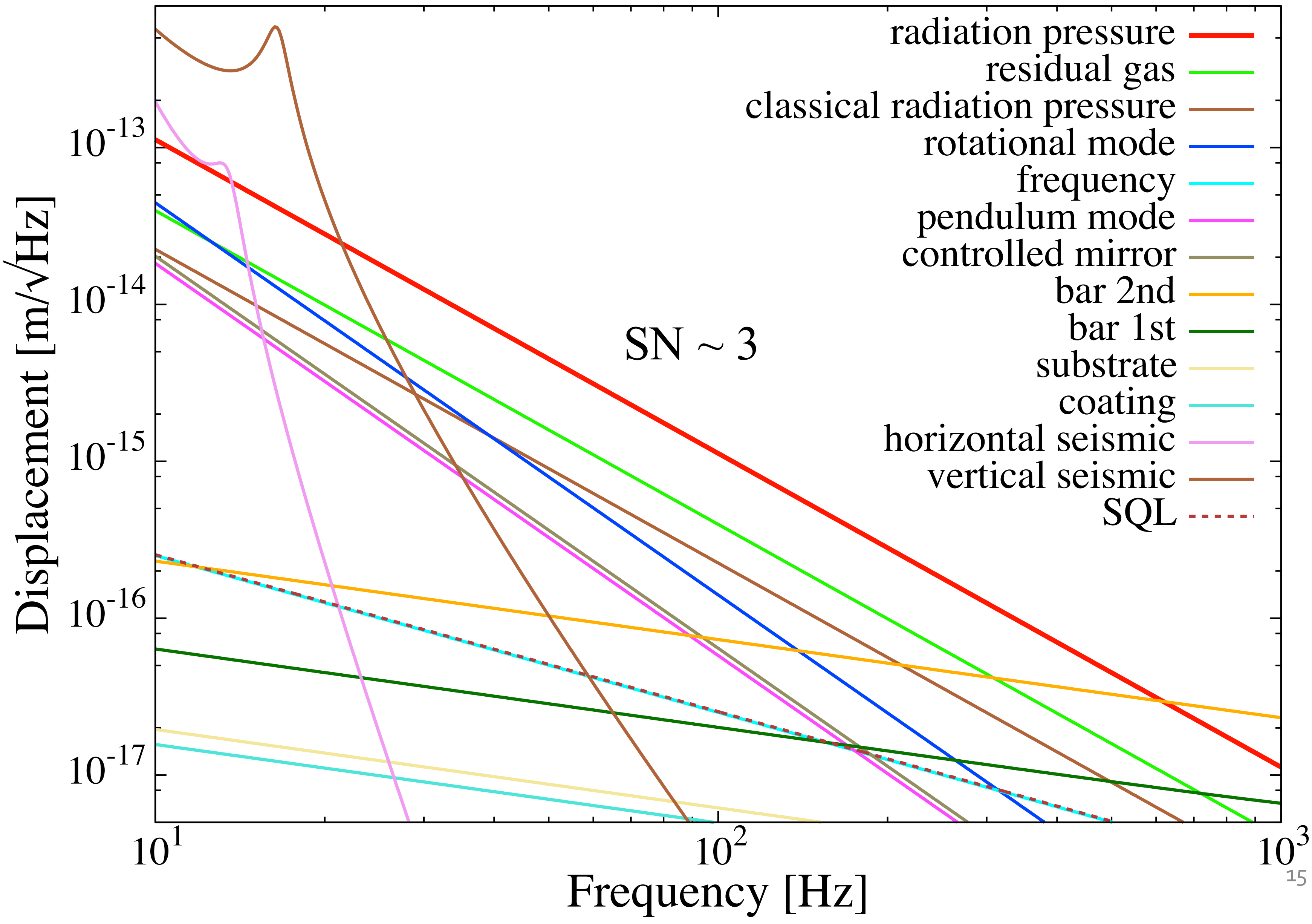


Two triangle cavities have a positive torque spring.

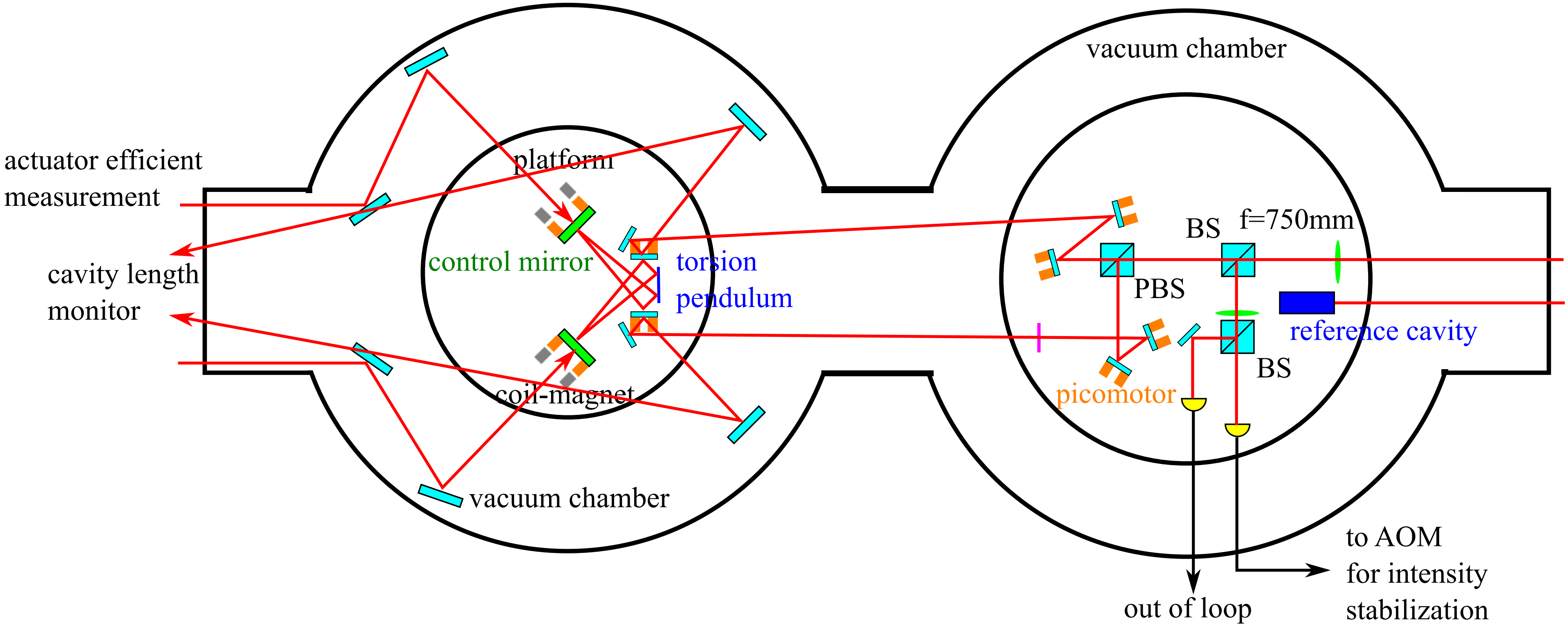
Parameters

- Finesse: 2000
- Input power: 20 mW
- Rotational resonant frequency: 70 mHz
- Rotational Q: 2000
- Pendulum Q: 50000
- Pressure: 2×10^{-4} Pa
- Frequency noise: 100/f $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$
- Intensity noise: $1\times10^{-8}/\sqrt{\mathrm{Hz}}$
- Cavity round trip length: 10 cm
- Common mode rejection ratio: 1/10

Design Sensitivity



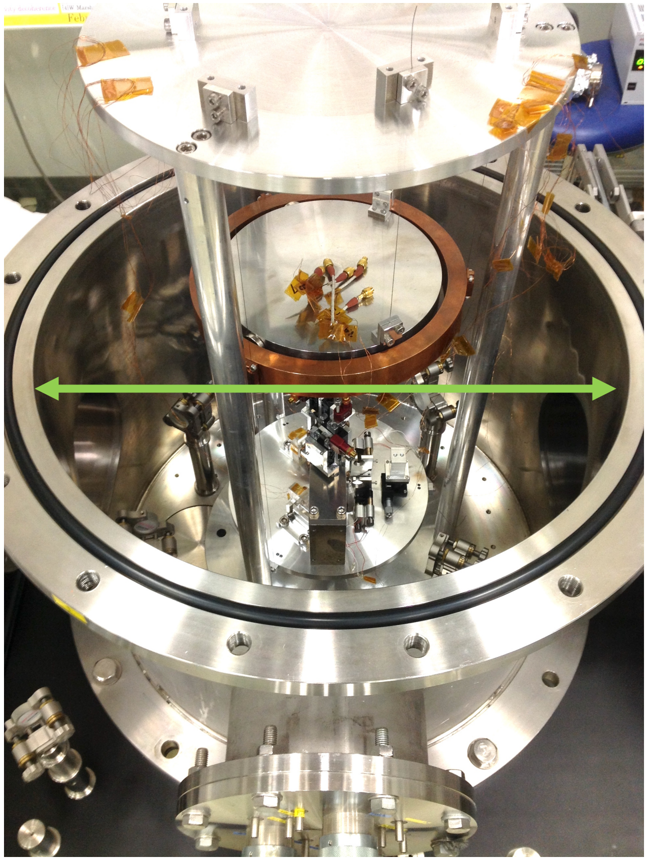
Experimental setup



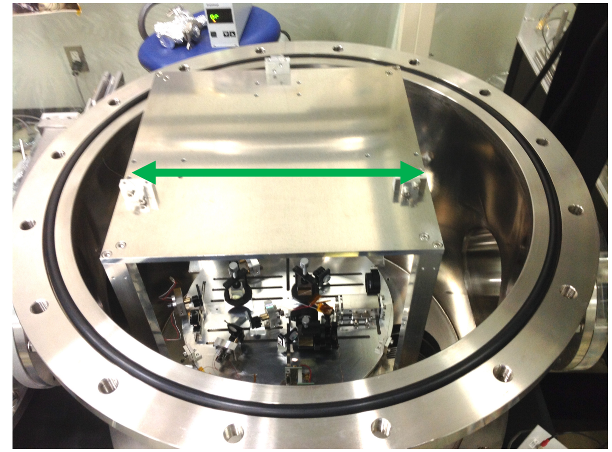
- Main cavity
- Each michelson interferometer for measurement of actuator efficiency
- Intensity stabilization with an AOM
- Frequency stabilization with reference cavity
- Sterring

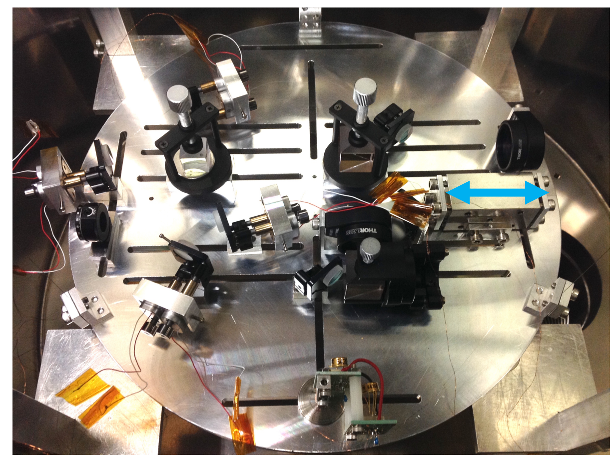
Experimental setup

580 mm



300 mm





50 mm

- Components are located on a double-suspended platform.
- The building is on rubbers.

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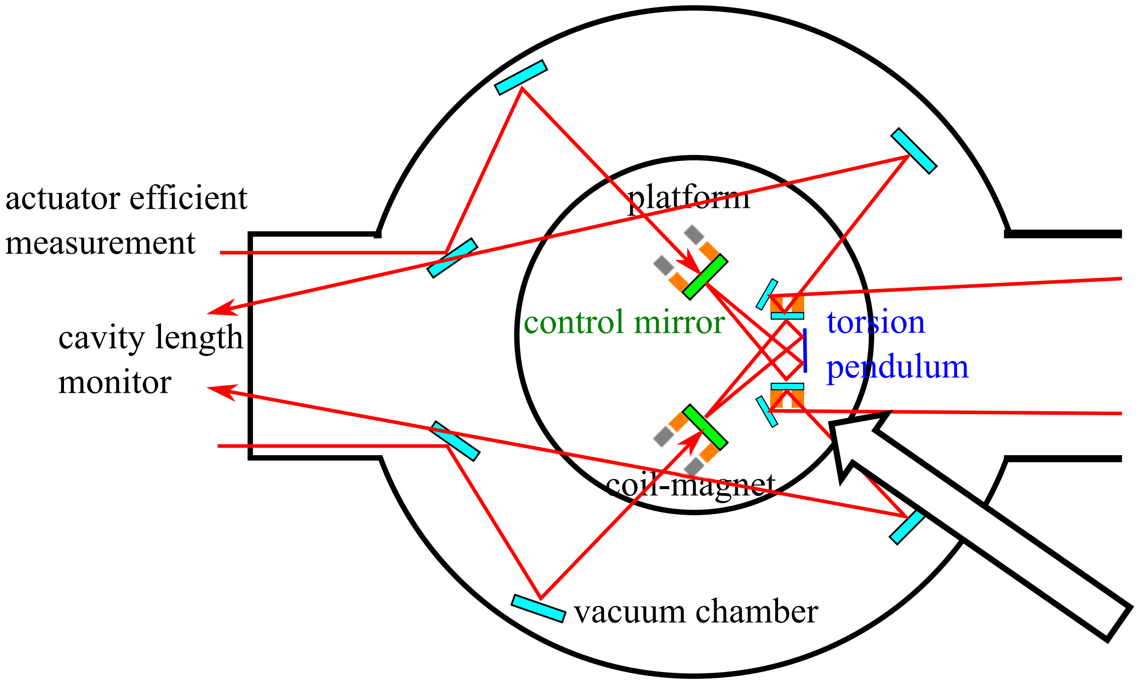
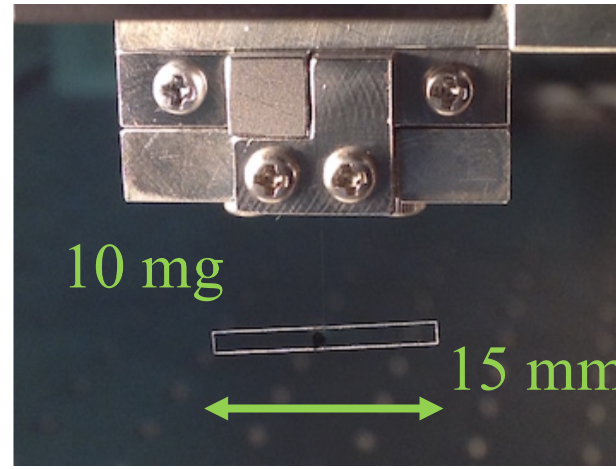
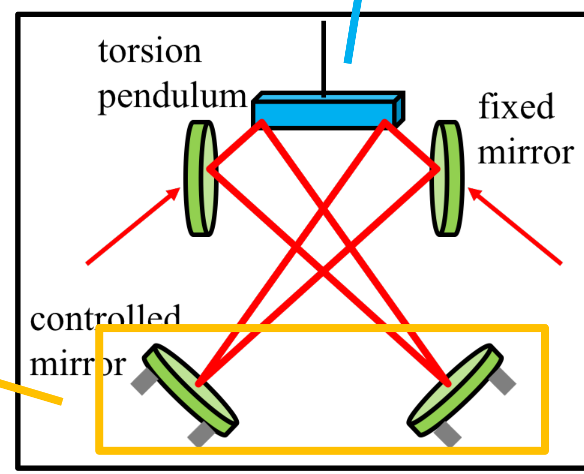
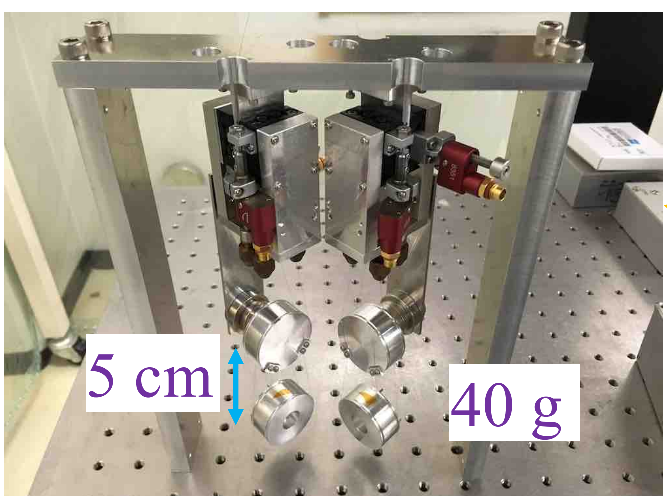
Experimental setup (Center part)





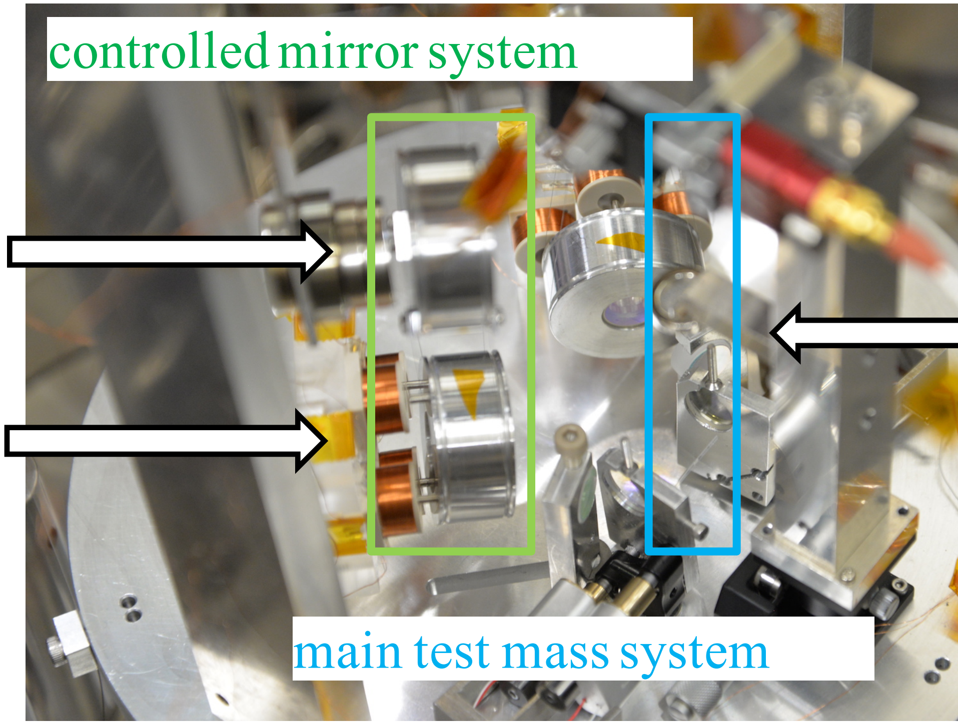




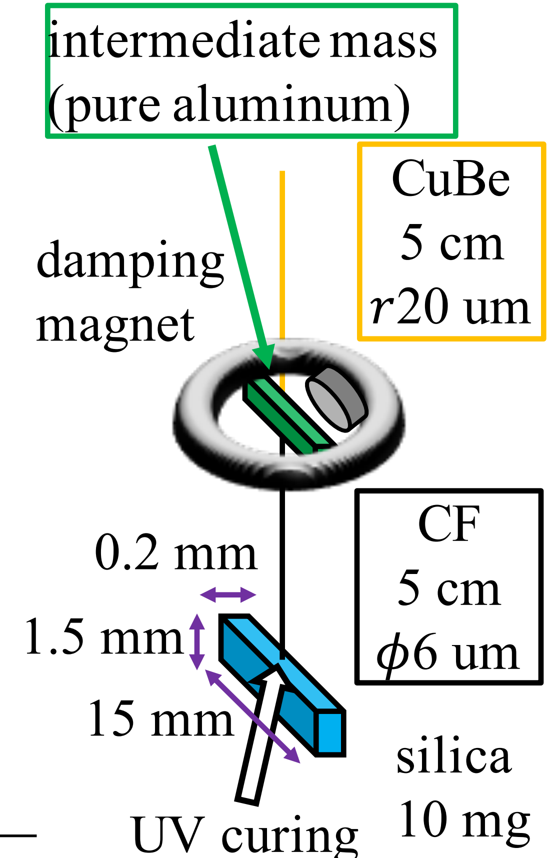
Experimental setup (Center part)

intermediate mass damped by magnet

coil-magnet actuators



damping magnet

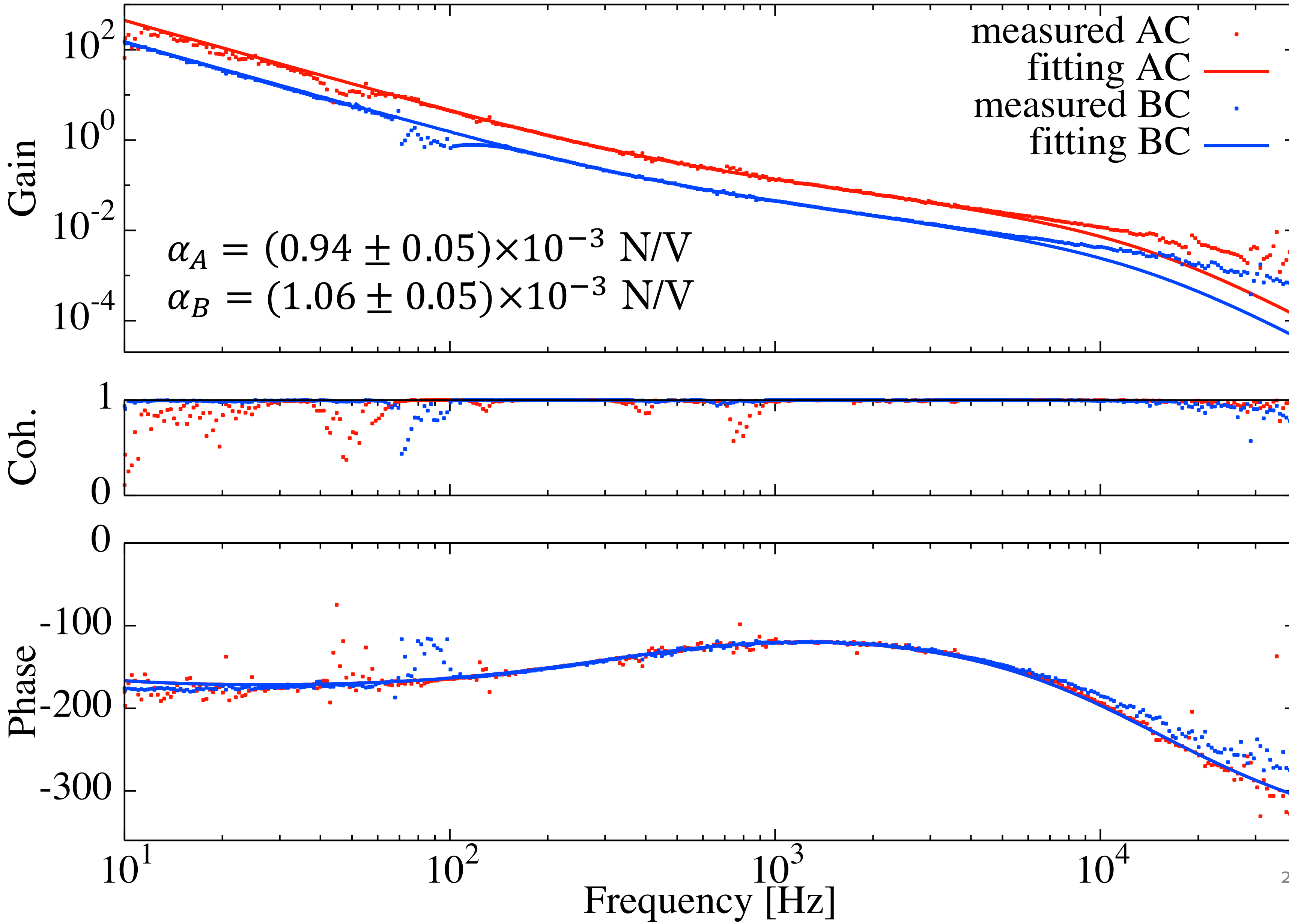


- Suspension fiber: Carbon Fiber
  - Thin ϕ~6 um
  - Low Young's modulus
  - Similar intrinsic Q-value as tungsten around 2000

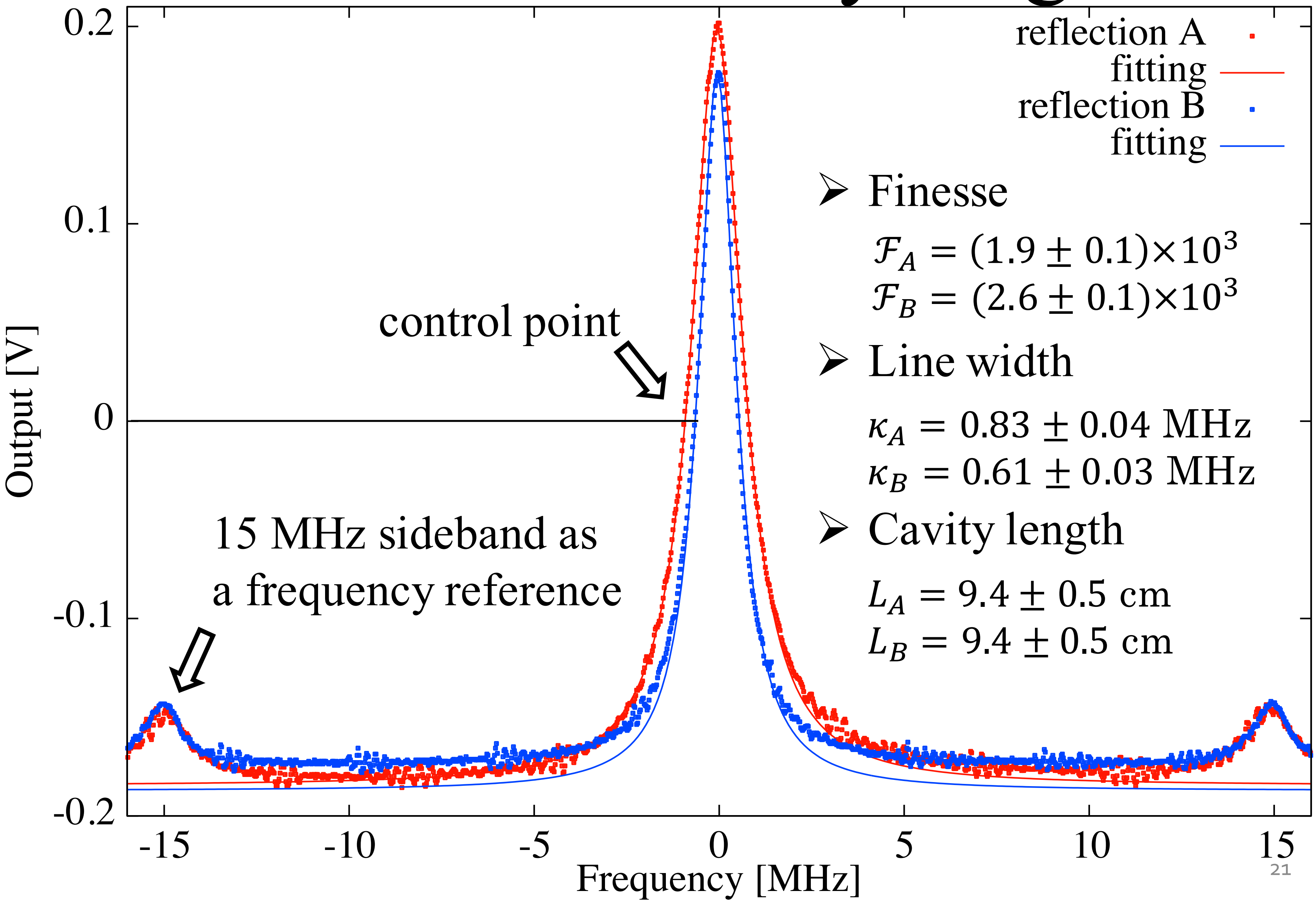
$$S_{th} = \sqrt{\frac{4k_B T_{th} I\omega_m^2}{Q\omega}}$$

$$I\omega_m^2 = \frac{\pi G\phi^4}{32l} \Longrightarrow \frac{\omega_m}{2\pi} \sim 70\ \text{mHz}$$

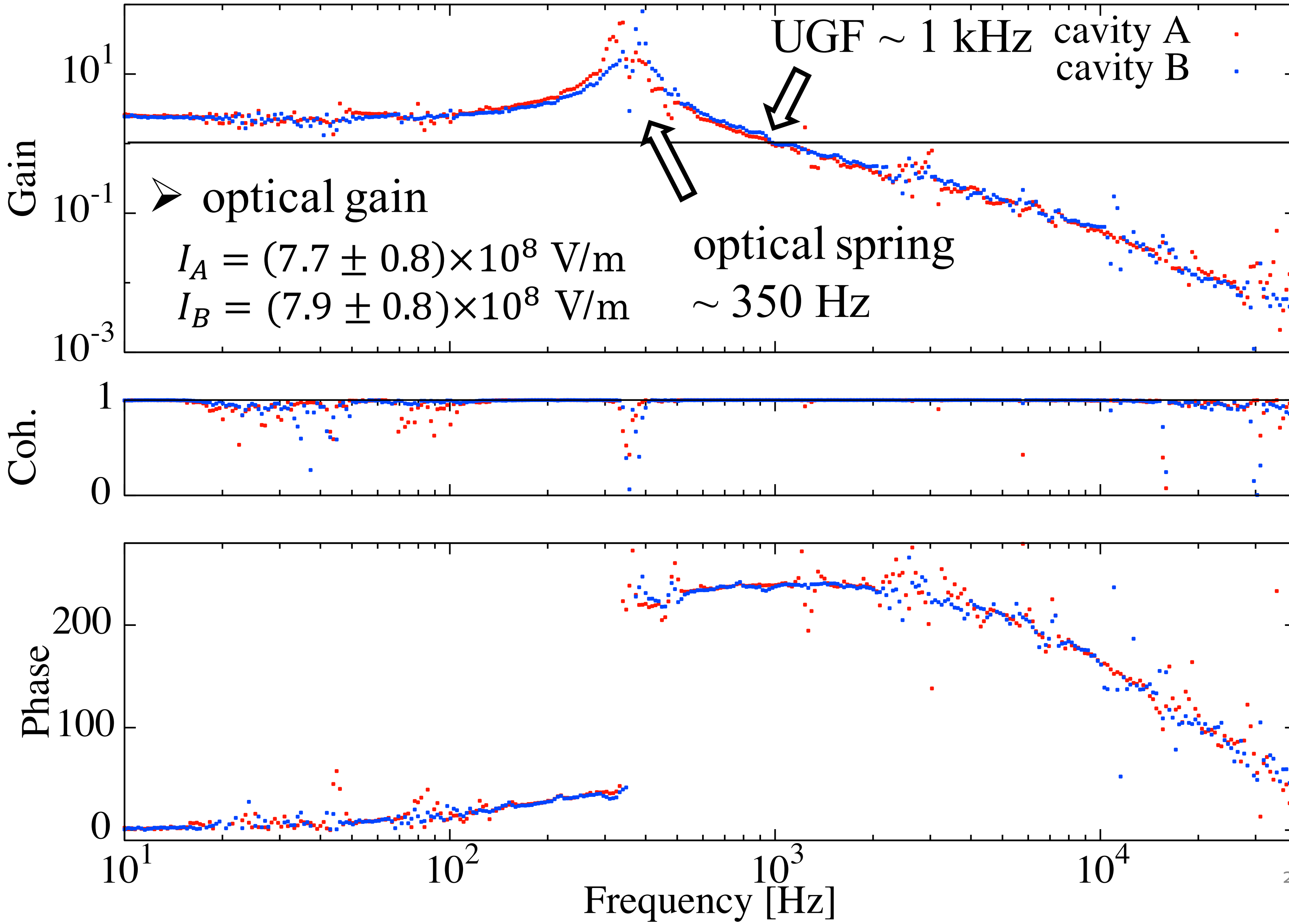
Actuator Efficiency



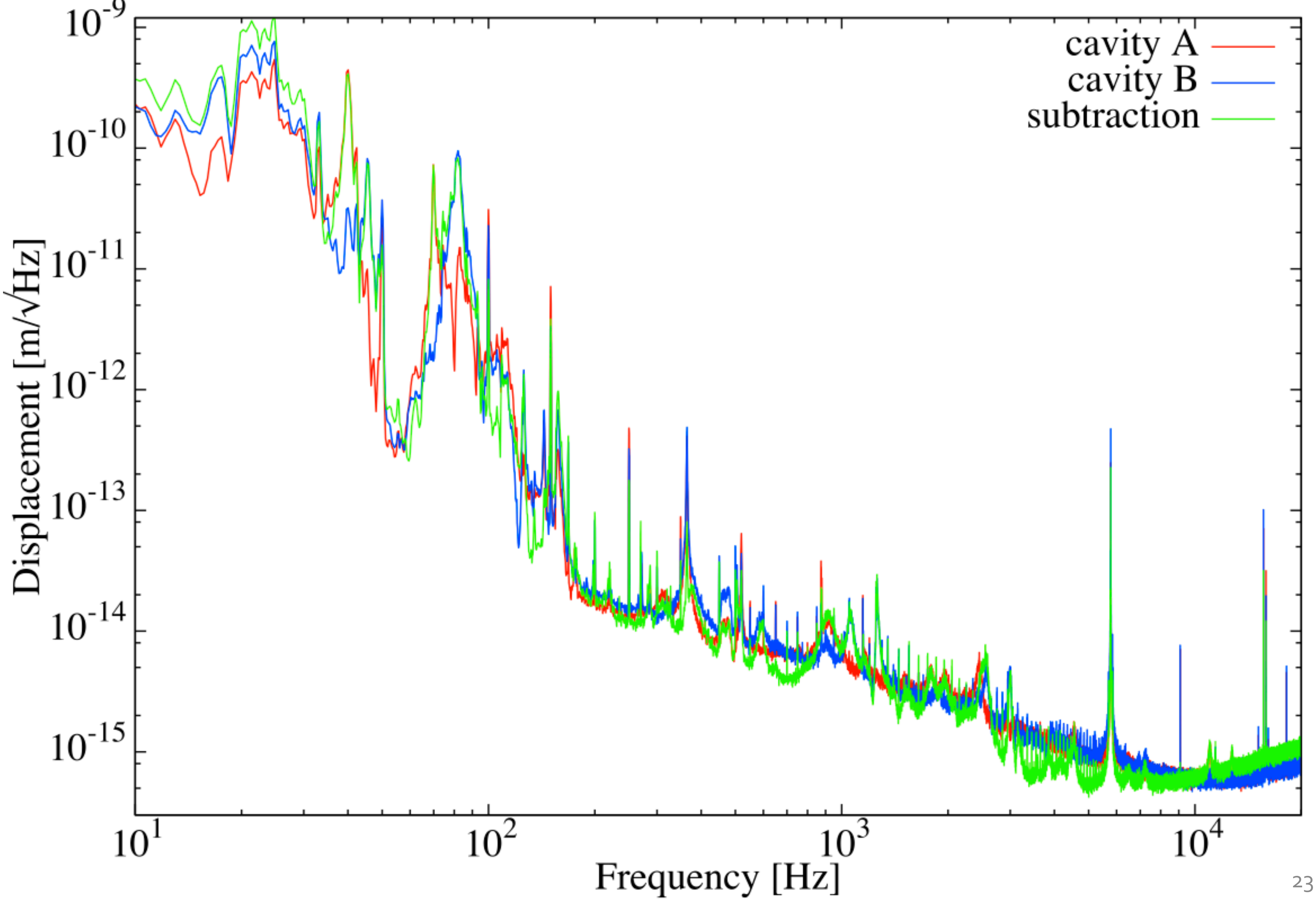
Finesse and cavity length



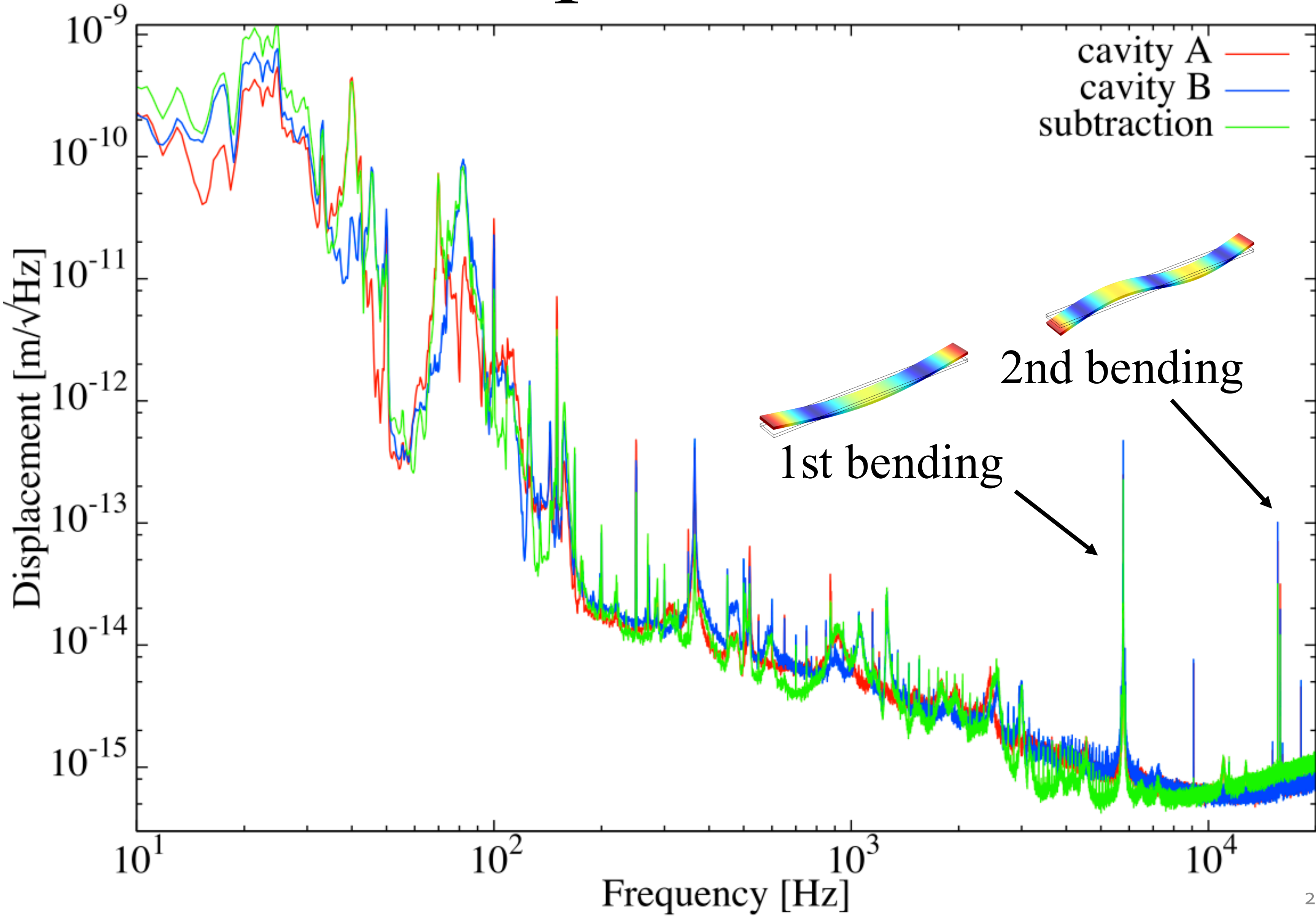
Open-loop transfer function



Displacement

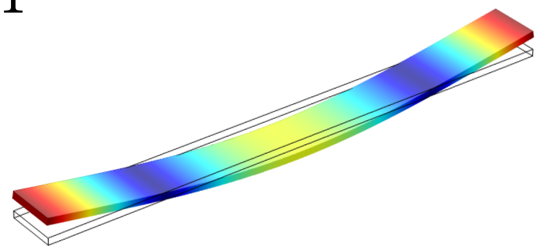


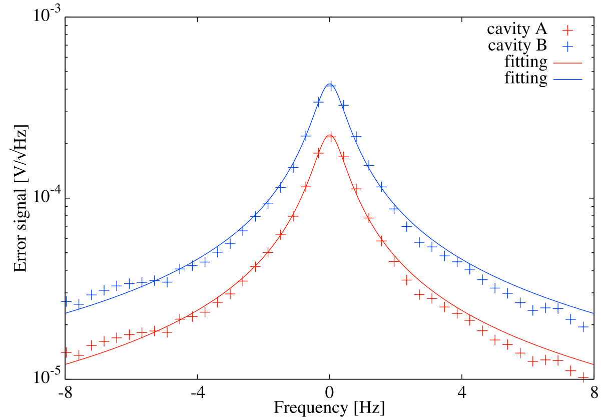
Displacement



Bending motion

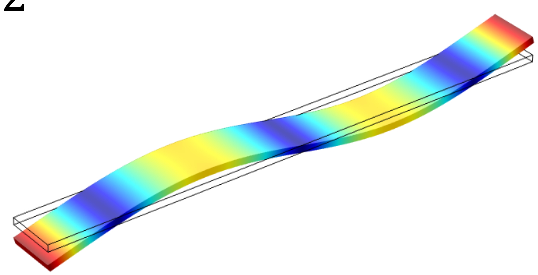
$f_1 = 5.774$ kHz

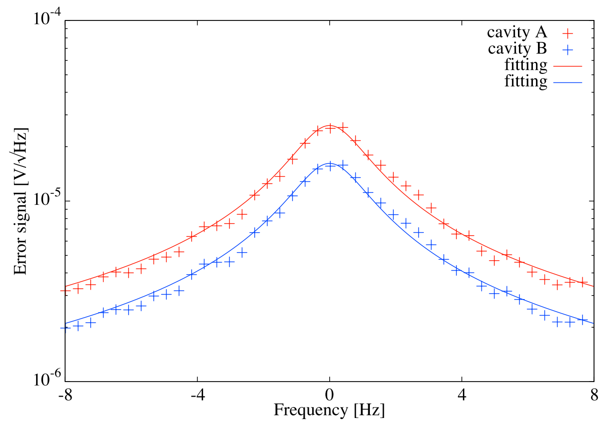




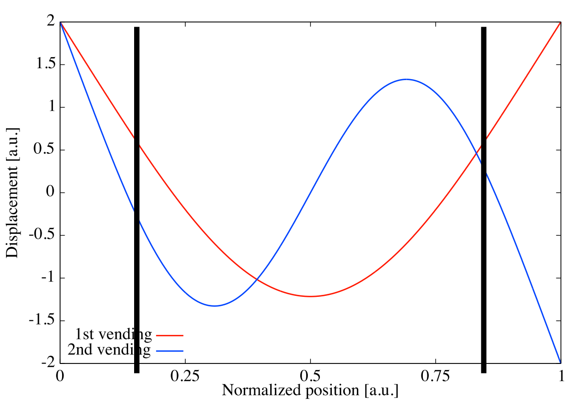
$Q_1 = (6.7 \pm 0.8) \times 10^3$

$f_2 = 15.89$ kHz





$Q_2 = (7.7 \pm 0.9) \times 10^3$

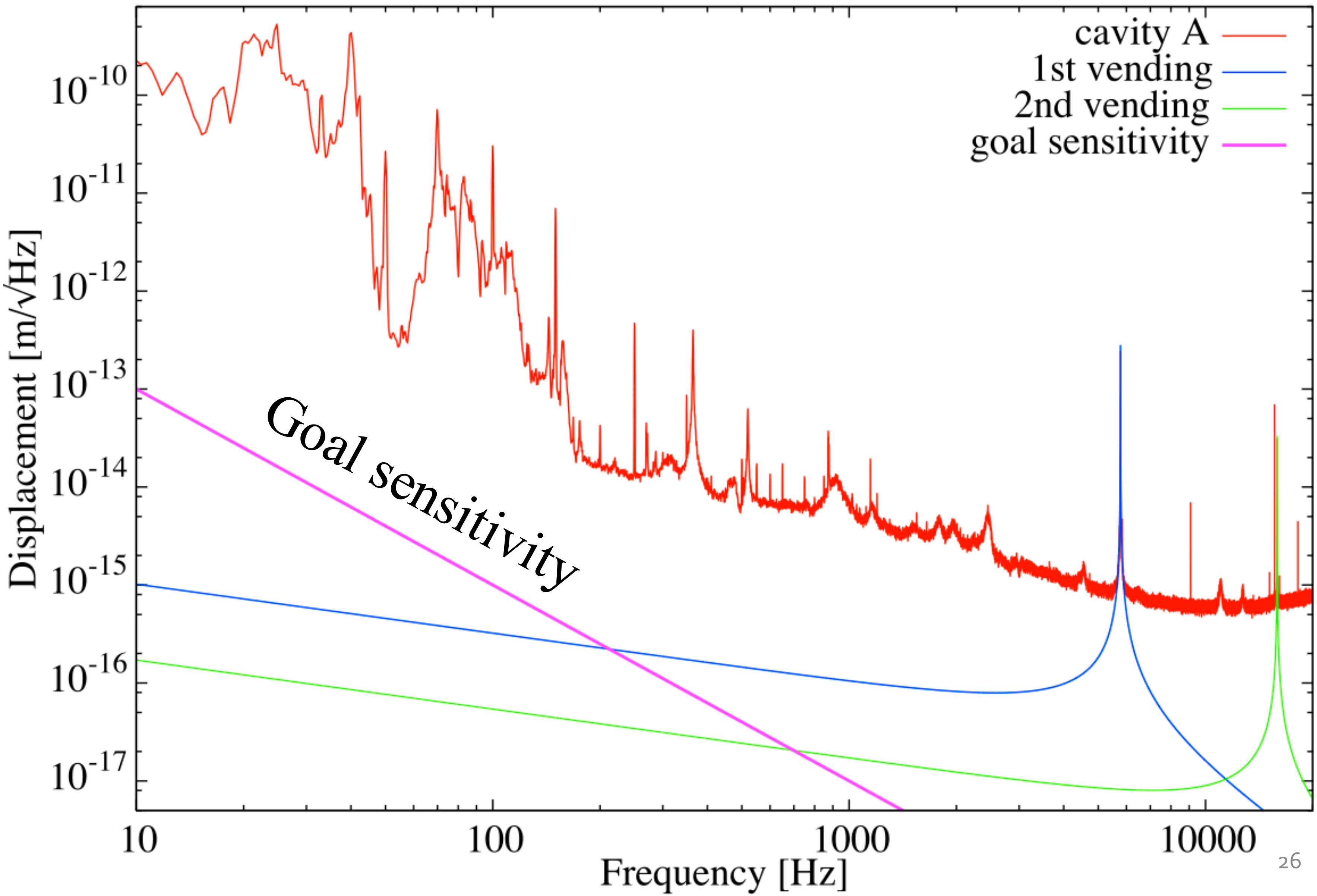


- Beam spot positions on the mirror are estimated by amplitude ratio of these two modes.

$$P_A = 2.3 \pm 0.2 \text{ mm}$$

$$P_B = 2.1 \pm 0.2 \text{ mm}$$

Displacement



Future works

- Higher intra-cavity power

Design: optical spring 800 Hz (intra-cavity power of 10 W)
Current: 350 Hz, actually 600 Hz has been realized.

- PDH control

Small detuning is better, but conversion from DC control to PDH control does not work now…

- Better sensitivity

Frequency noise seems to limit the sensitivity?
Vibration noise is probably also dominant.

Timeline on the last year

Apr. | May | Jun. | Jul.

3/31: took out all previous components from vacuum chamber

design

construction and install

noneq thermal noise

KAGRA sensitivity

Aug. | Sep. | Oct. | Nov.

frequency and intensity stabilization

alignment
cannot see fringe…

found the bar mirror curved! ordering and reconstruction

Dec. | Jan. | Feb. | Mar.

12/17: first observation of fringe
12/18: one arm lock
12/20: second fringe

1/24: 1 second simultaneous lock
1/31: first stable simultaneous lock

commissioning
found 5 Hz oscillation

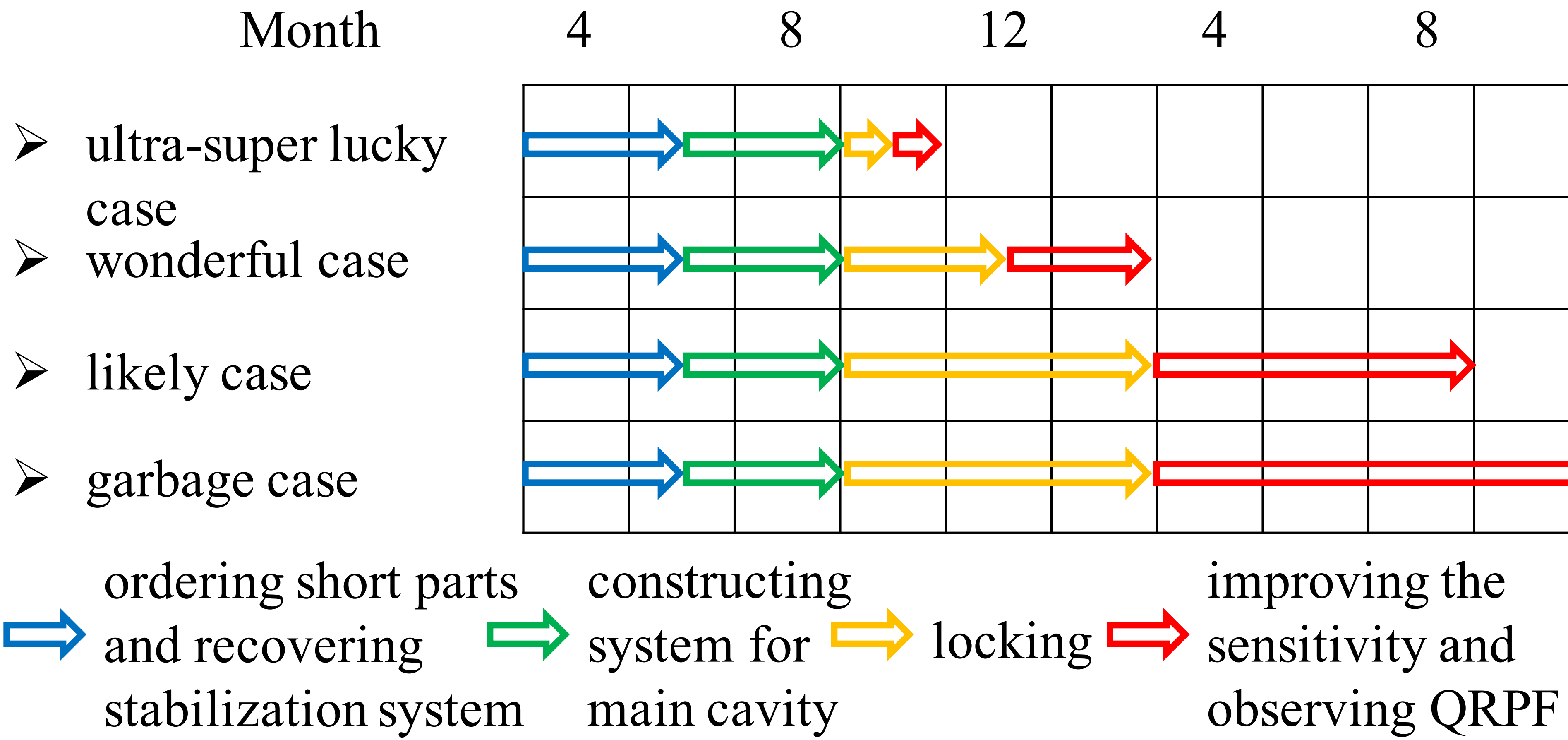
double pendulum

Apr.

damping

4/18: simultaneous lock revived
5/1: got shown data
5/5: reached 600 Hz

Estimation in the last year



- I am on the likely case, not garbage case.

Summary

- We try to measure quantum radiation pressure fluctuation acting on a torsion pendulum.

- A bar-shaped mirror as a torsion pendulum has advantages such as low suspension thermal noise, common mode rejection, light effective mass.

- We succeeded in locking two cavities at both edges simultaneously with high power. Higher power by a few and better sensitivity by two orders are needed towards the goal.