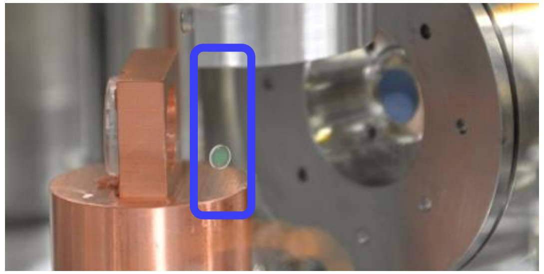
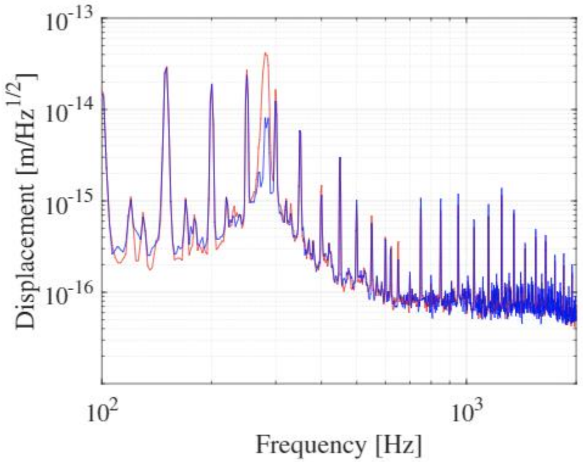
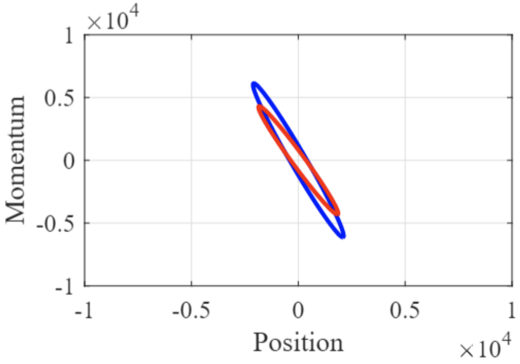


Continuous meas.



Quantum filter



Demonstration of conditional mechanical squeezing of a massive pendulum

Gakushuin University

Nobuyuki Matsumoto

2022/2/10 @KEK

Contents

- Massive objects and thermal decoherence

- Linear continuous measurement

(related article: PRL 122, 071101 (2019))

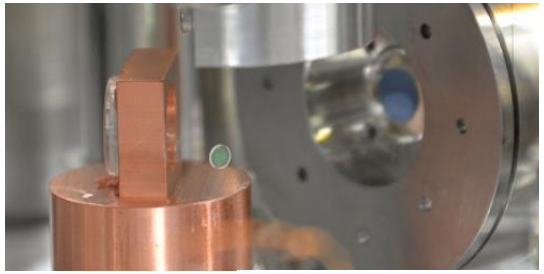
- Conditional mechanical position squeezing

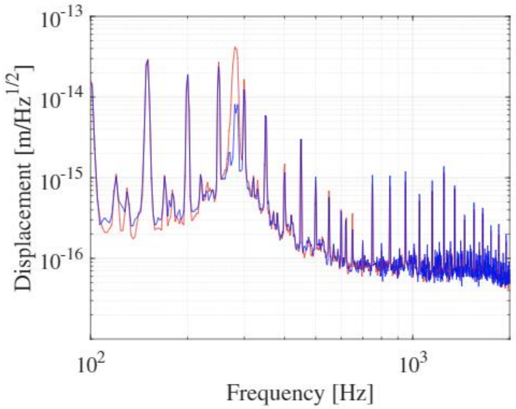
(related article: arXiv:2008.10848)

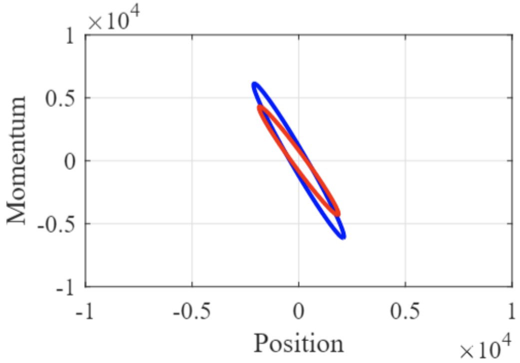
- Low-loss pendulum towards quantum squeezing

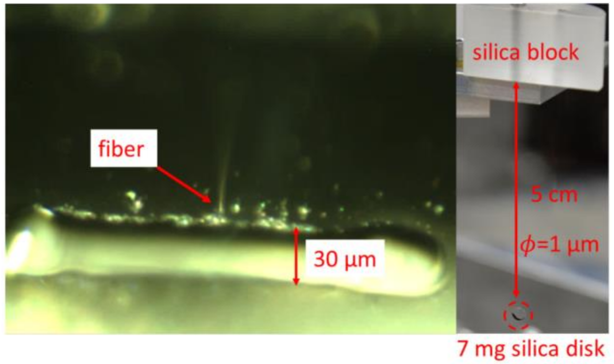
(related article: PRL 124, 221102 (2020))

- Summary



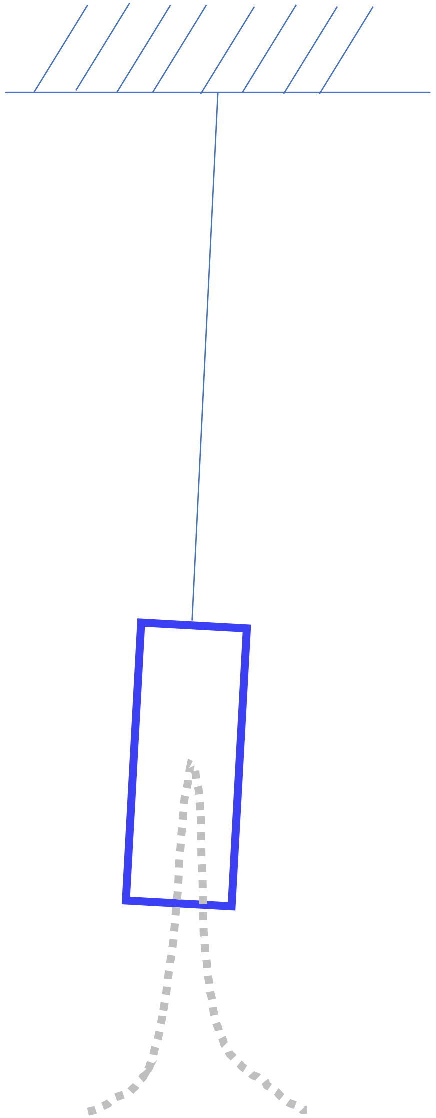






Massive objects and thermal decoherence

- Mass m
- Frequency Ω
- Dissipation γ



- zero point fluctuation spectrum: $S_x^{zp}(\Omega) = \frac{8x_{zpf}^2}{\gamma(\Omega)}$
- $x_{zpf} = \sqrt{\frac{\hbar}{2m\Omega}} = 3 \times 10^{-18}\ \mathrm{m}\ \left(\frac{1\ \mathrm{kg}}{m}\right)^{0.5} \left(\frac{1\ \mathrm{Hz}}{\frac{\Omega}{2\pi}}\right)^{0.5}$

Massive objects and thermal decoherence

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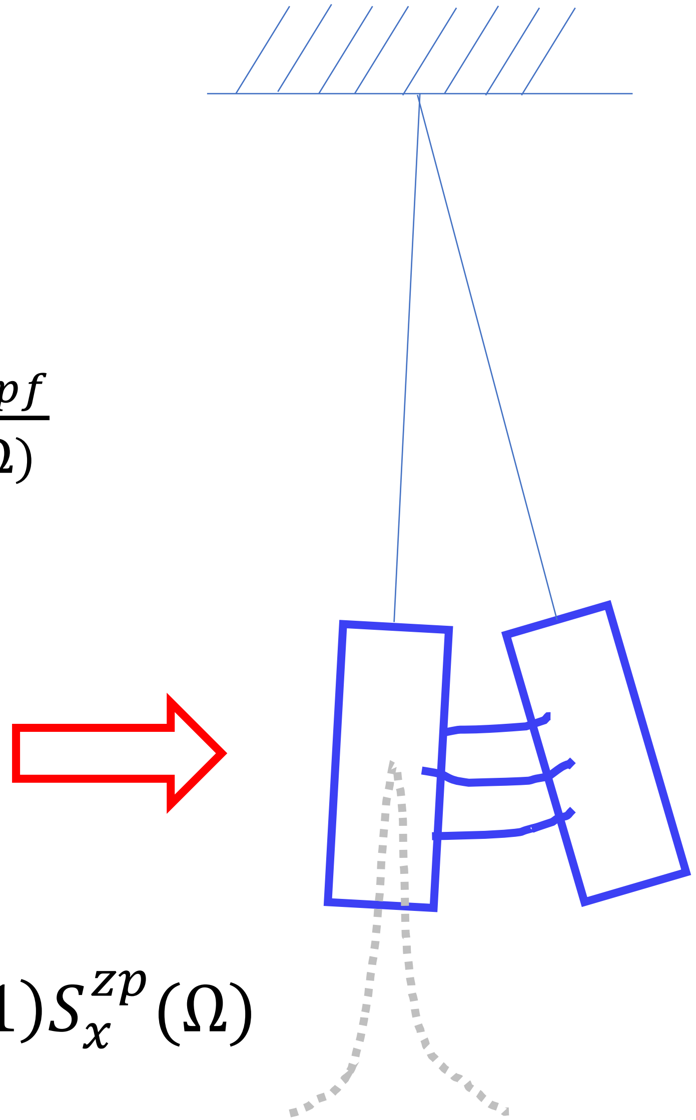
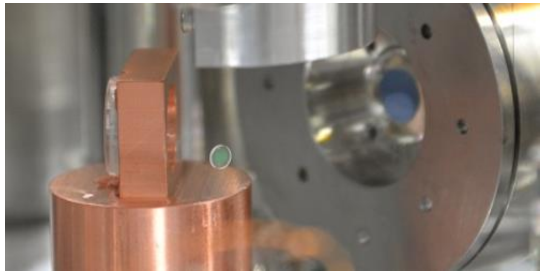


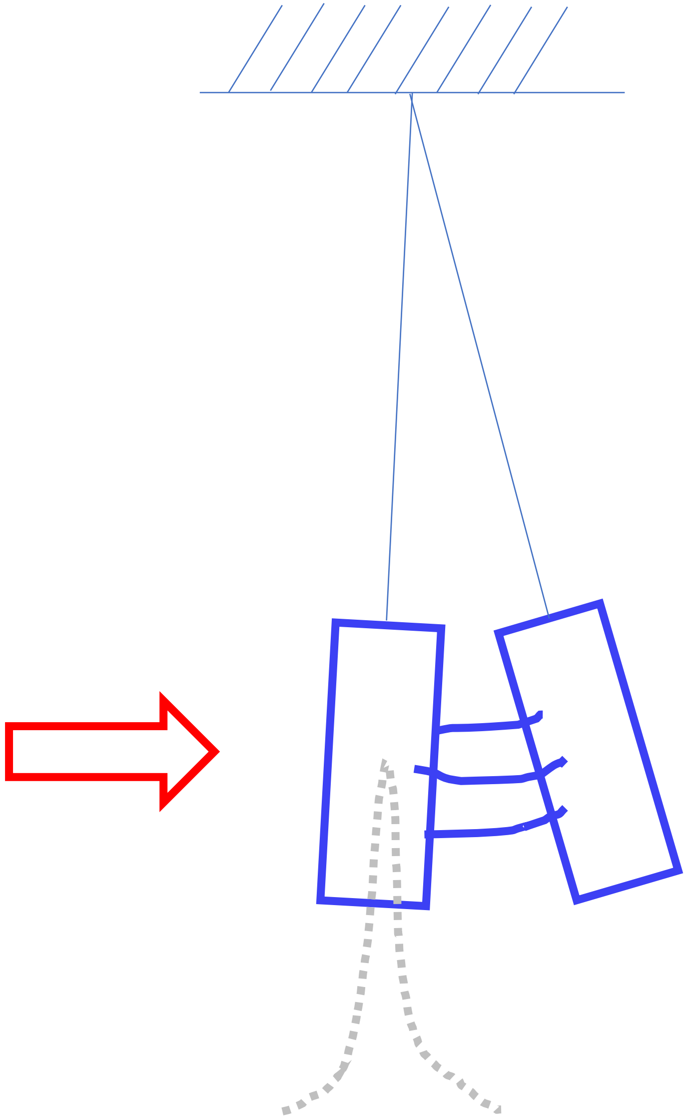
- Thermal decoherence

→Quantum + Brown motion: $S_{xx}(\Omega) = (2n_{th} + 1)S_x^{zp}(\Omega)$

Thermal phonon

- $n_{th} \simeq \frac{k_B T}{\hbar\Omega} \sim 2 \times 10^{10} \left(\frac{T}{300\ \mathrm{K}}\right)\left(\frac{300\ \mathrm{Hz}}{\frac{\Omega}{2\pi}}\right)$





Measurement-based control

- Feedback control

Control algorithm implemented in real physical world

e.g. Coin probability $P(k) = \frac{1}{2}, k = heads, tails$

Measurement-based control

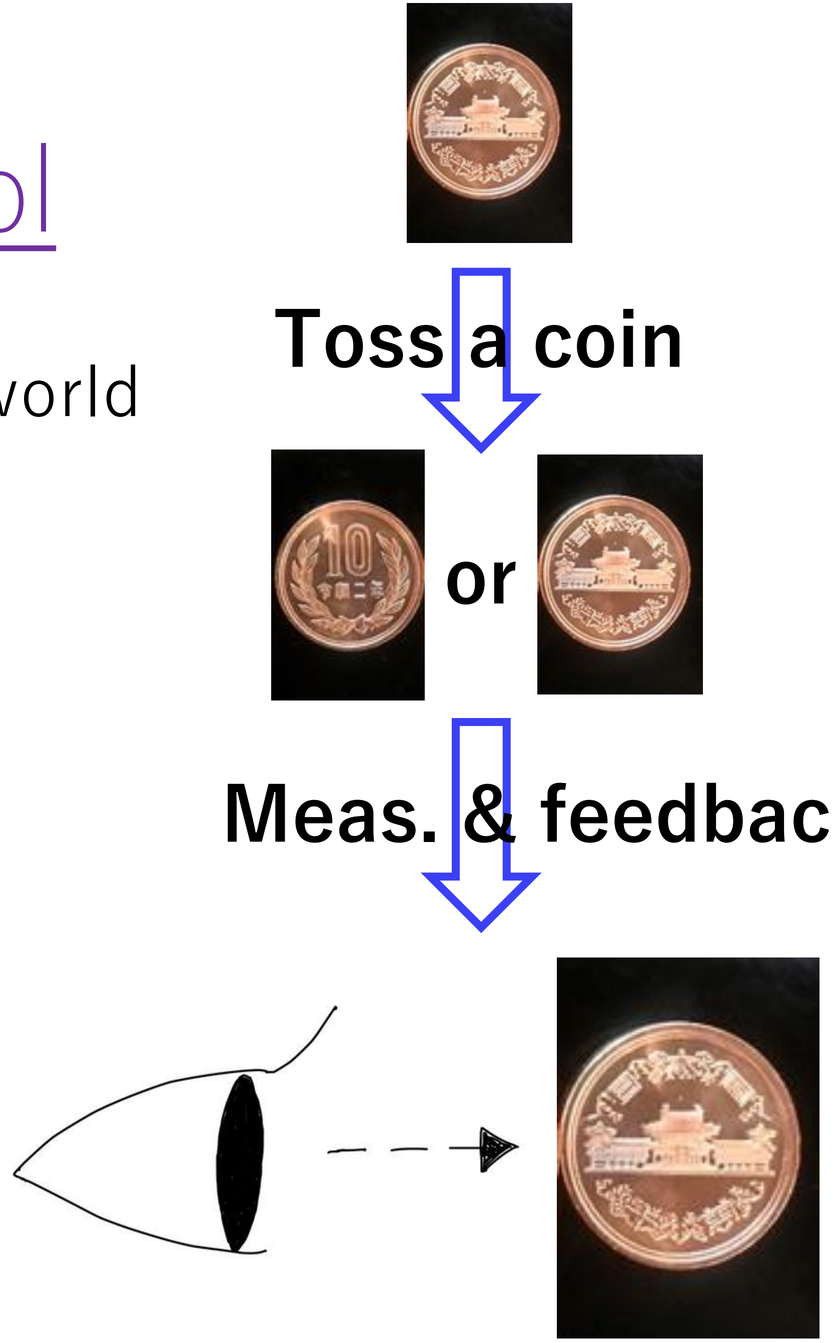
- Feedback control

Control algorithm implemented in real physical world

e.g. Coin probability $P(k) = \frac{1}{2}, k = heads, tails$

Coin is back, then actuators turn it over

$P(heads) = 1$



Measurement-based control

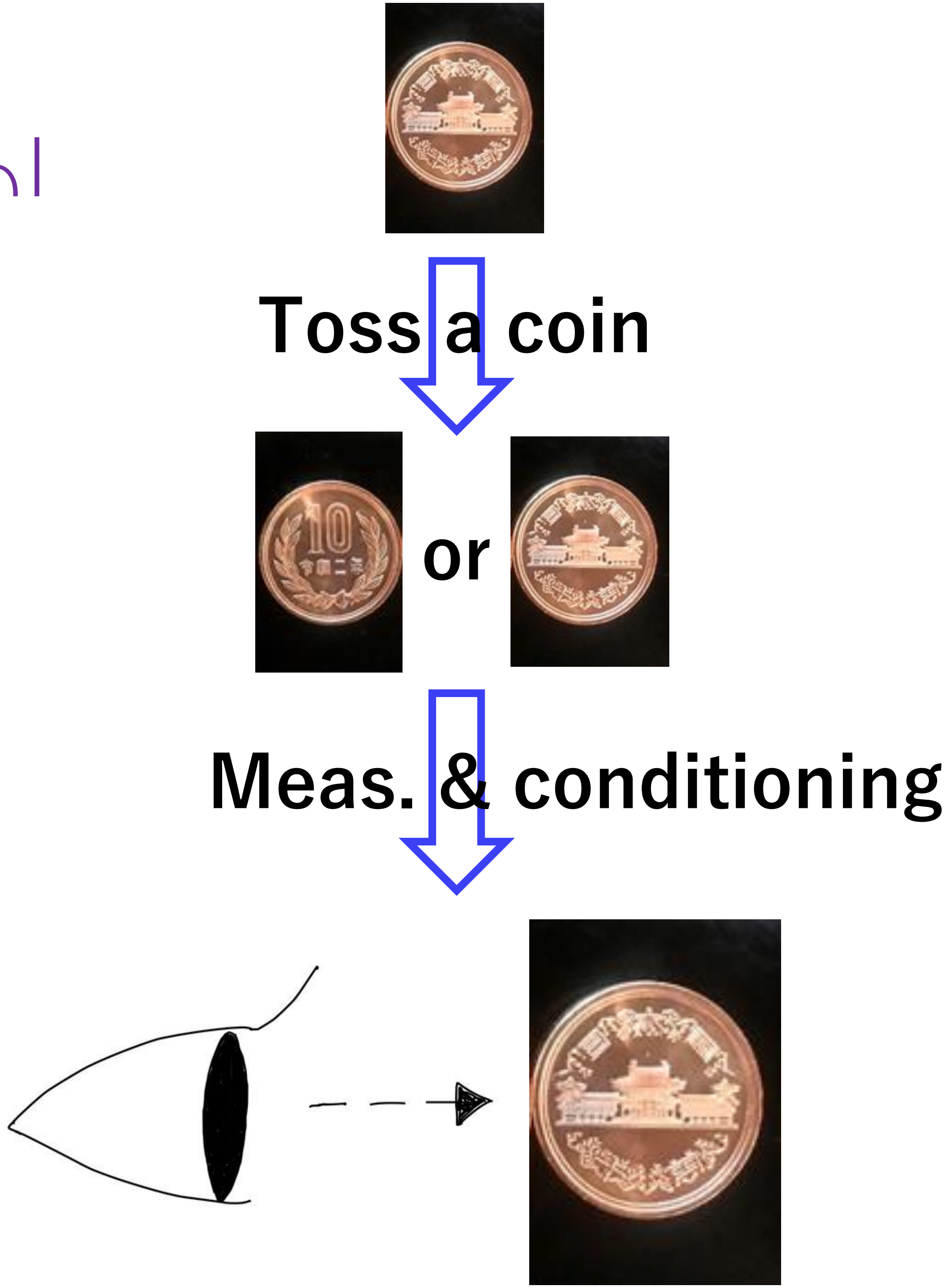
- Conditioning

Control algorithm without actuator

→create a conditional state

e.g. Coin probability $P(k) = \frac{1}{2}, k = heads, tails$

Measurement-based control



- Conditioning

Control algorithm without actuator

→create a conditional state

e.g. Coin probability $P(k) = \frac{1}{2}, k = heads, tails$

Someone tells you it is front, then

$P(heads|heads) = 1$

Measurement-based control

- Continuous position measurement

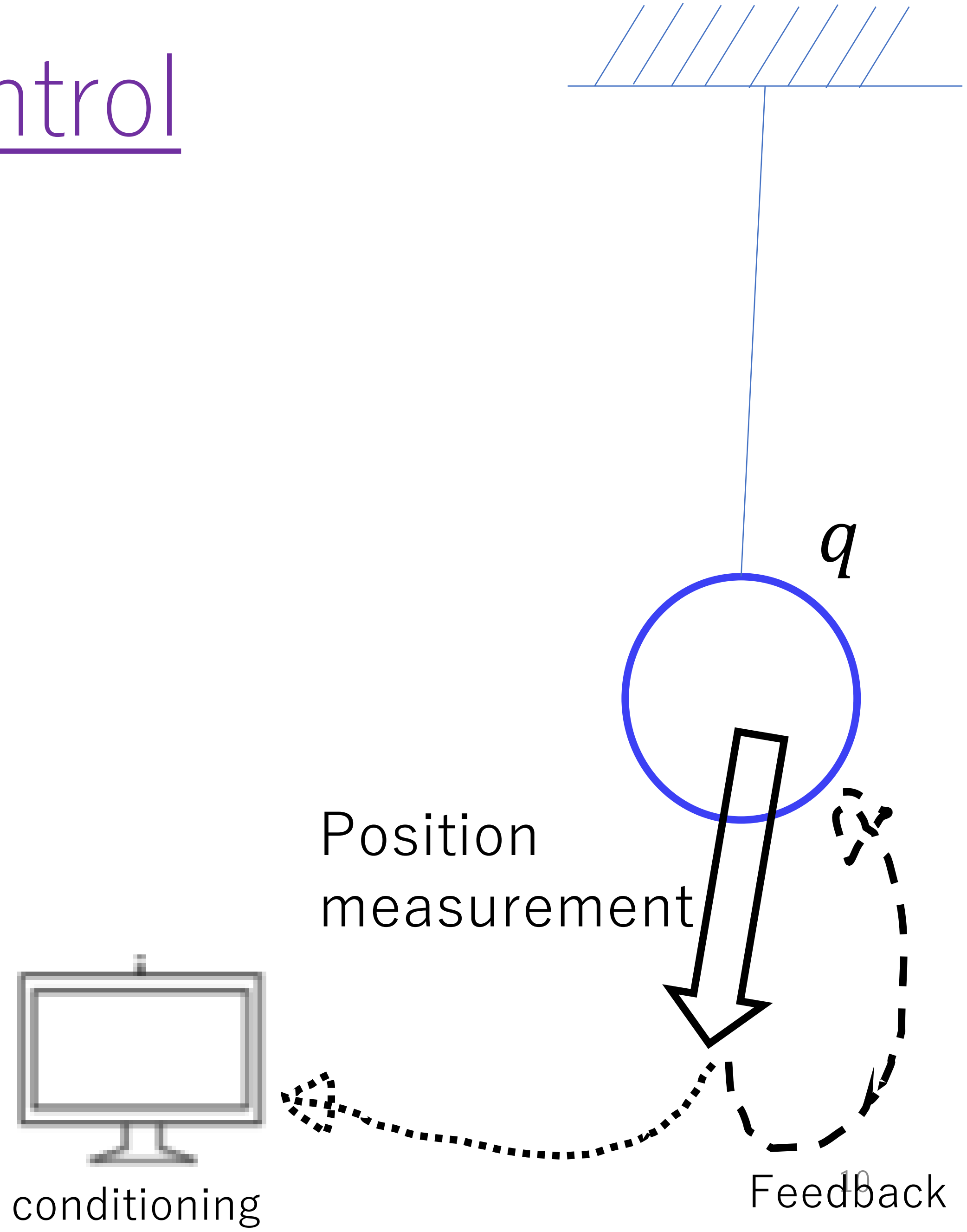
→Obtain velocity by differentiating

- Reduce velocity by FB or conditioning

→reduce mode temperature

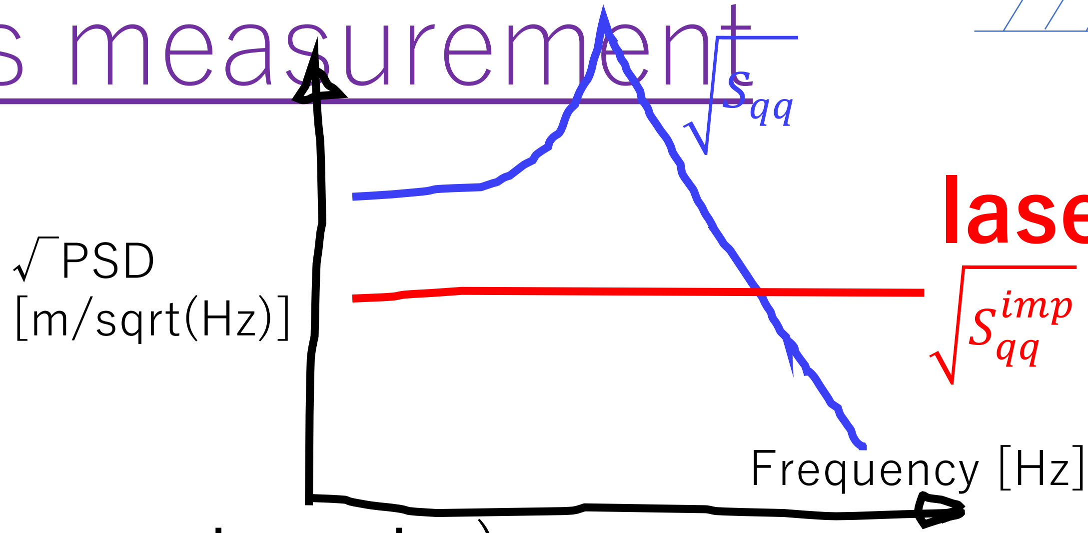
→cooling

- We use the both of control

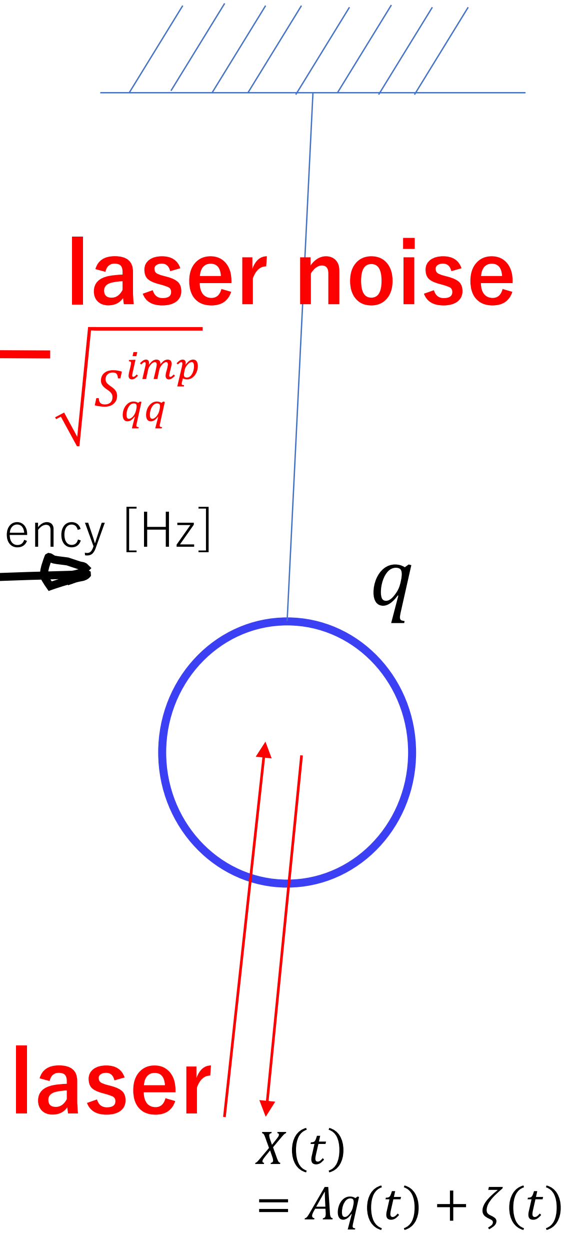


Linear continuous measurement

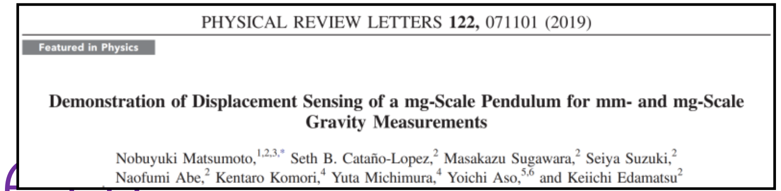
- $X(t) = Aq(t) + \zeta(t)$
- X: optical power
- q: position
- A: sensitivity coefficient
- ζ: sensing noise (read out noise, impression noise)



- Displacement-referred noise level: $S_{qq}^{imp} = \dfrac{S_{\zeta\zeta}}{A^2}$
- Sensitivity (ZPF-referred noise level): $n_{imp} = \dfrac{S_{qq}^{imp}}{2S_{qq}^{zpf}} \propto \gamma$
- Requirement: $n_{imp} \sim \dfrac{1}{2n_{th}} \sim 2 \times 10^{-11} \left(\dfrac{300\ \mathrm{K}}{T}\right)\left(\dfrac{\frac{\Omega}{2\pi}}{300\ \mathrm{Hz}}\right)$



Result1: continuous measurement

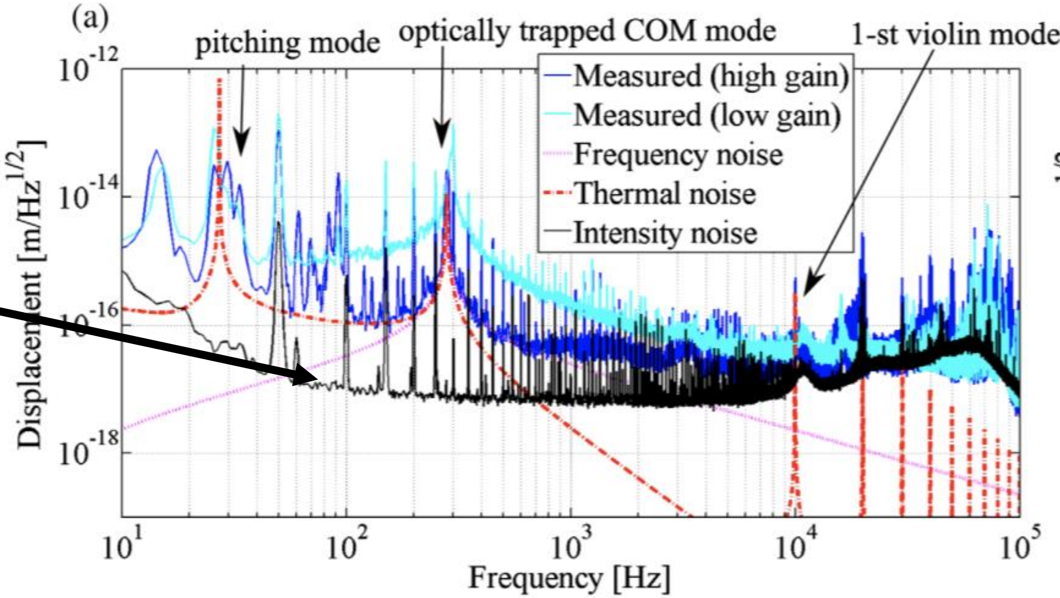

PHYSICAL REVIEW LETTERS 122, 071101 (2019)

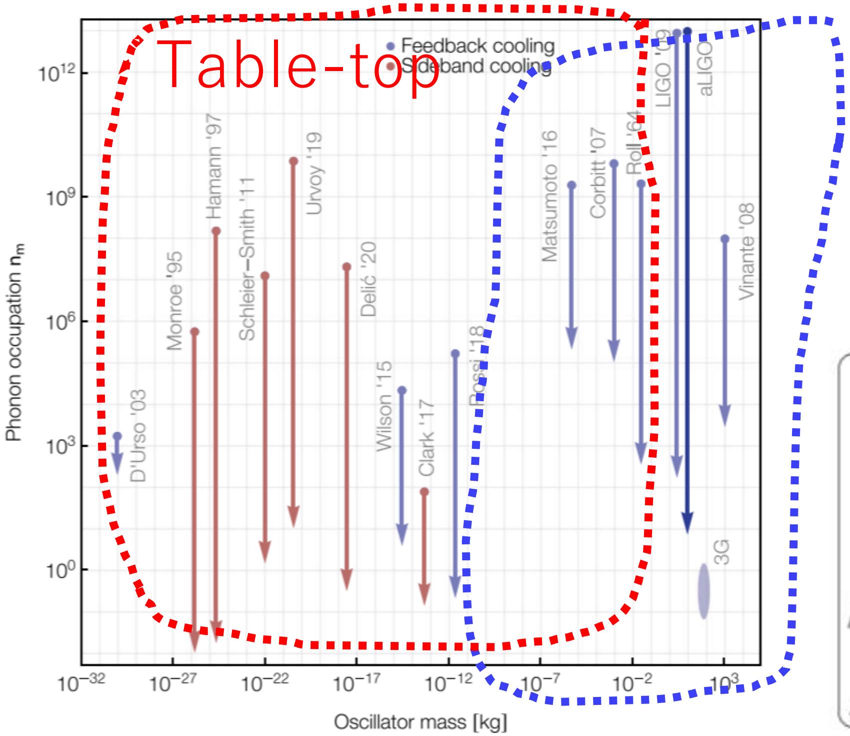
Featured in Physics

Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements

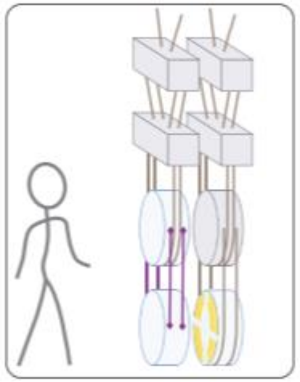
Nobuyuki Matsumoto,[1,2,3,*] Seth B. Cataño-Lopez,[2] Masakazu Sugawara,[2] Seiya Suzuki,[2] Naofumi Abe,[2] Kentaro Komori,[4] Yuta Michimura,[4] Yoichi Aso,[5,6] and Keiichi Edamatsu[2]

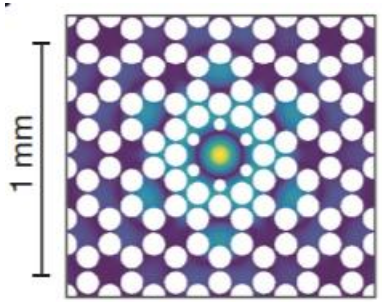
- $\sqrt{S_{qq}^{imp}} \simeq 10^{-17}\ \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$
- $n_{imp} \simeq 3 \times 10^{-8}$
- Requirement: $n_{imp} \sim 2 \times 10^{-11}$

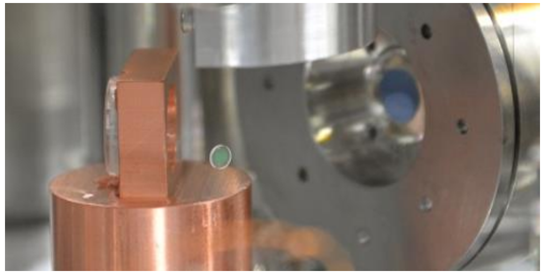




Unexplored region



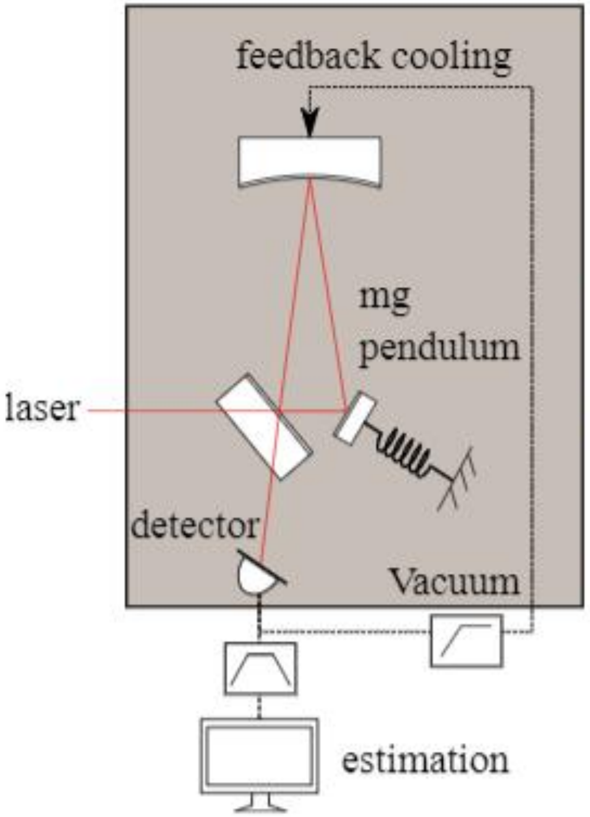


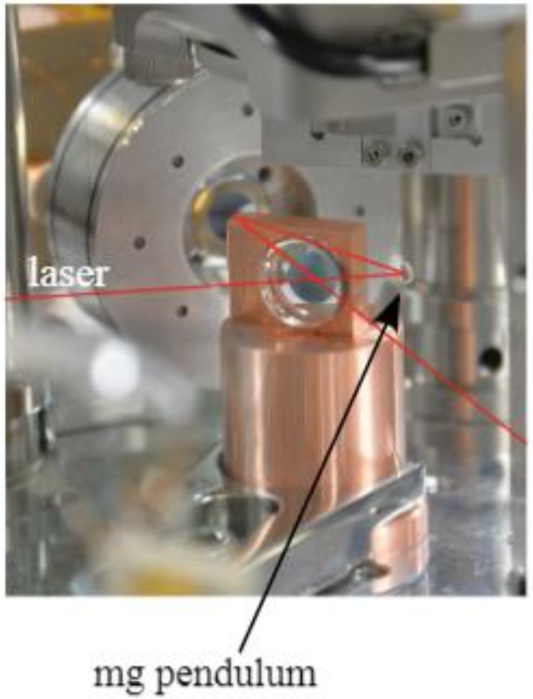


$n_{imp} \simeq 10^{-7}$, Nature 563, 53–58 (2018).
$n_{imp} \simeq 3.5 \times 10^{-13}$, Science 372, 1333-1336 (2021)

Our system

- Hamiltonian
- $H = \frac{\hbar\Omega}{4}(q^2 + p^2) - \frac{\hbar\Delta}{4}(x^2 + y^2) + \hbar g x q$



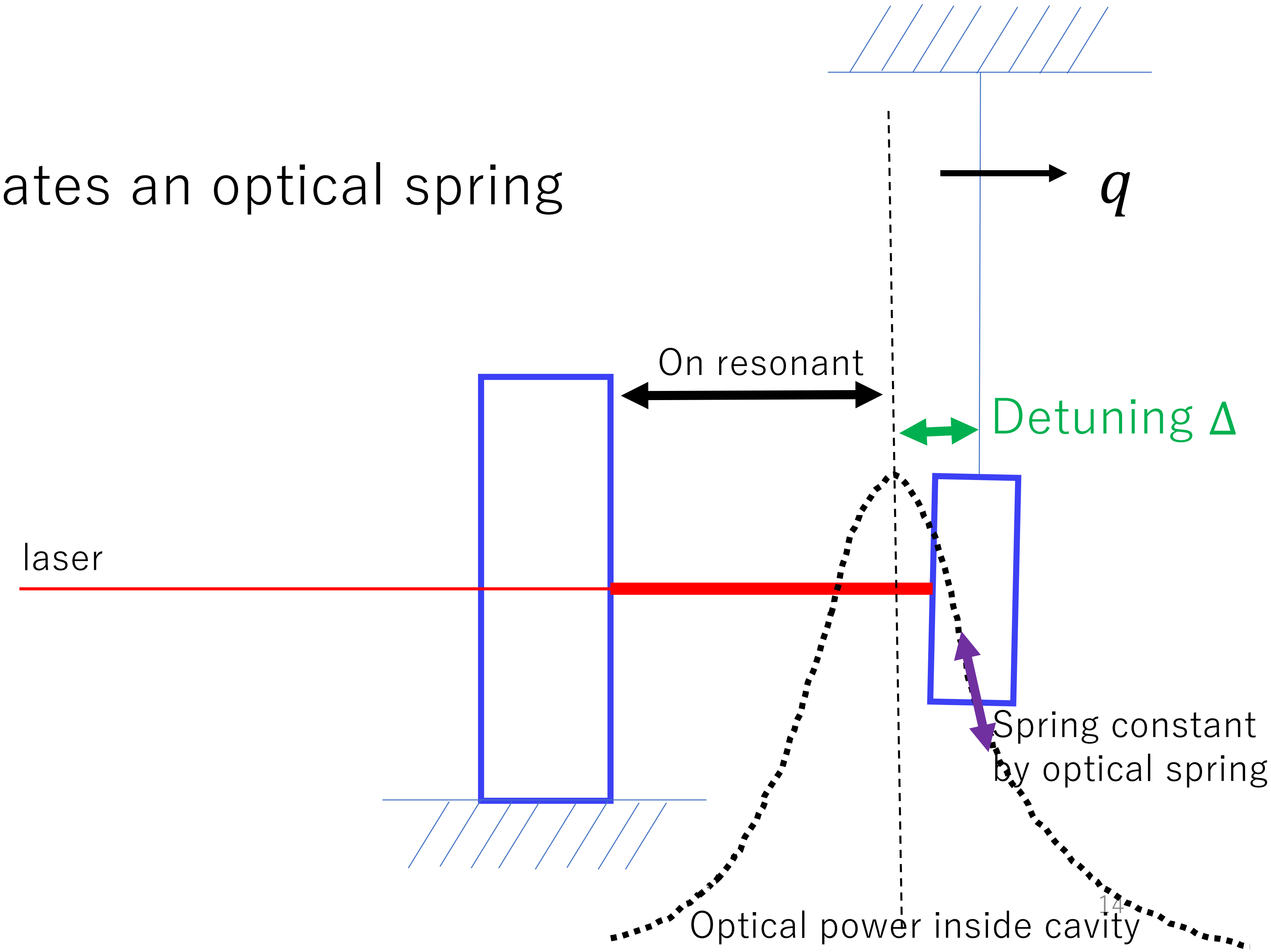


- Equation of motion
- $\dot{q} = \omega_m p$
- $\dot{p} = -\omega_m q - \gamma_m p + noise\ terms$
- $X = Aq + noise\ terms$ （X: traveling wave, x: cavity mode）

- Optical spring increases resonance: $\Omega \to \omega_m$
- Feedback cooling decreases mode temperature

Optical spring

- Detuned cavity creates an optical spring



Optical spring

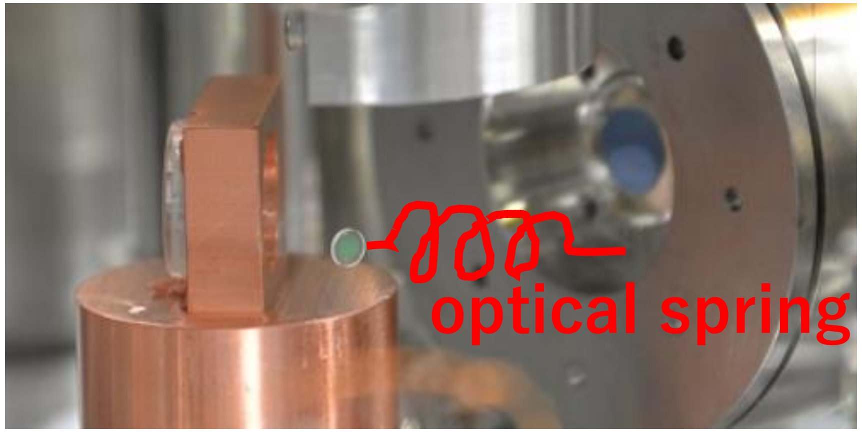
- Cavity with a pendulum

→**optically trapped pendulum**

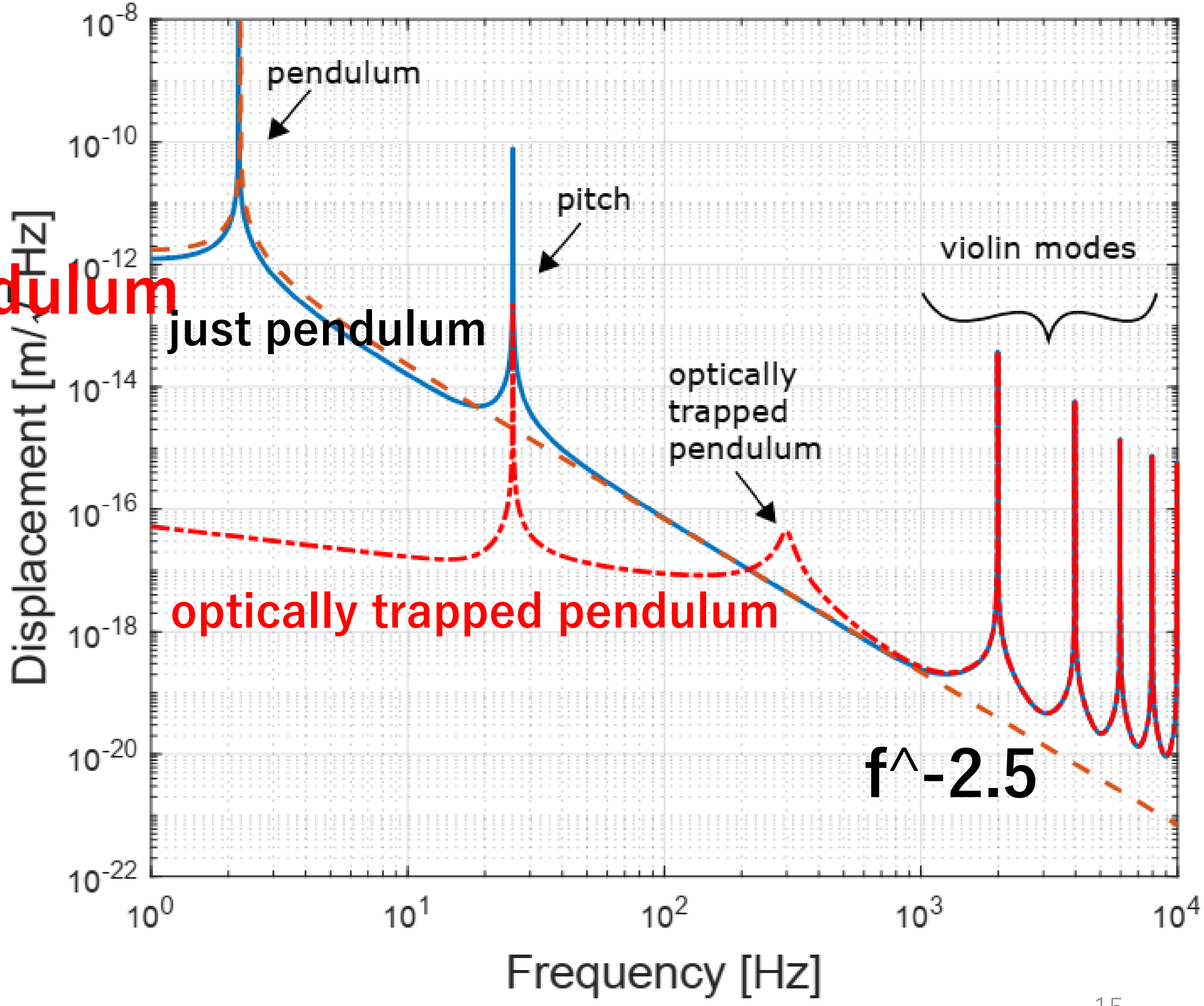
- $n = \frac{1}{\exp\frac{\hbar\omega}{k_B T} - 1} \simeq 0$

→entropy is about 0

→0 K thermal bath



Spectrum of Brownian motion



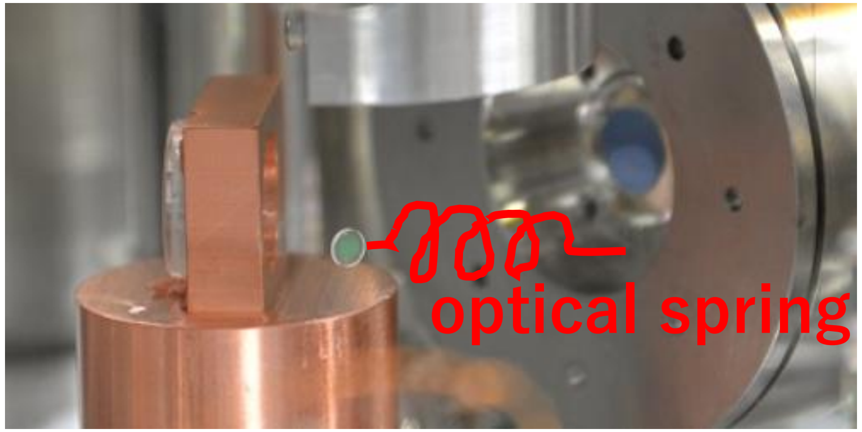
Optical spring

- **Cavity with a pendulum**

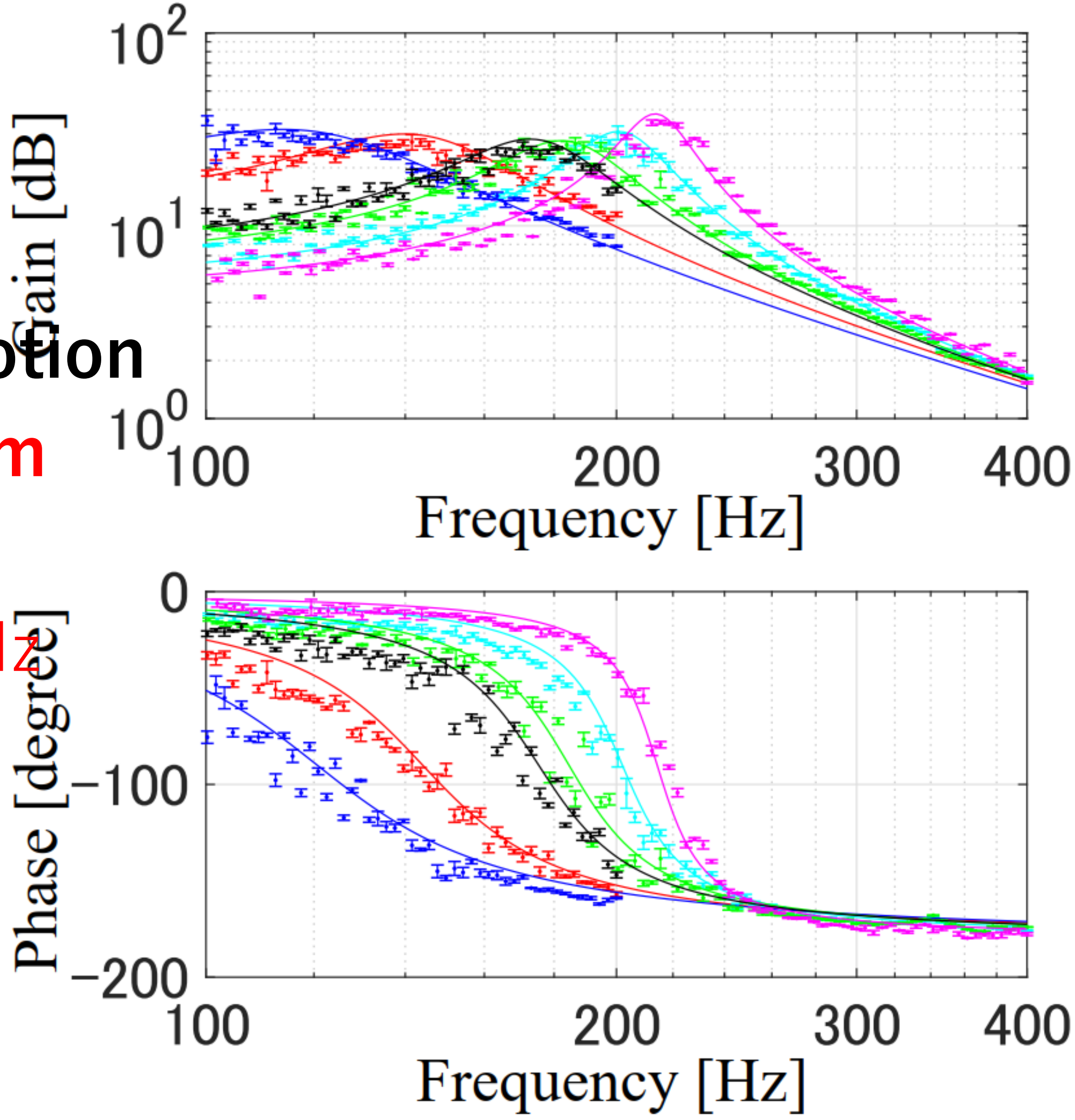
→measurement of Brown motion

of optically trapped pendulum

Main experiment. 4 Hz→300 Hz



characterization of optical spring



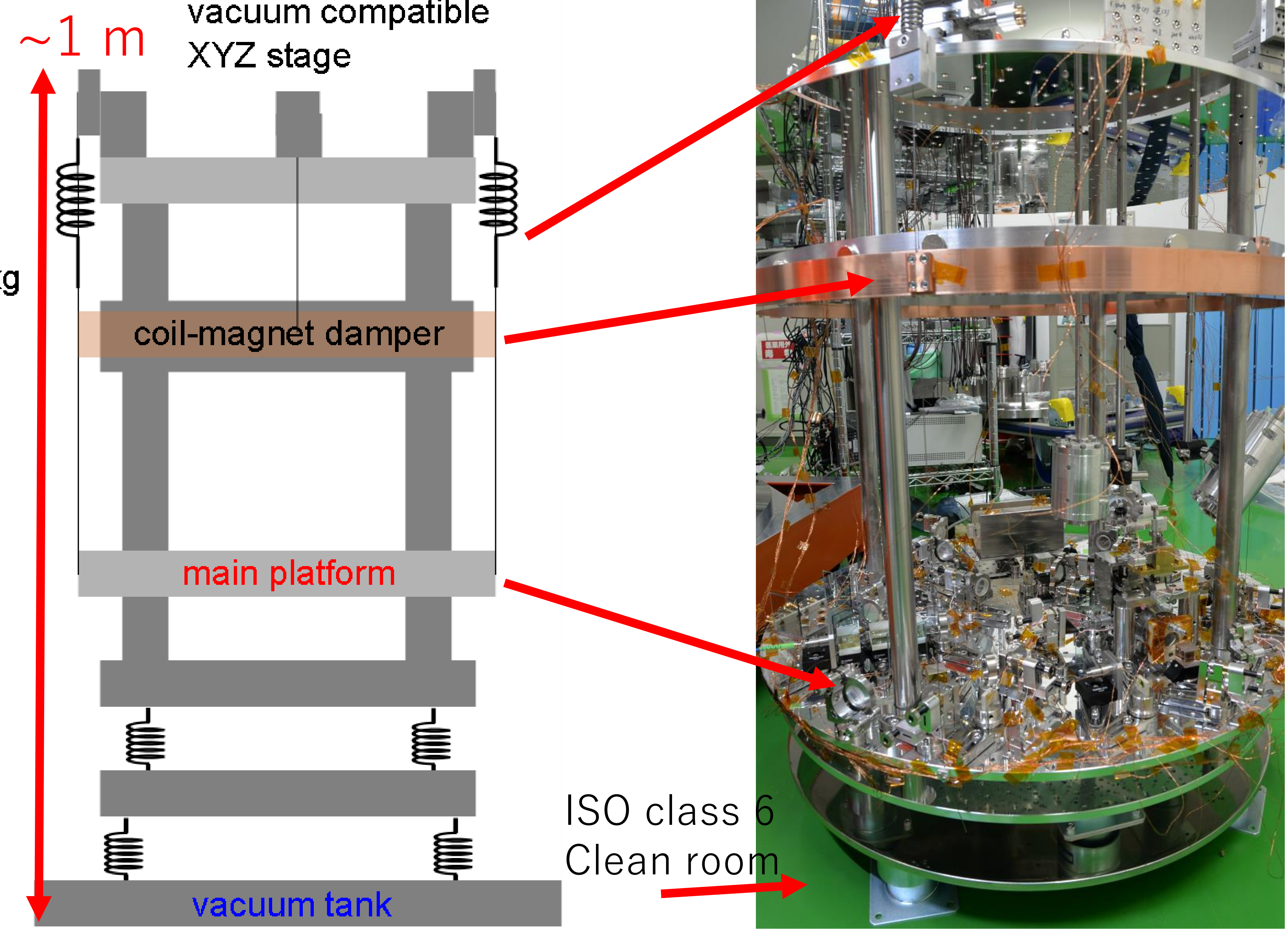
Setup

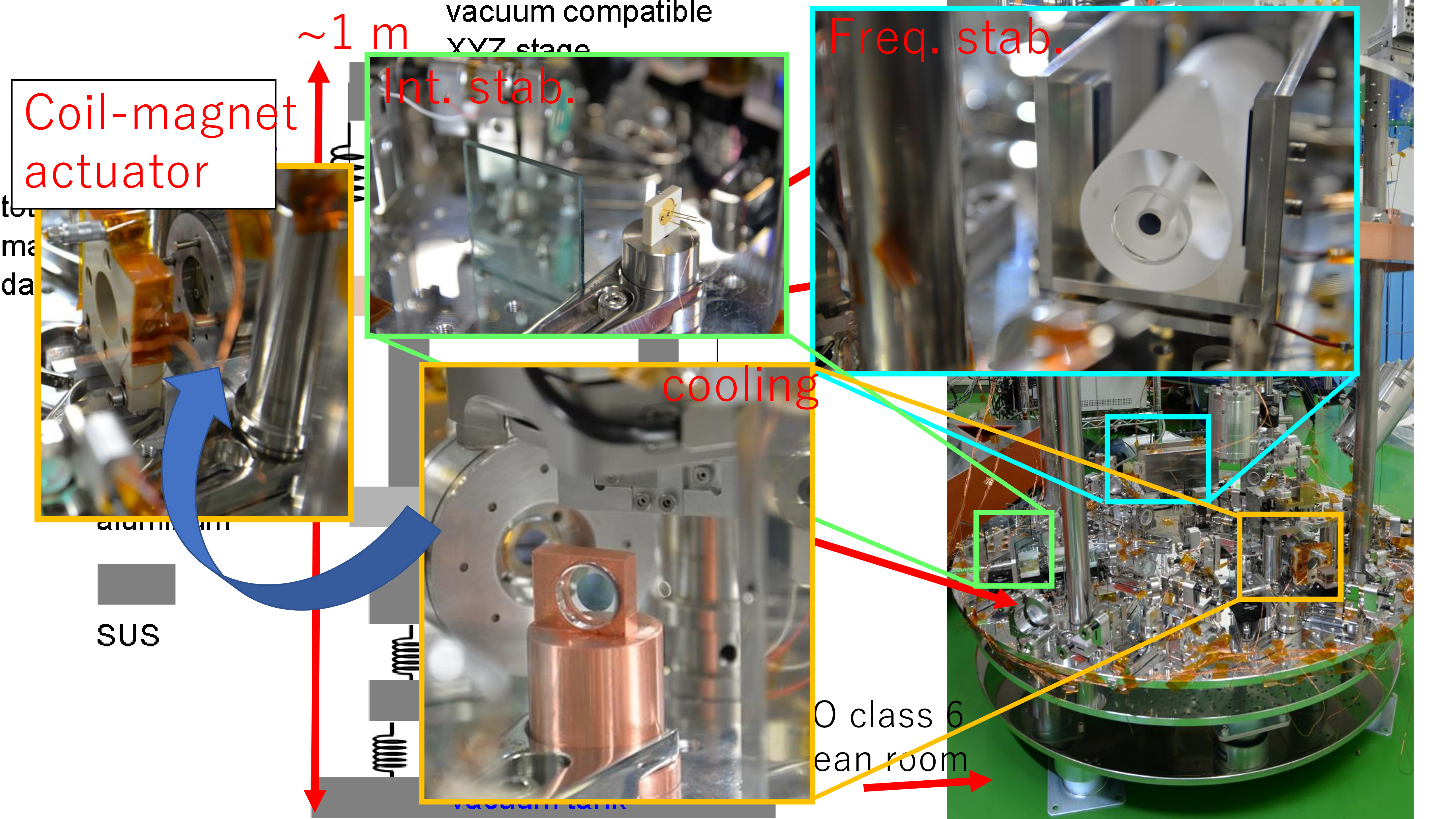
total mass ~ 120 kg
main platform ~ 20 kg
damper ~ 10 kg × 2

copper

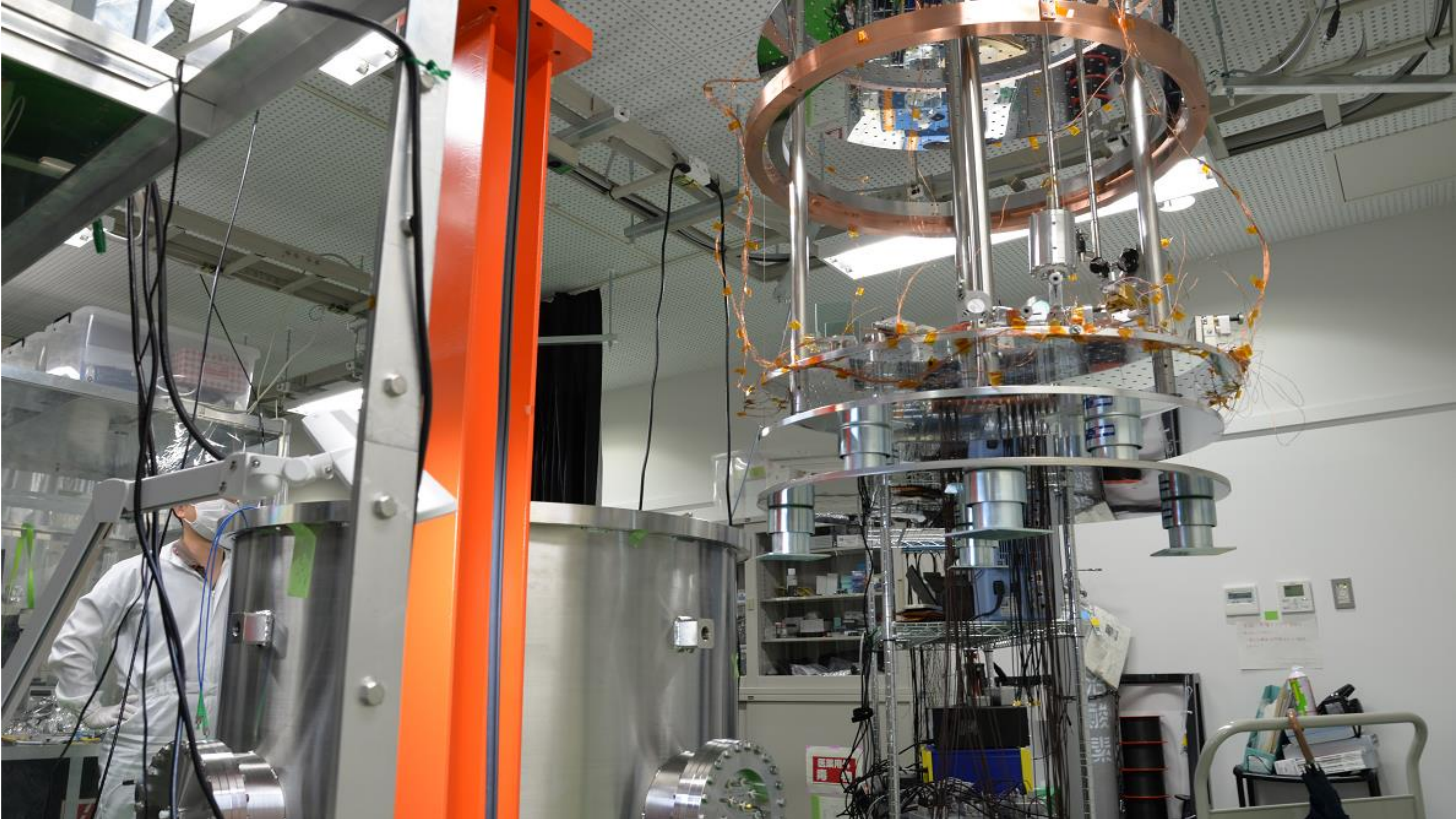
aluminum

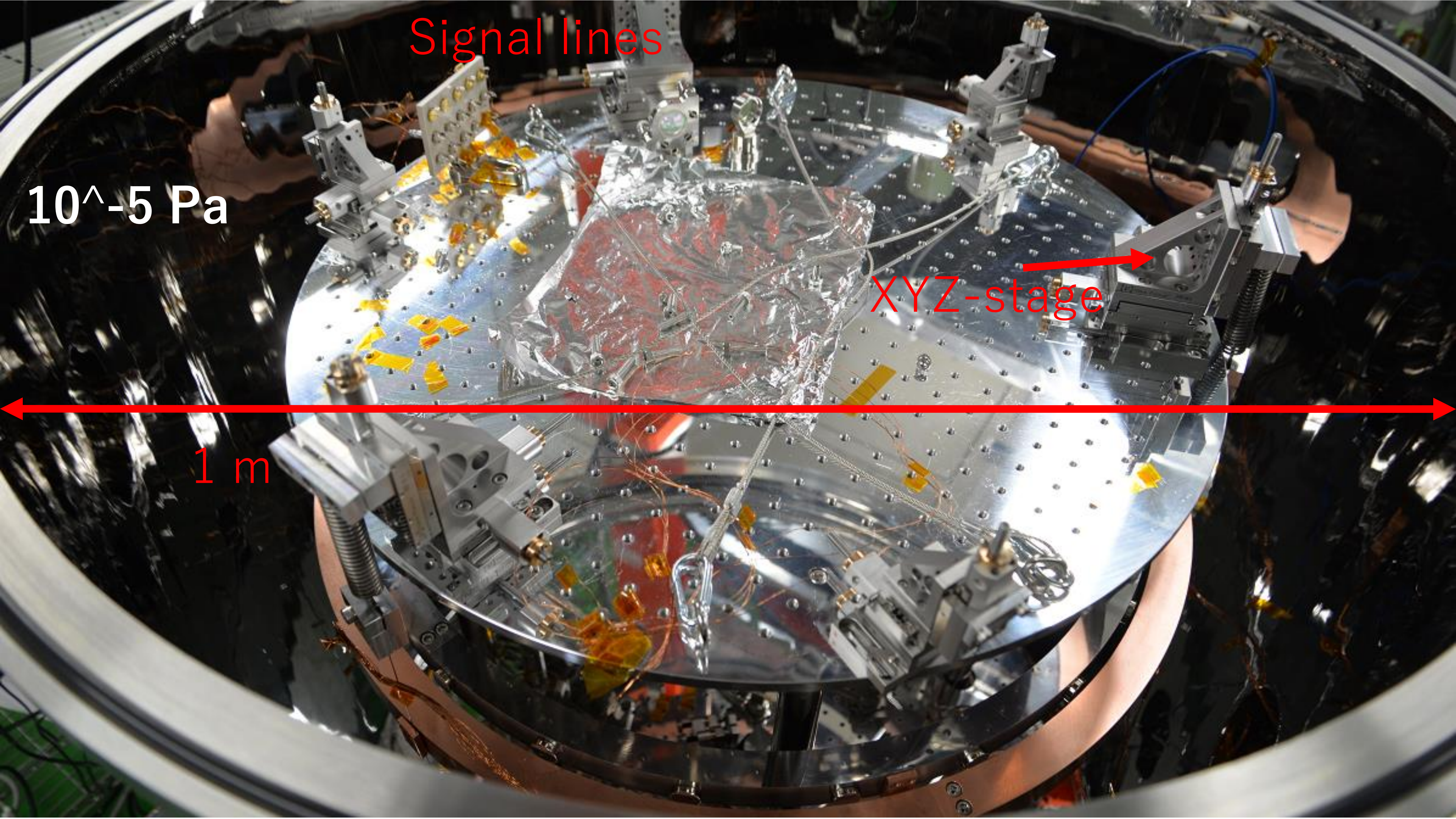
SUS

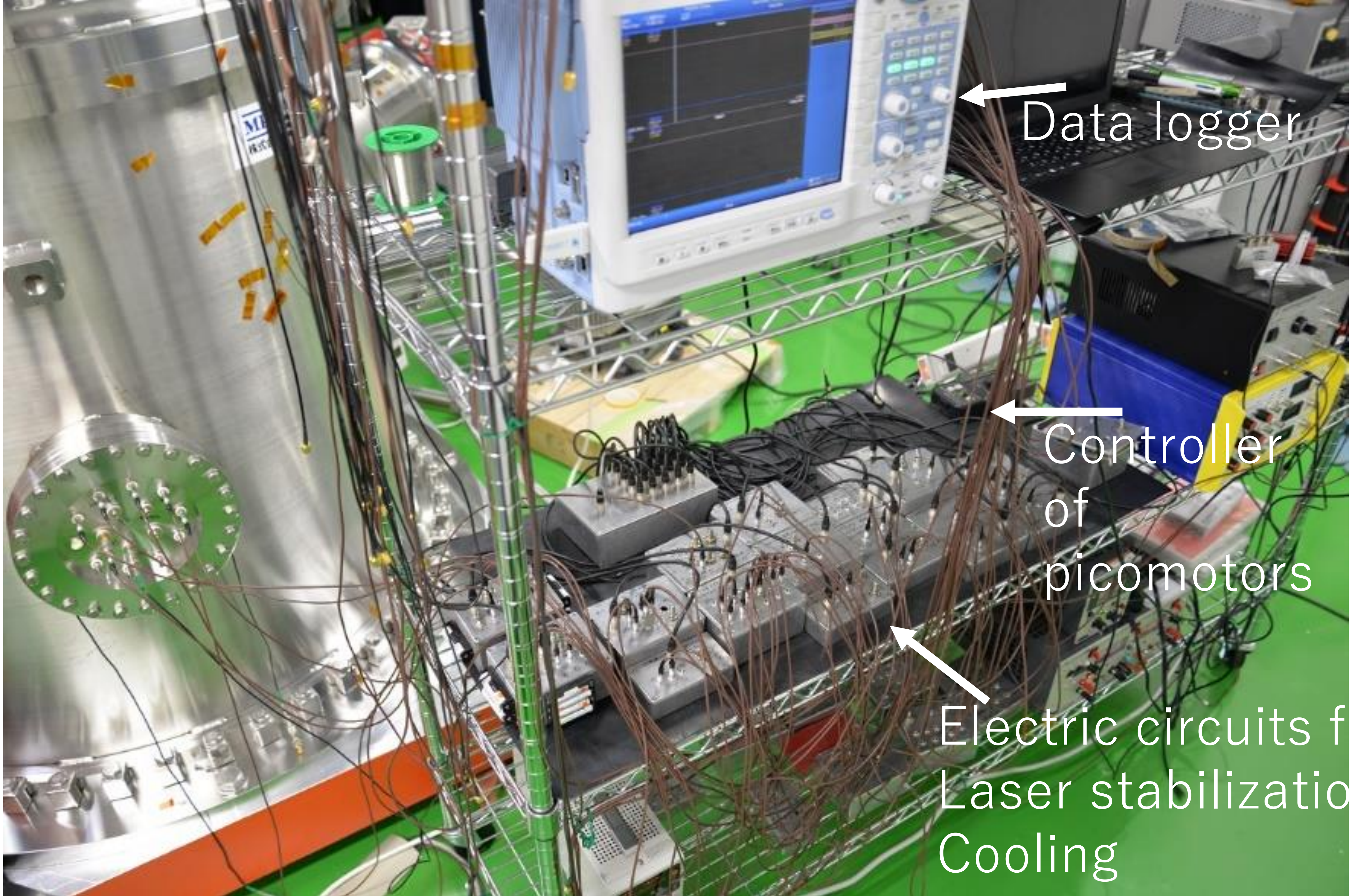




vacuum compatible
~1 m
Coil-magnet
actuator
Int. stab.
Freq. stab.
cooling
SUS

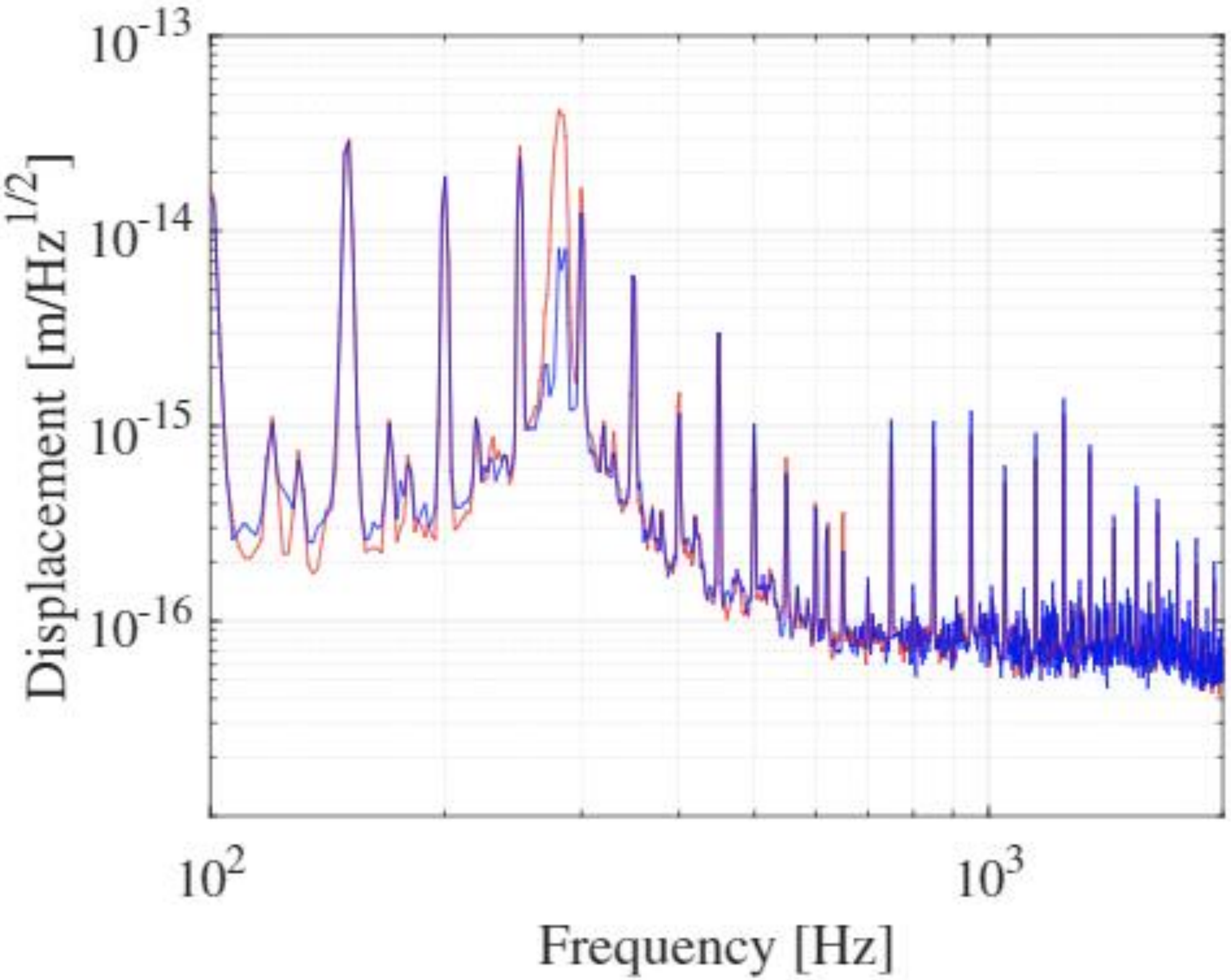



Signal lines
10^-5 Pa
XYZ-stage
1 m


Data logger
Controller of picomotors
Electric circuits f
Laser stabilizatio
Cooling

Diaplacement sensing

Mode temperature
Blue: 420 uK
Red: 11 mK



Conditional mechanical squeezing

- $X(t) = Aq(t) + \zeta(t)$
- Conditional position: $q_c = E[q|X]$
- Conditional position variance:

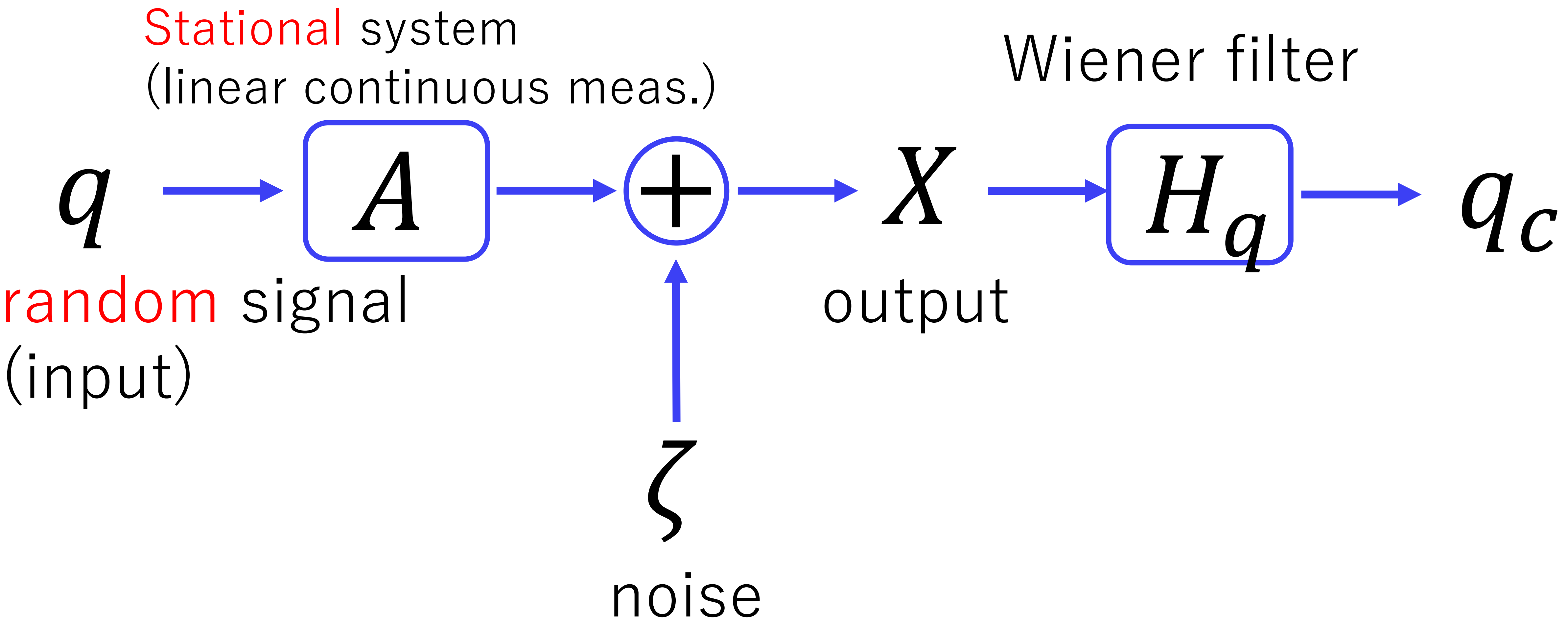
$$V_c(q) = E[(q - q_c)^2] = V(q) - V(q_c) < V(q)$$

- $V_c(q)$ can be maximumly reduced at the expense of increasing $V_c(p)$

→Uncertainty principle is satisfied

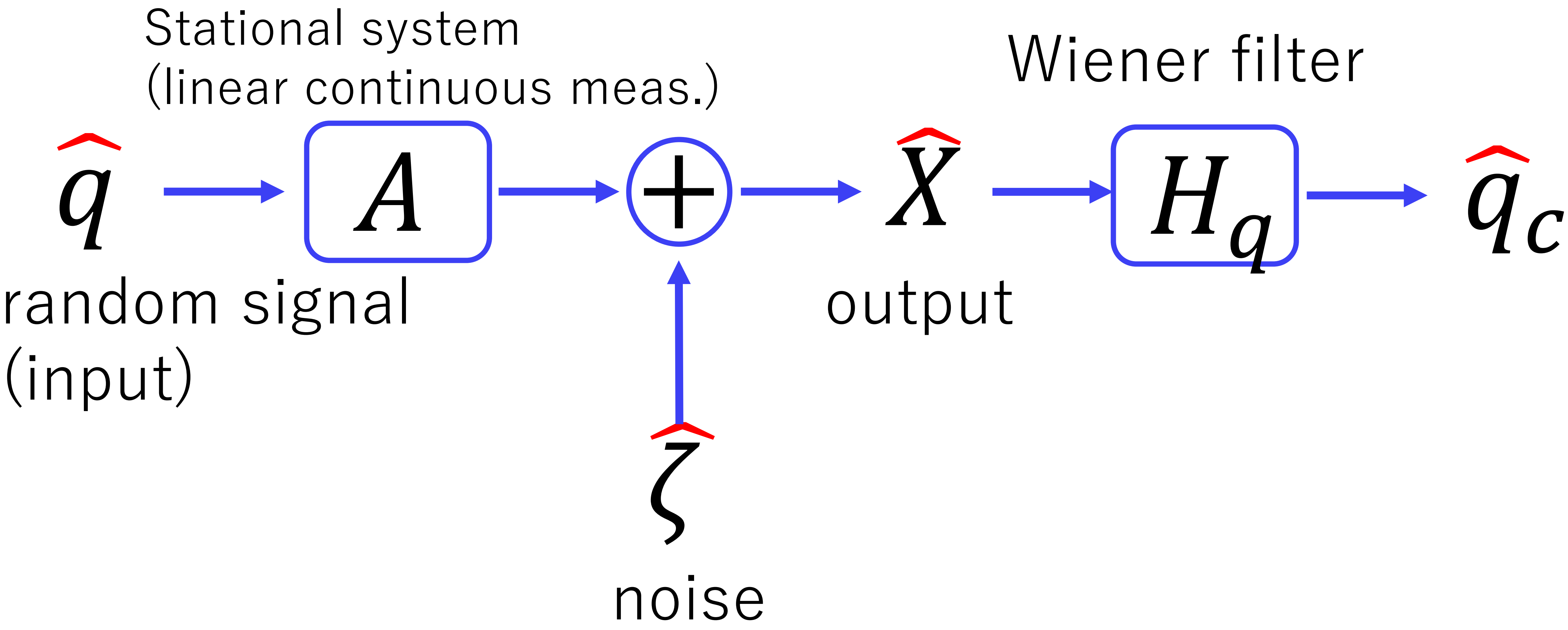
Wiener filter

$$X(t) = Aq(t) + \zeta(t)$$



Quantum Wiener filter

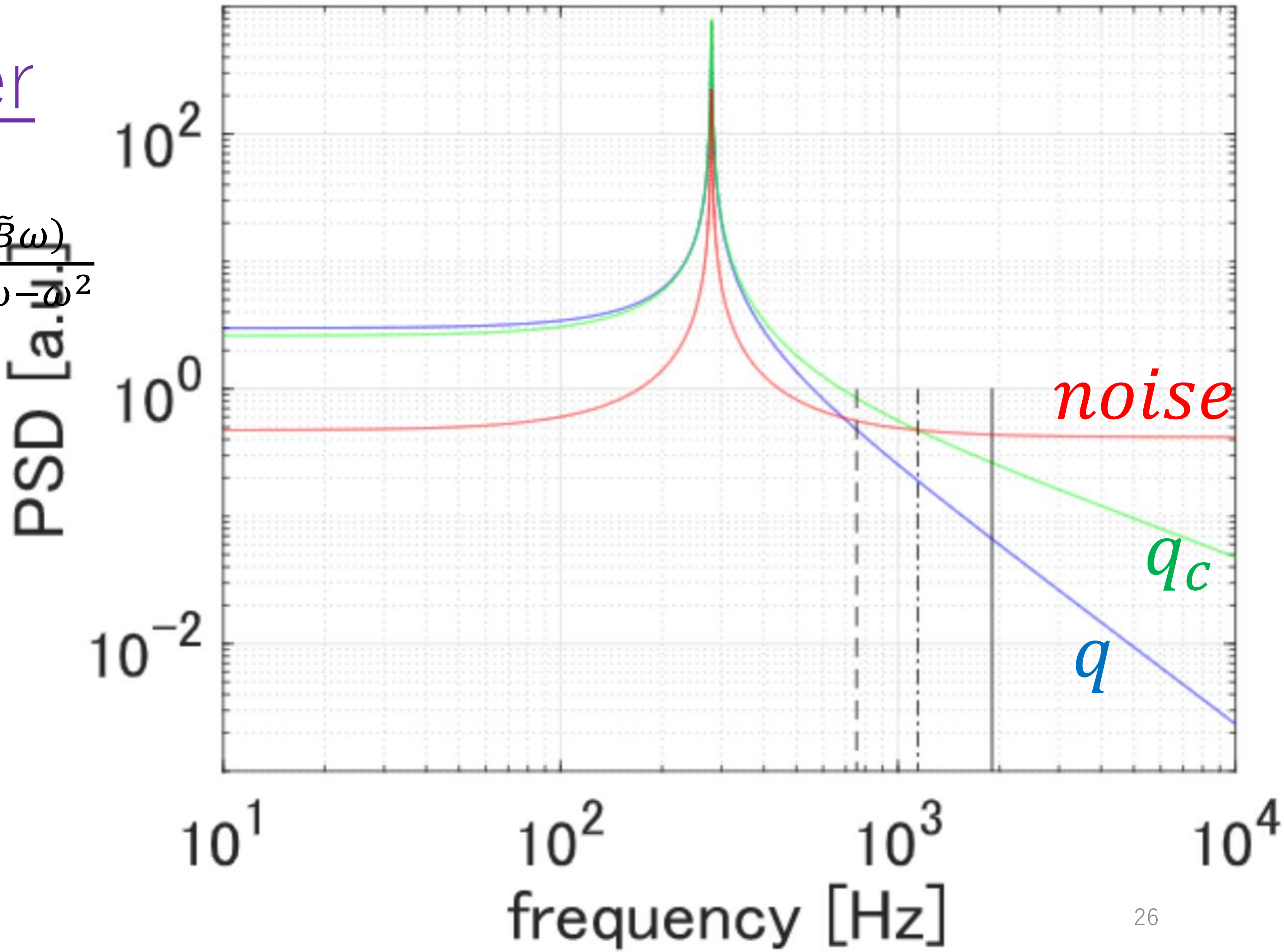
$$X(t) = Aq(t) + \zeta(t)$$



Quantum noise preserves the heisenberg uncertainty principle

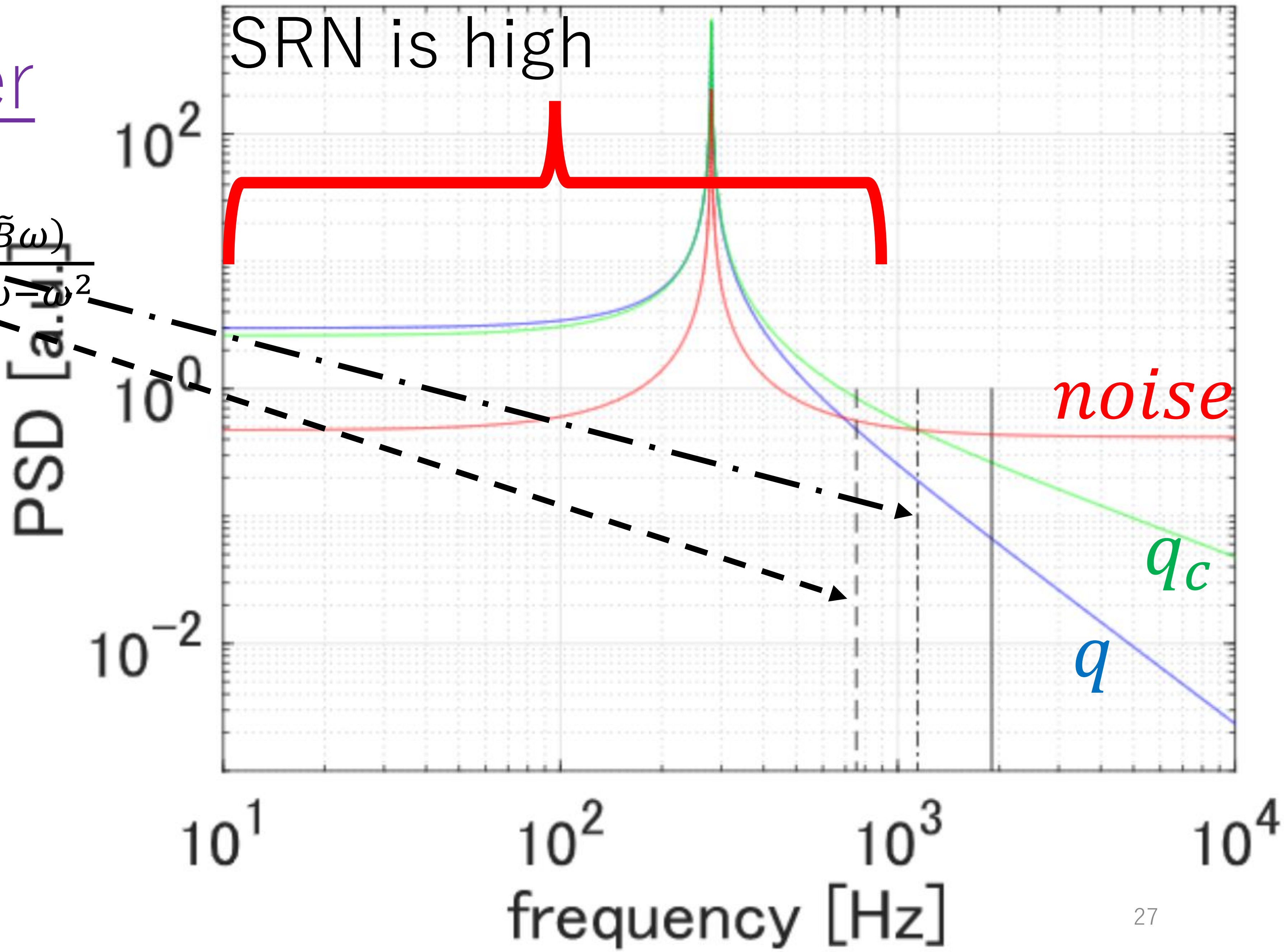
Wiener filter

- $H_q(\omega) = \frac{\tilde{A}(1 - i\tilde{B}\omega)}{\Omega' - i\Gamma'\omega - \omega^2}$
- $q_c = H_q X$



Wiener filter

- $H_q(\omega) = \frac{\tilde{A}(1 - i\tilde{B}\omega)}{\Omega' - i\Gamma'\omega - \omega^2}$



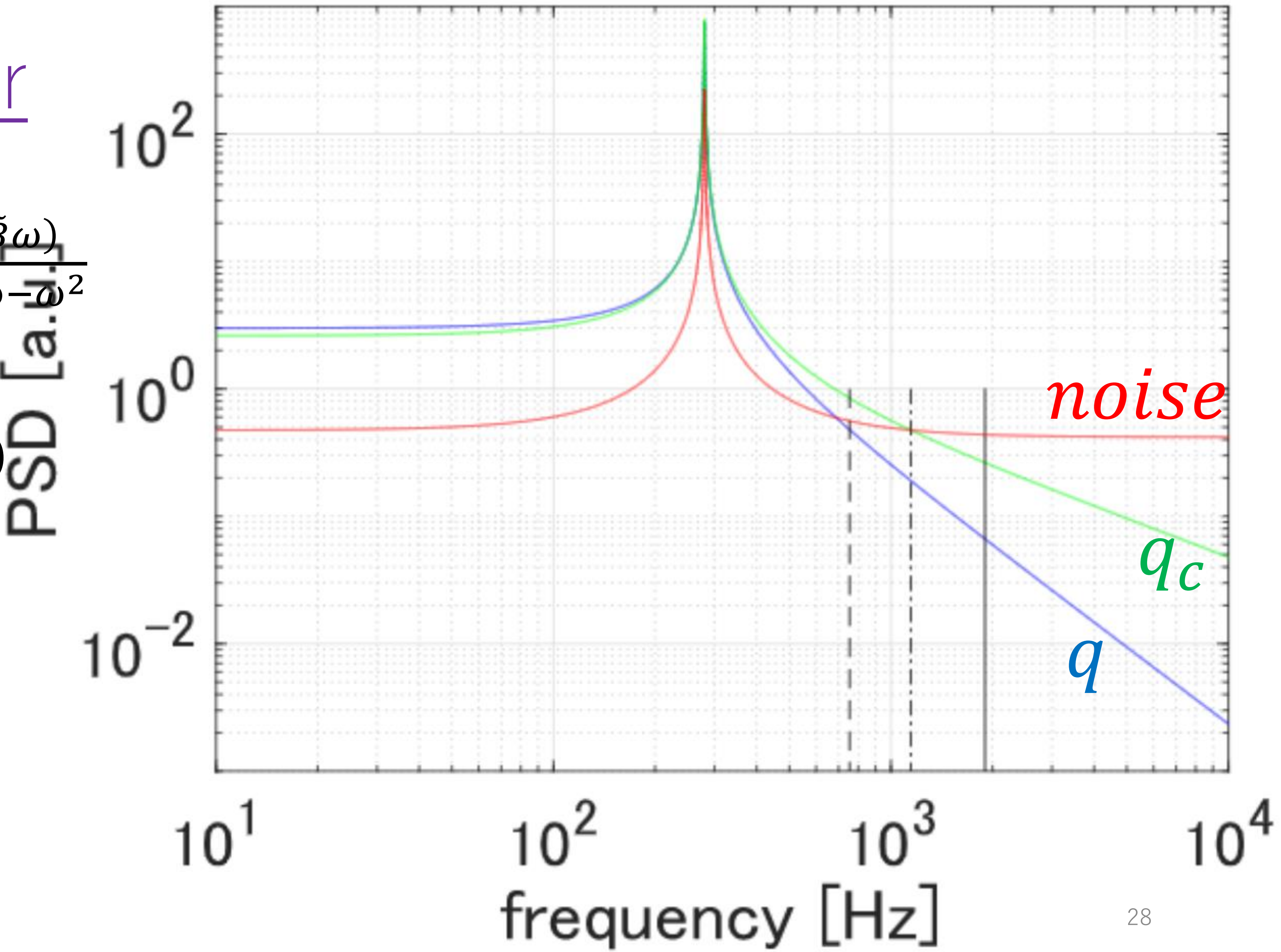
Wiener filter

- $H_q(\omega) = \frac{\tilde{A}(1-i\tilde{B}\omega)}{\Omega' - i\Gamma'\omega - \omega^2}$

Conditional variance

$$V_c(q) = E[(q - q_c)^2]$$
$$= V(q) - V(q_c) < V(q)$$

$$V = \int_{-\infty}^{\infty} S\, df$$



Wiener filter

- $H_q(\omega) = \frac{\tilde{A}(1-i\tilde{B}\omega)}{\Omega' - i\Gamma'\omega - \omega^2}$

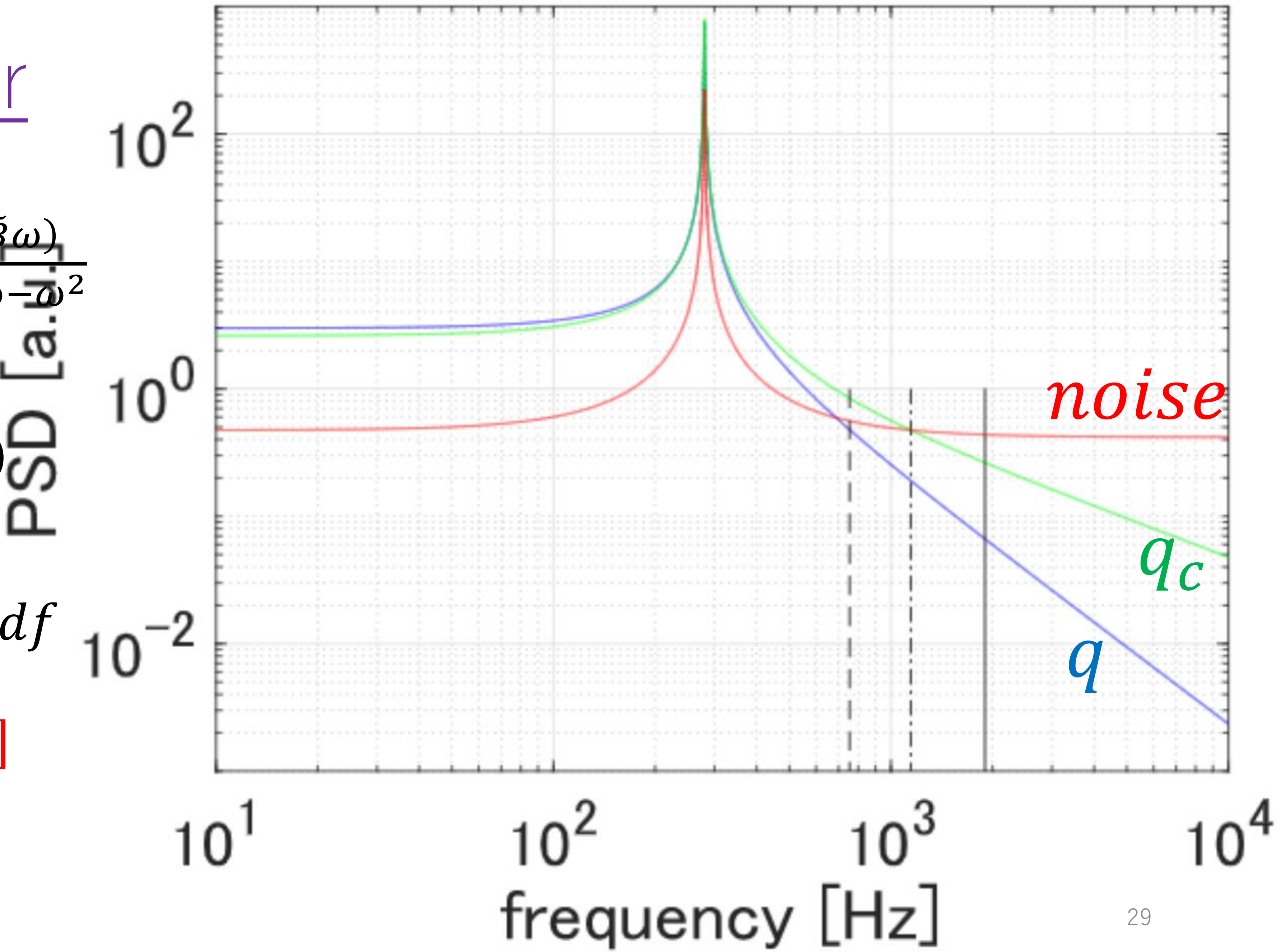
Conditional variance

$$V_c(q) = E[(q - q_c)^2]$$
$$= V(q) - V(q_c) < V(q)$$

$$V = \int_{-\infty}^{\infty} S\,df \simeq \int_{-f_{bw}}^{f_{bw}} S\,df$$

$$V_c(q) \simeq E[(X/A - q_c)^2]$$

$$X = Aq + \zeta, \qquad q \simeq \frac{X}{A}$$



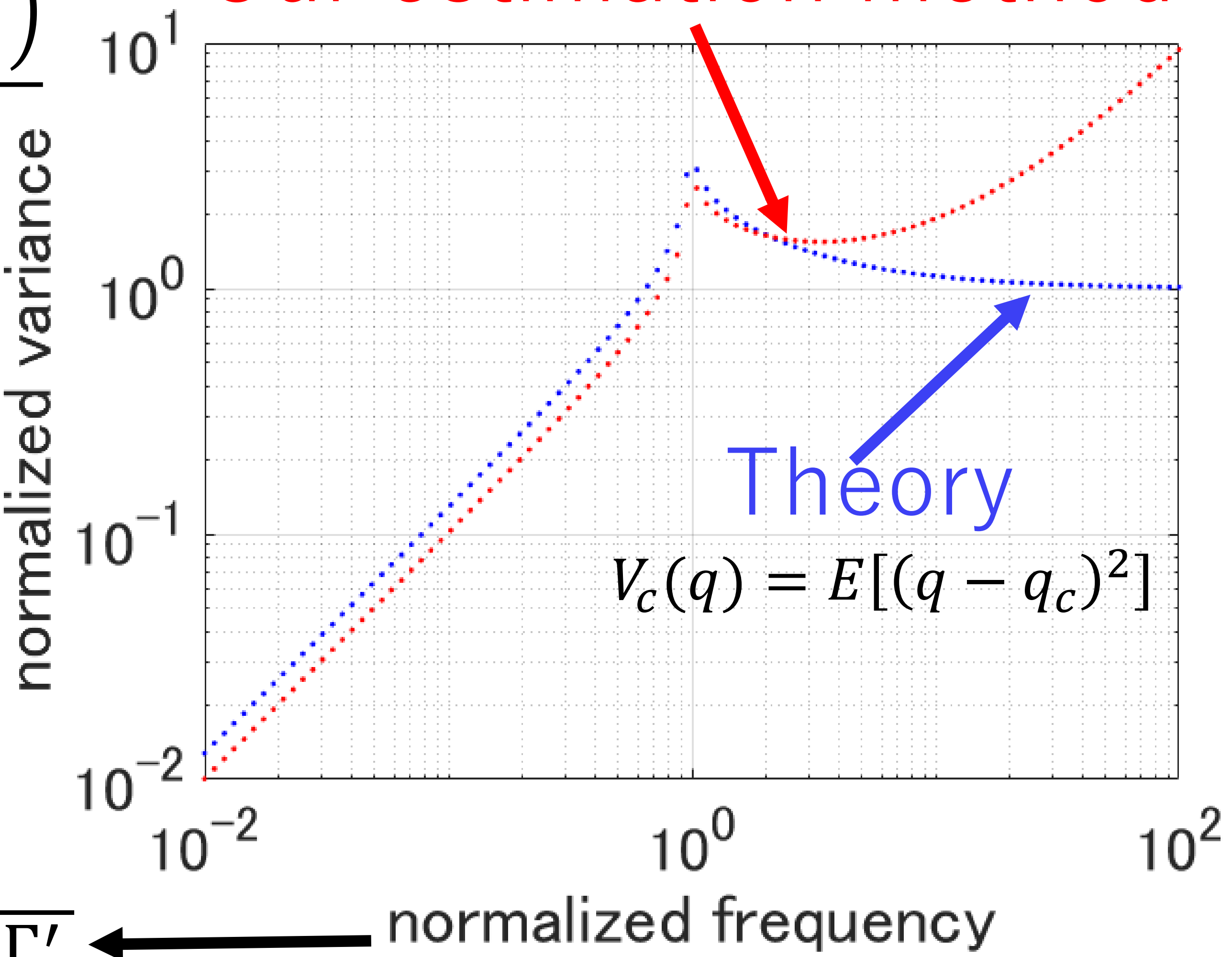
Bandwidth for integration

$$V_c(q) \simeq E[(X/A - q_c)^2]$$

Our estimation method

$$\frac{\left(\int_{-f_{bw}}^{f_{bw}} S\, df\right)}{\int_{-\infty}^{\infty} S\, df}$$

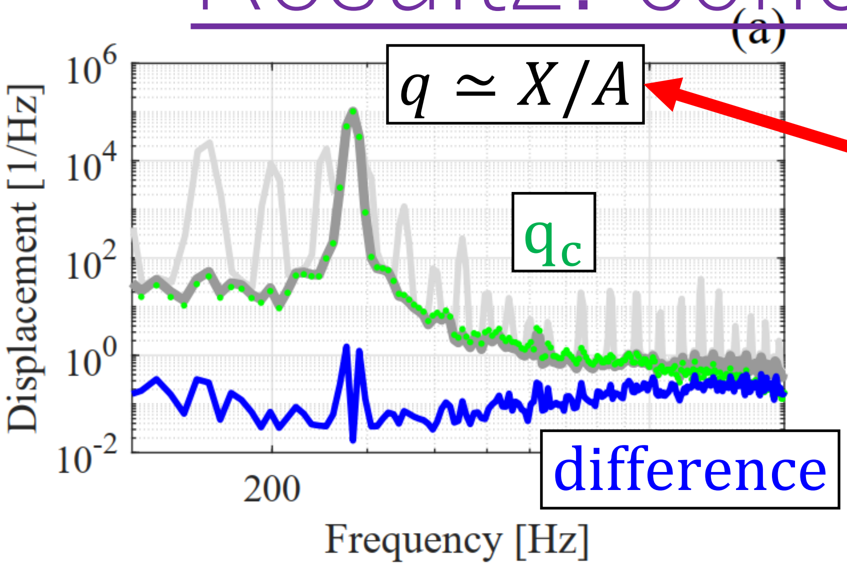
$$V = \int_{-\infty}^{\infty} S\, df \simeq \int_{-f_{bw}}^{f_{bw}} S\, df$$



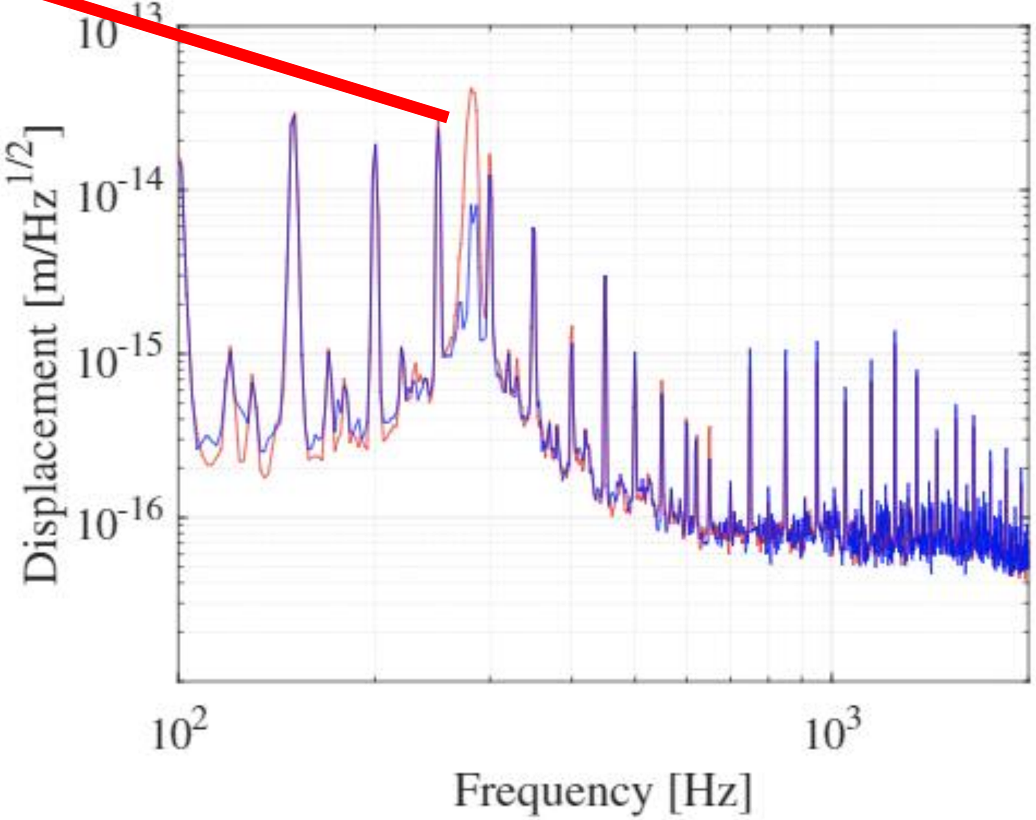
$$V_c(q) = E[(q - q_c)^2]$$

$$\frac{f_{bw}}{\frac{\Omega'}{2\pi} + \frac{\Gamma'}{2\pi}}$$

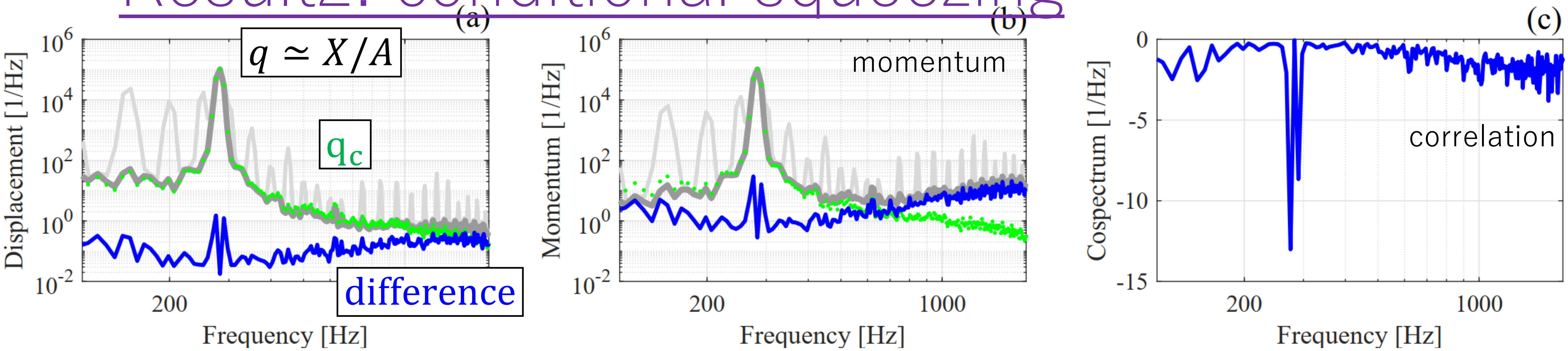
Result2: conditional squeezing



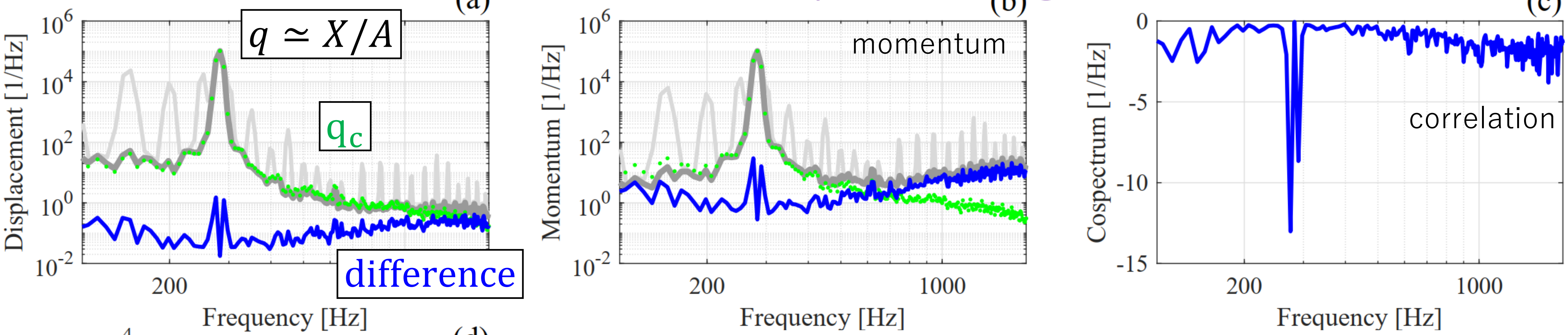
notch filtering

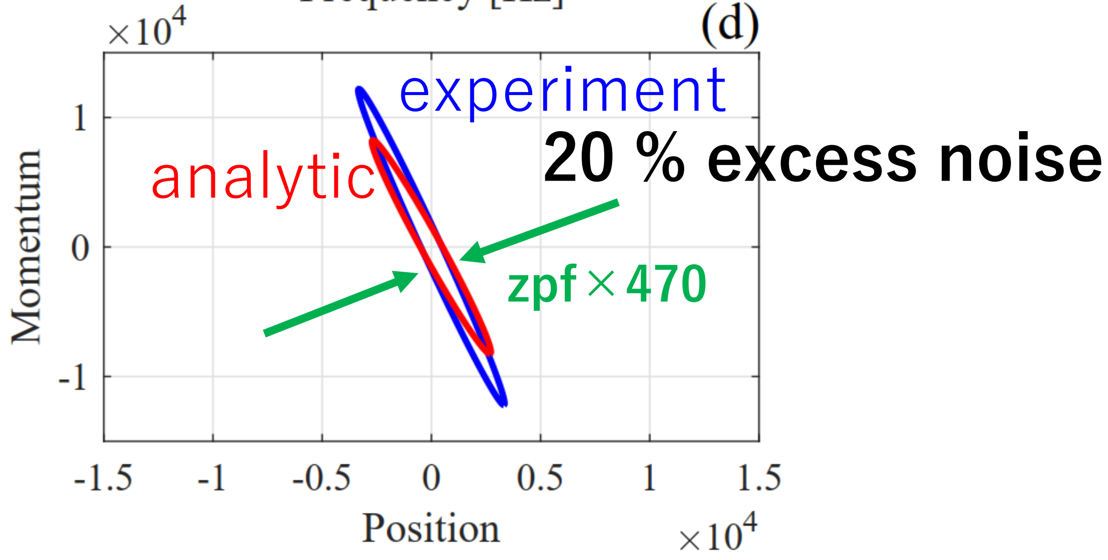


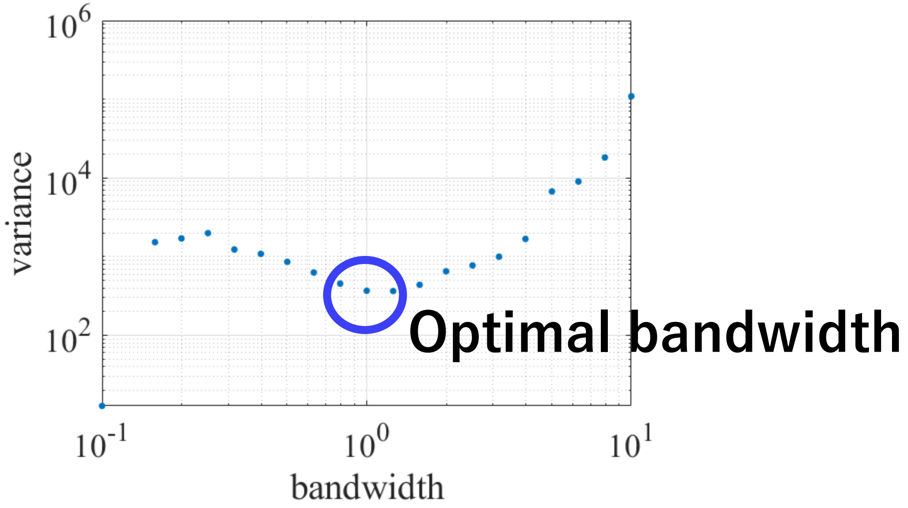
Result2: conditional squeezing



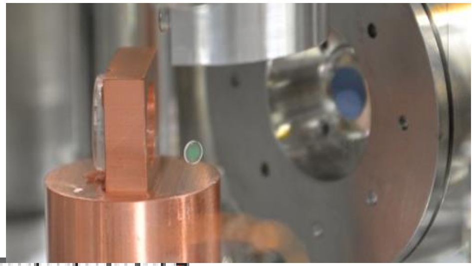
Result2: conditional squeezing

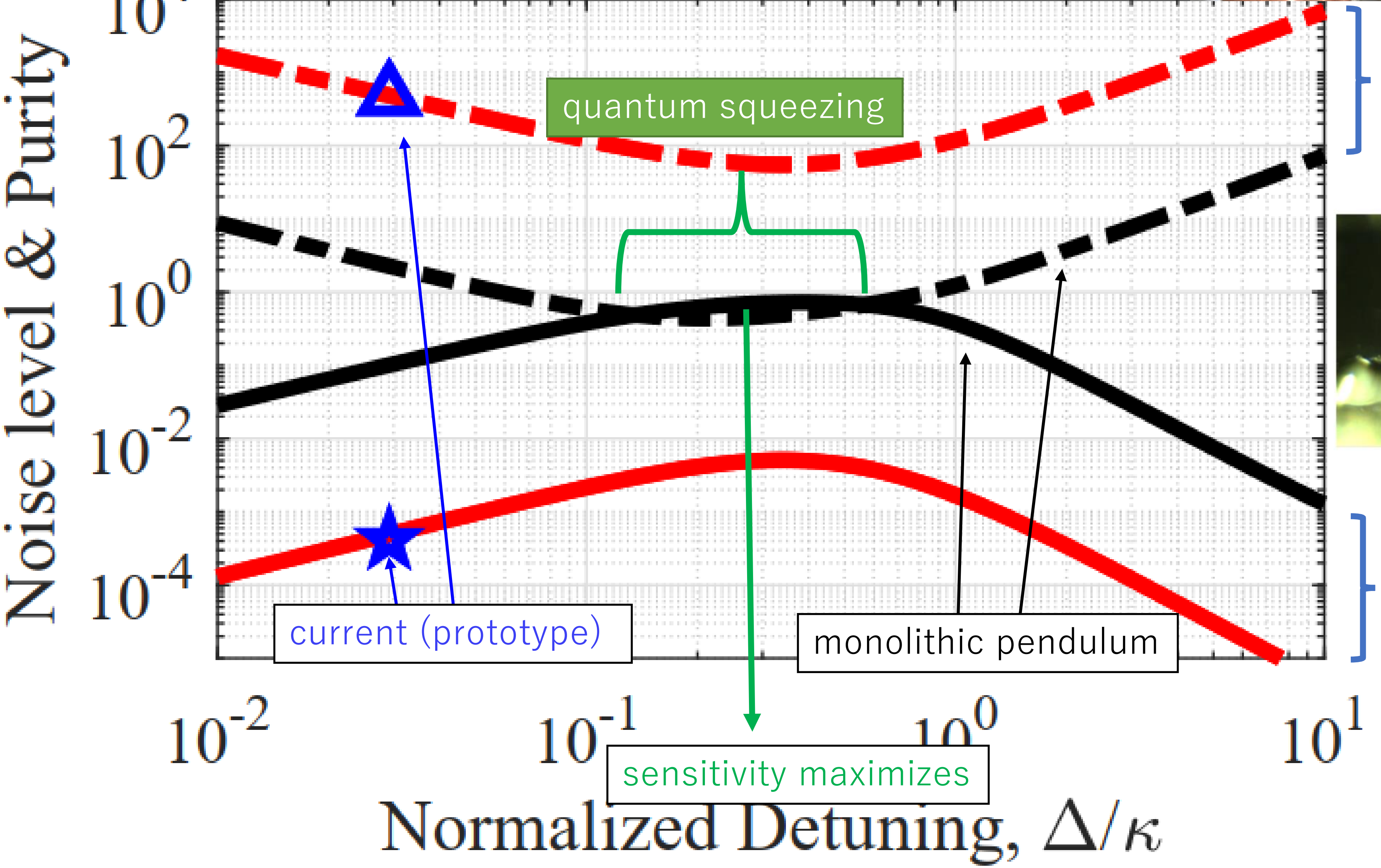


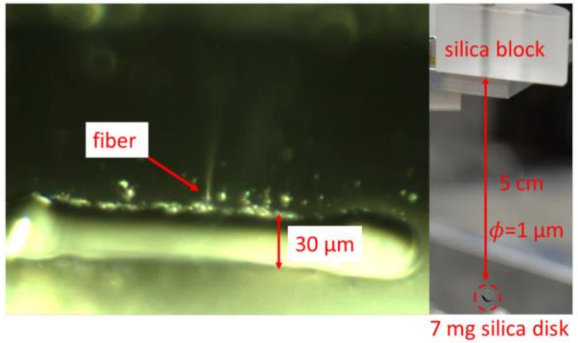




Future: monolithic pendulum

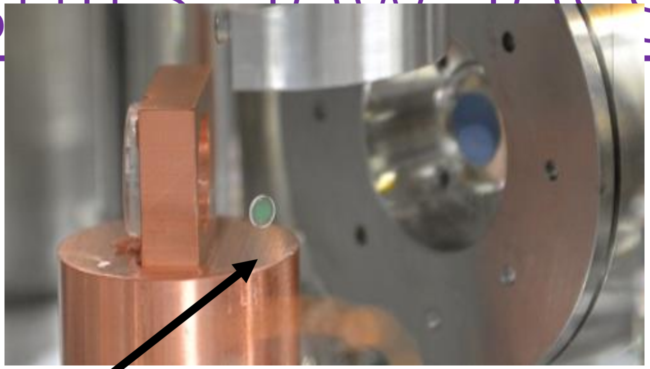


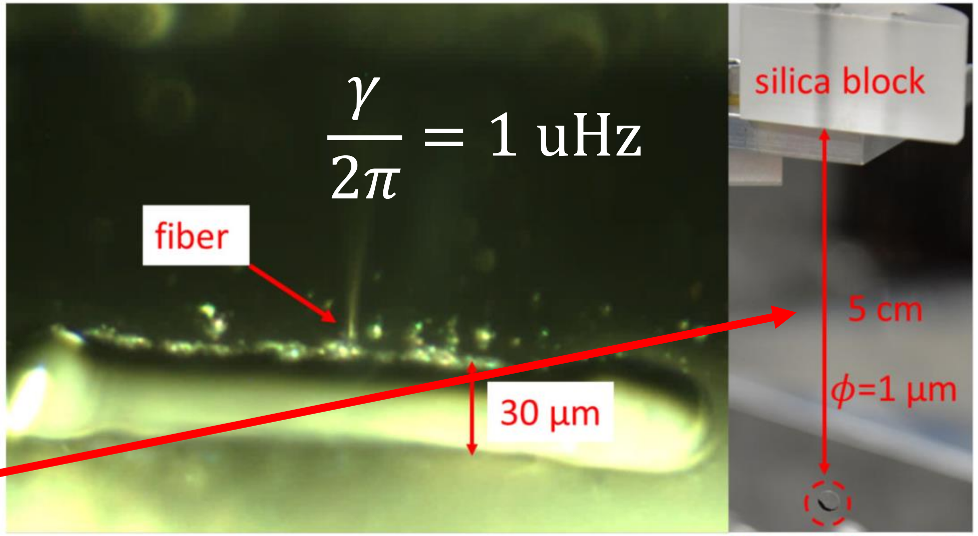


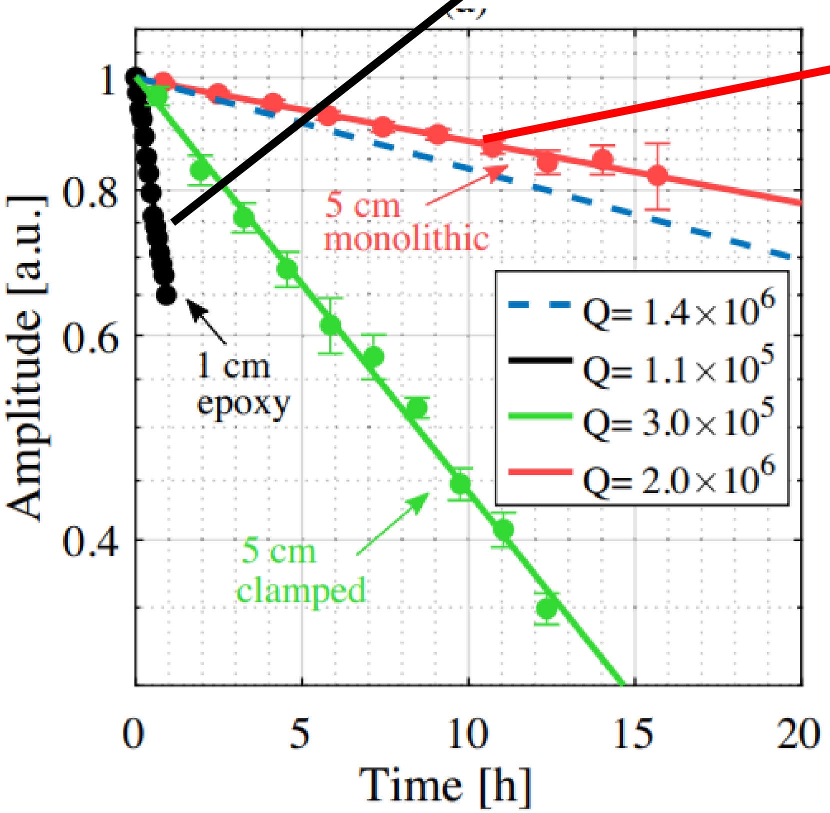


Result3: low loss pendulu

$$\frac{\gamma}{2\pi} = 40\ \mathrm{uHz}$$







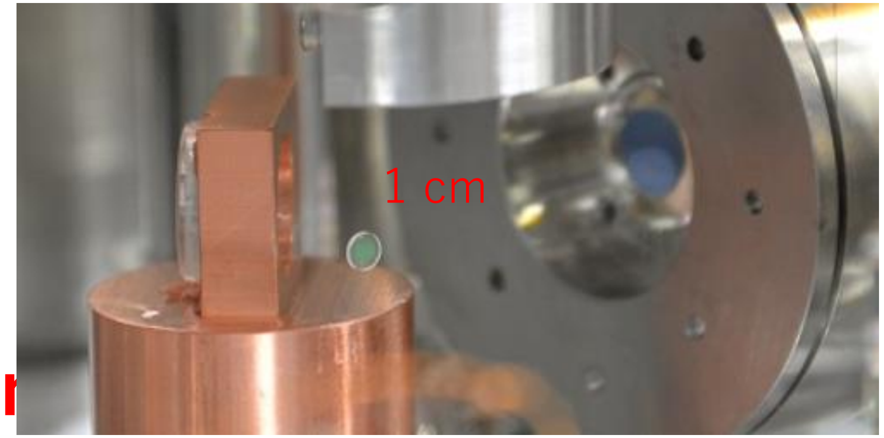
$$\sqrt{S_{qq}^{imp}} \simeq 10^{-17}\ \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

$$n_{imp} = \frac{S_{qq}^{imp}}{2S_{qq}^{zpf}} \simeq 3 \times 10^{-8} \rightarrow 2 \times 10^{-11} (@500\ \mathrm{Hz})$$

Requirement: $n_{imp} \sim 2 \times 10^{-11}$

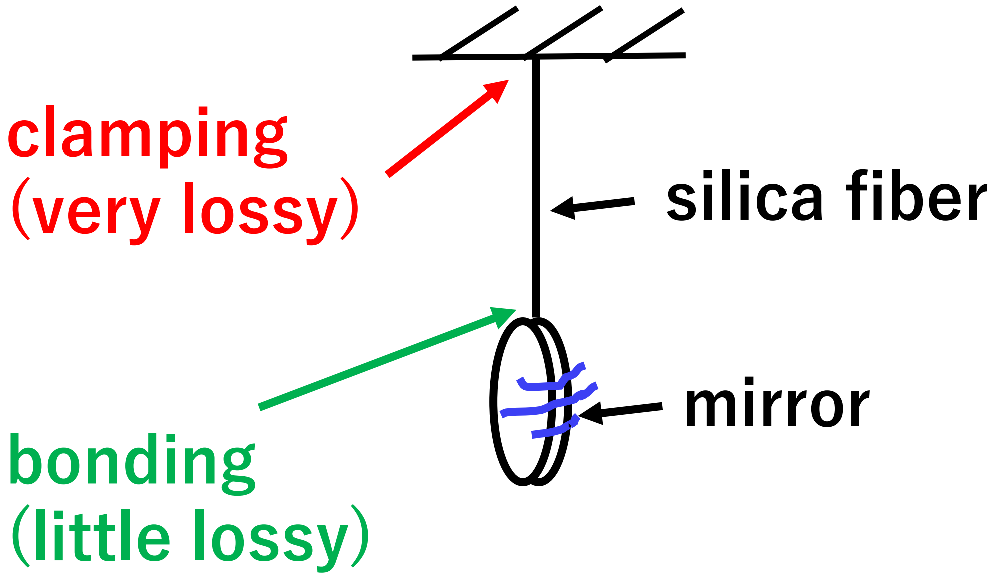
Old pendulum

- Simple pendulum **with small dissipatio**

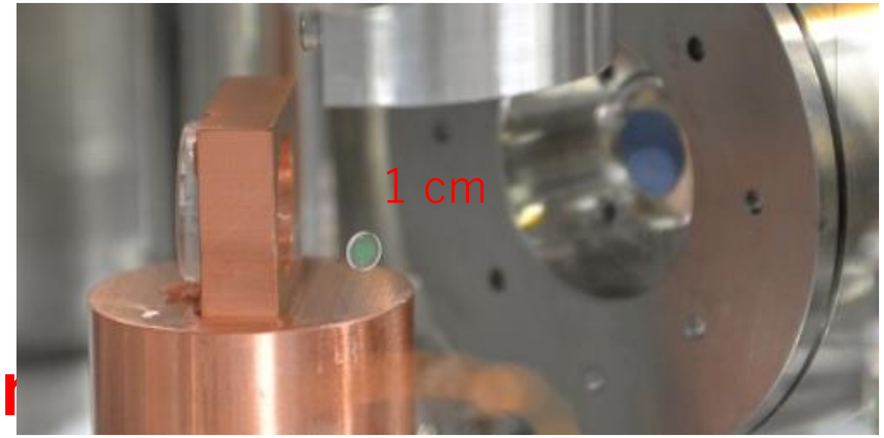


prototype(2015~2019)

resonance ~ 4 Hz
Q ~ 1e5
dissipation ~ 4e-5 Hz



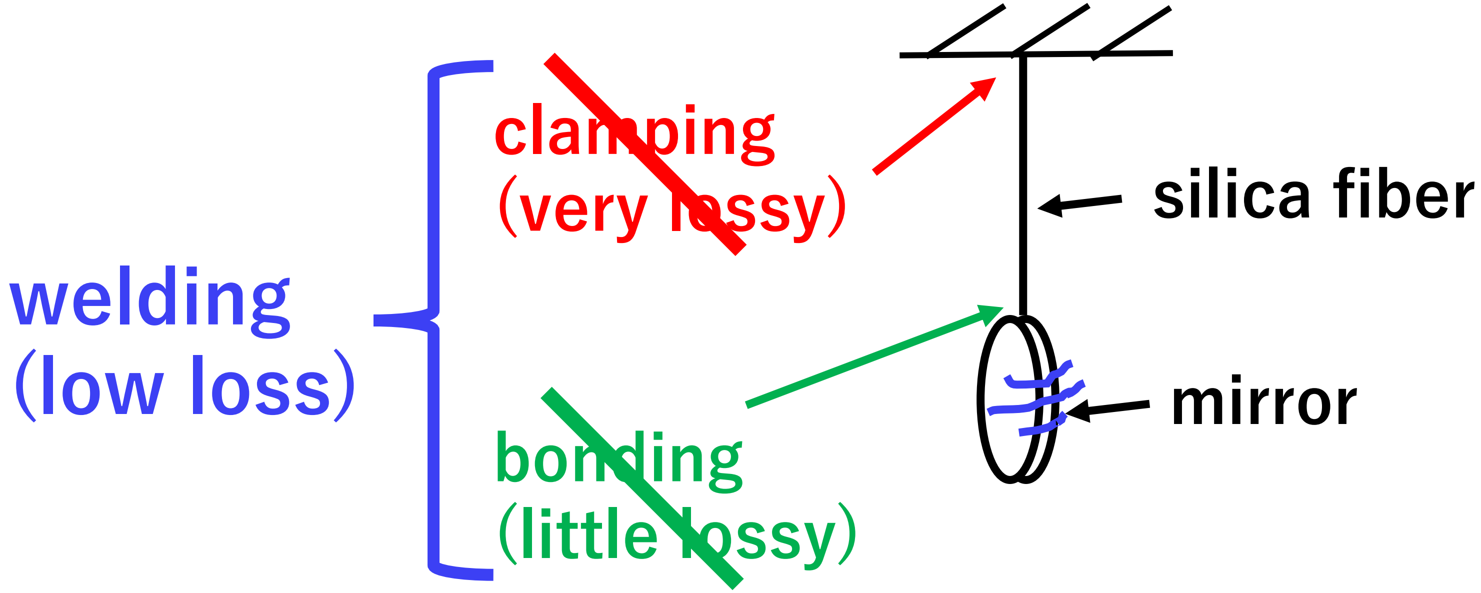
New pendulum: monolithic



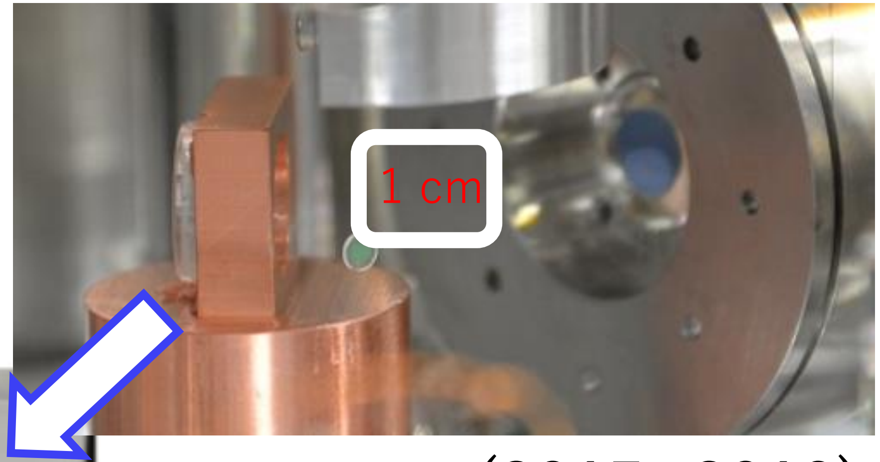
- Simple pendulum **with small dissipatio**

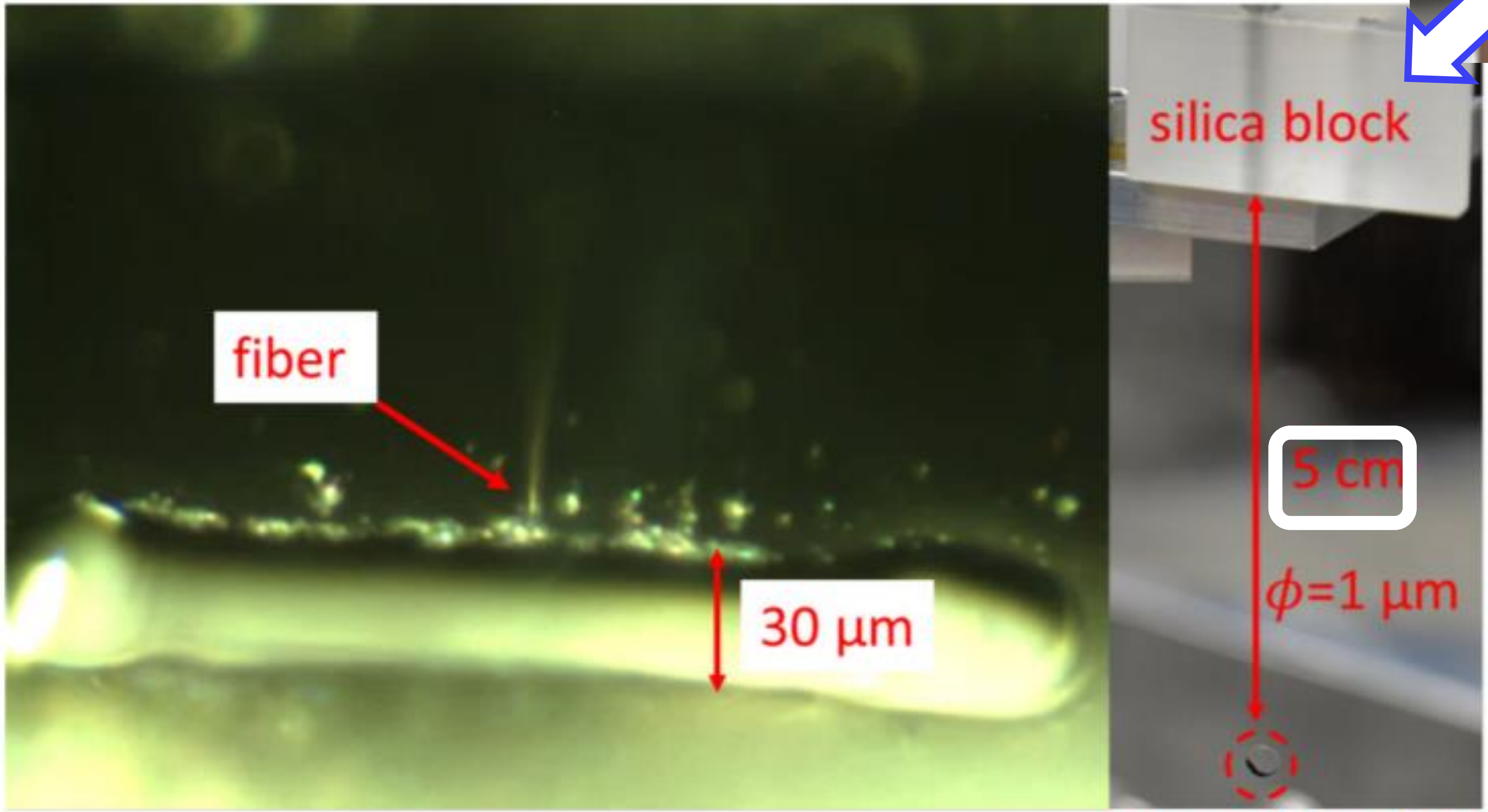
prototype(2015~2019)

resonance ~ 4 Hz
Q ~ 1e5
dissipation ~ 4e-5 Hz



Monolithic pendulum





7 mg silica disk

prototype(2015~2019)

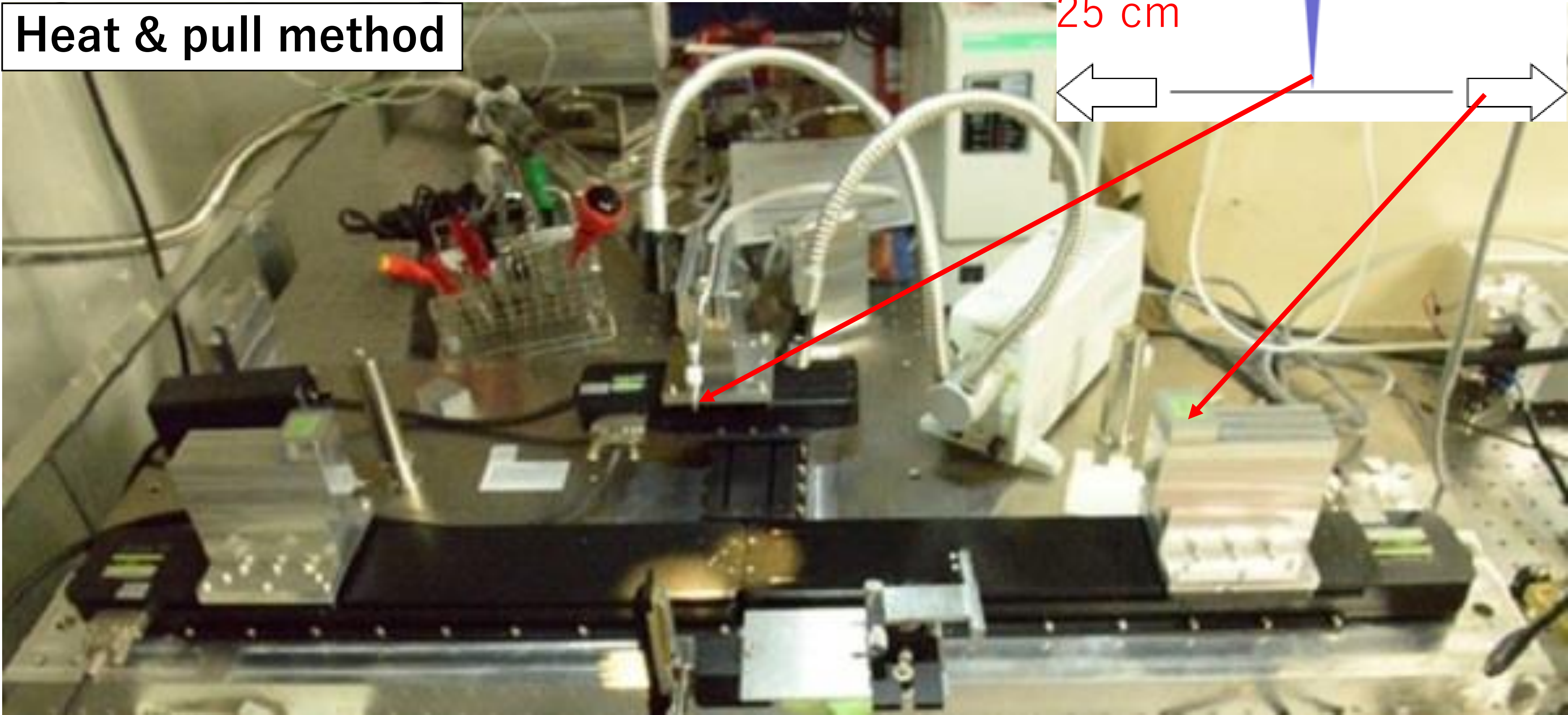
resonance ~ 4 Hz
Q ~ 1e5
dissipation ~ 4e-5 Hz

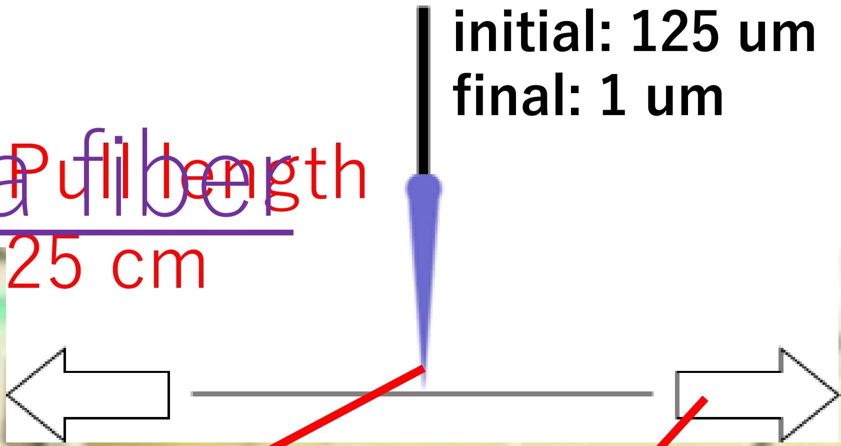
monolithic(2020~)

resonance ~ 2 Hz
Q ~ 2e6
dissipation ~ 1e-6 Hz

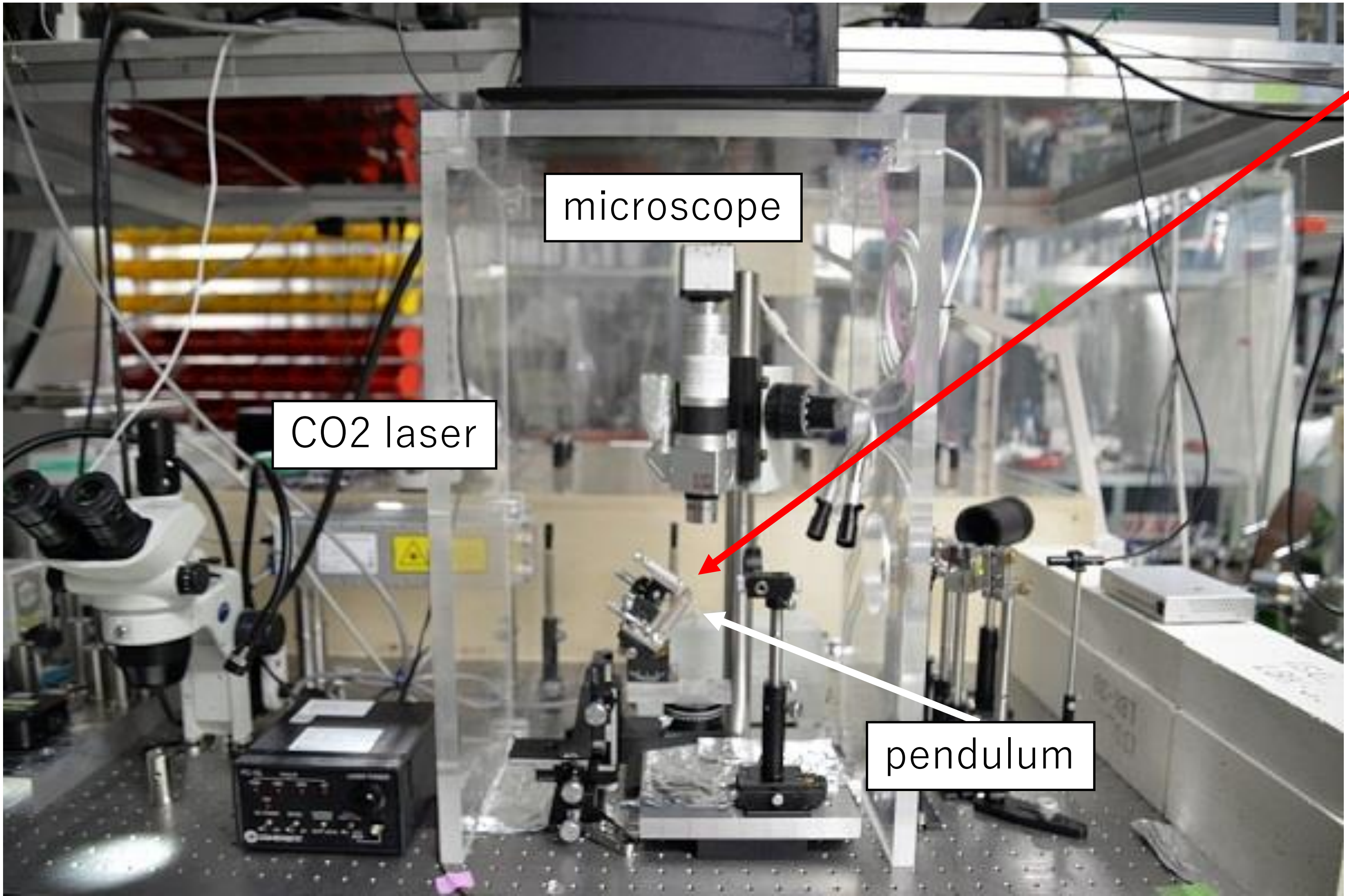
thin (1 um) & long (5 cm) silica fiber

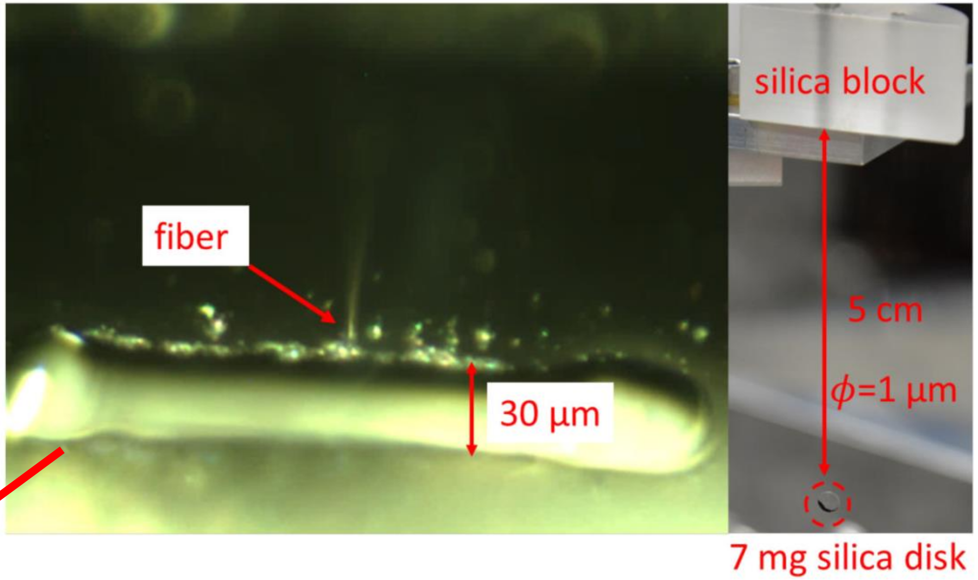
Heat & pull method





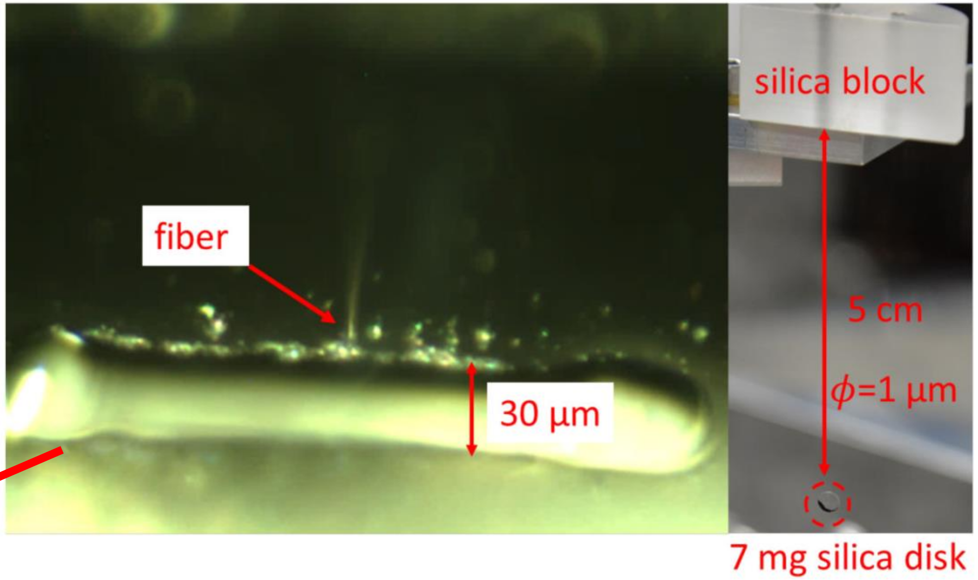
Monolithic pendulum

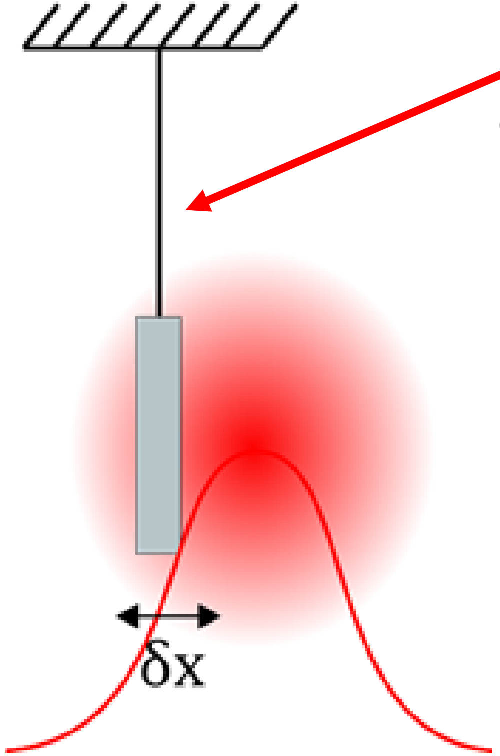




Shadow sensing

measurement of ringdown (damped oscillation) by shadow sensing





on a viblation isolation inside a vacuum chamber (~1e-5 Pa)

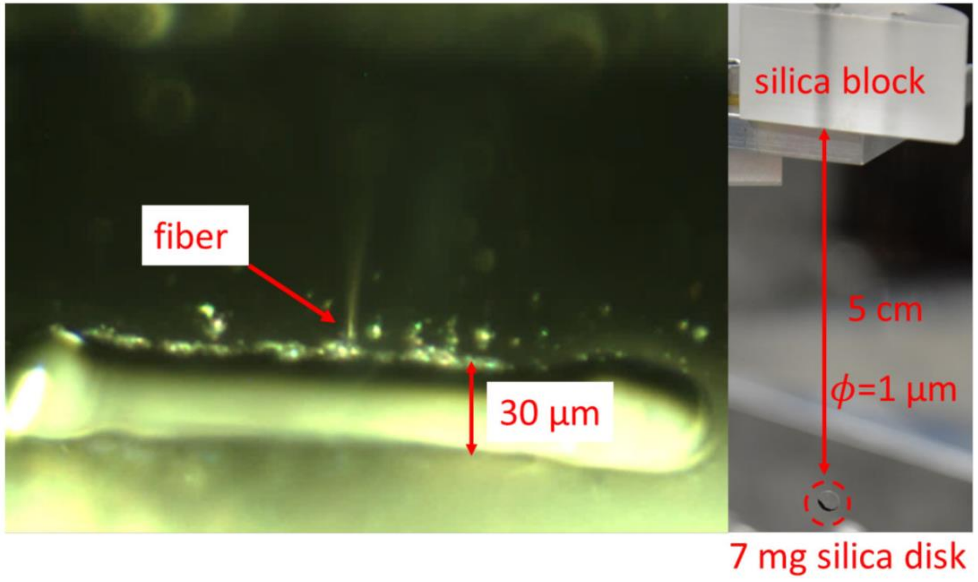
Using the linear range of a Gaussian beam, we detect the "shadow" on a PD

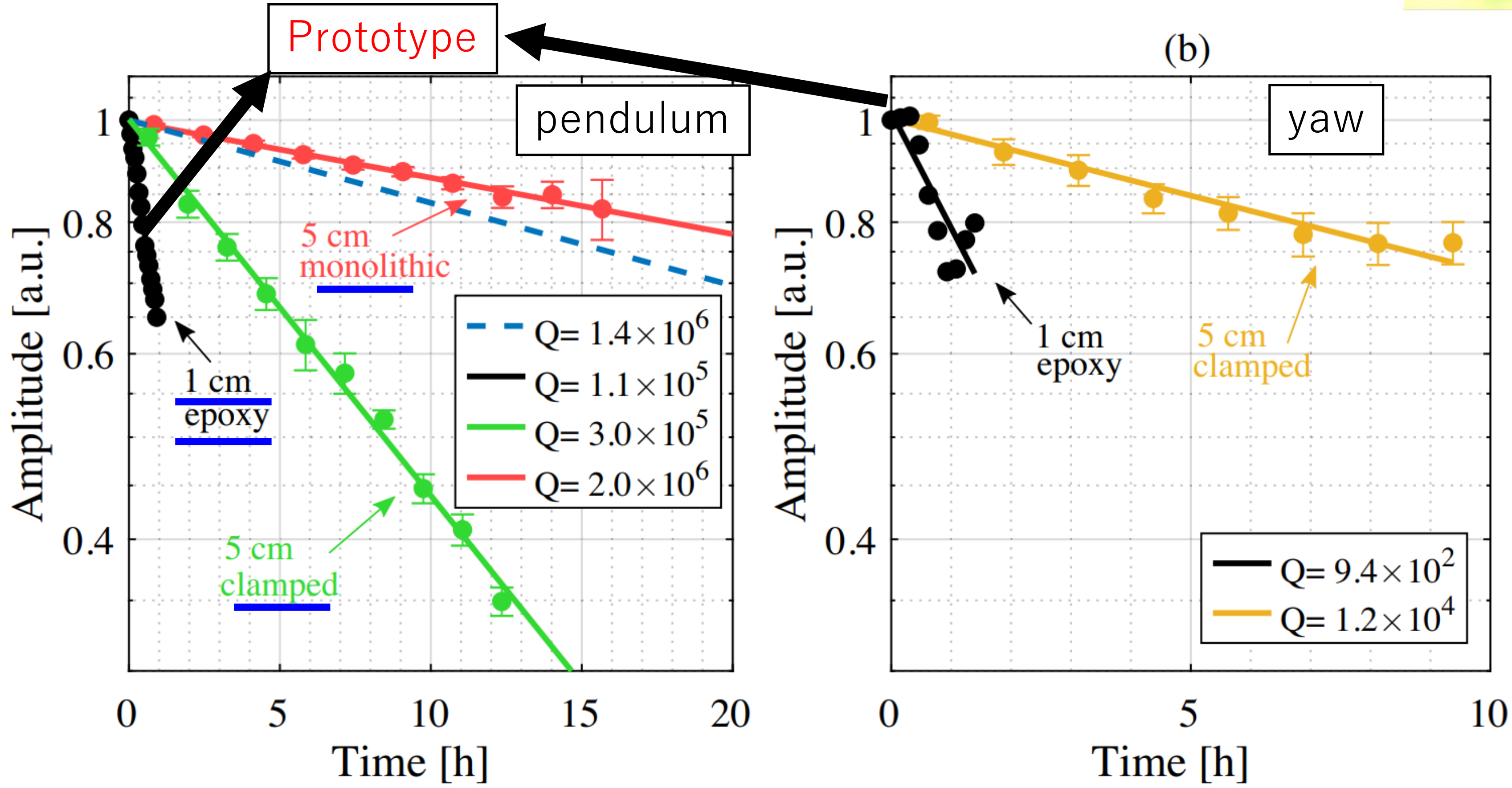
result

PHYSICAL REVIEW LETTERS **124,** 221102 (2020)

High-*Q* Milligram-Scale Monolithic Pendulum for Quantum-Limited Gravity Measurements

Seth B. Cataño-Lopez,[1,*] Jordy G. Santiago-Condori,[1] Keiichi Edamatsu,[1] and Nobuyuki Matsumoto[1,2,3,†]





result

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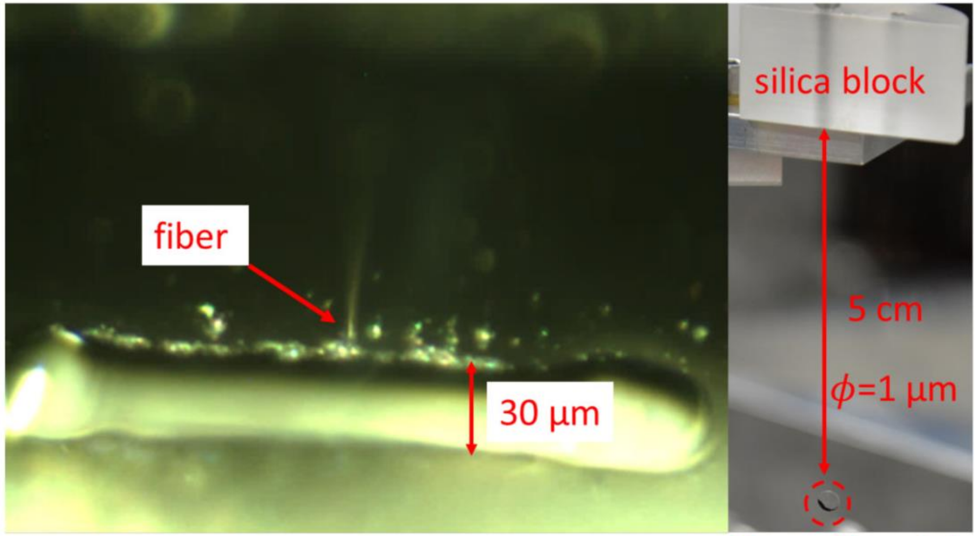

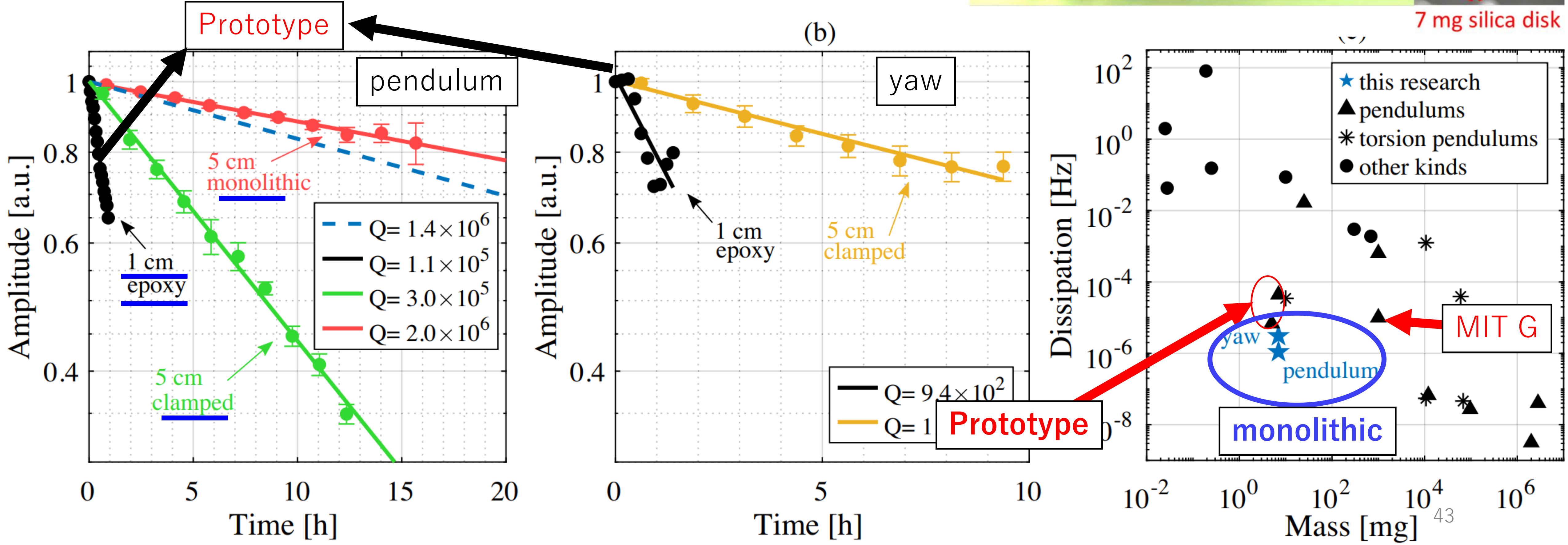

Summary

- Goal: quantum sensing and control of a massive pendulum
- Approach: measurement-based control, development of low-loss pendulum, optical spring
- Current status: conditional squeezing ($\sim 400 \times x_{zpf}$)
- Future: quantum squeezing