Table-top experiments for fundamental physics based on technology of gravitational-wave detectors

Tohoku University

Nobuyuki Matsumoto

重力波研究交流会　2019/4/5

Background

- 2005~2009 Keio Univ. Ohashi lab. (study of GL theory)

- 2009~2013 Tsubono lab. (squeezing)
- 2013~2014 Ando lab. (radiation pressure)
- 2014~2015 JSPS Postdoc @ Ando lab. (job hunting)

- 2015~ Tohoku University (cooling, gravity sensor, job hunting)

Background

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]

[1]*Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai 980-8578, Japan*
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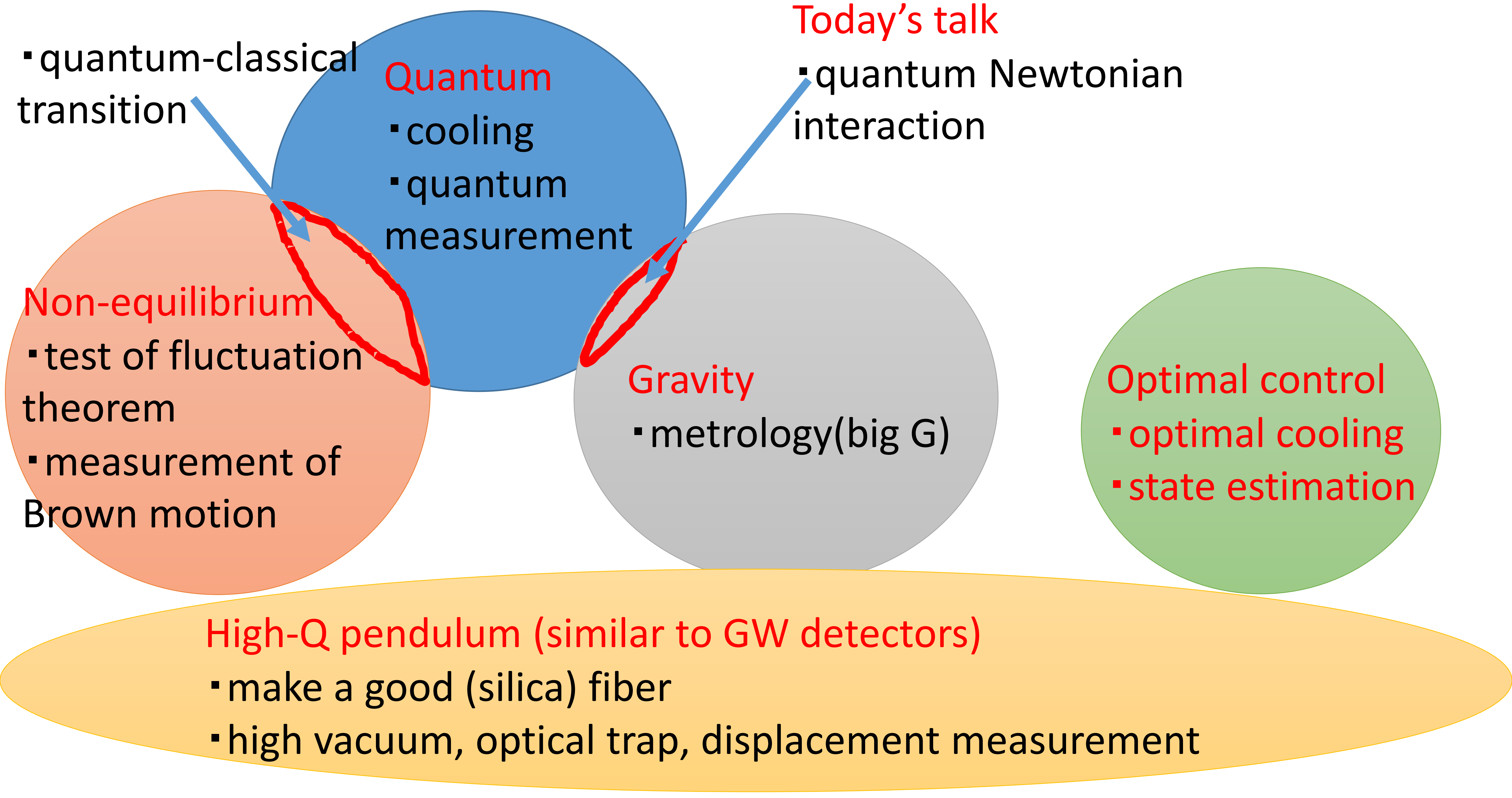
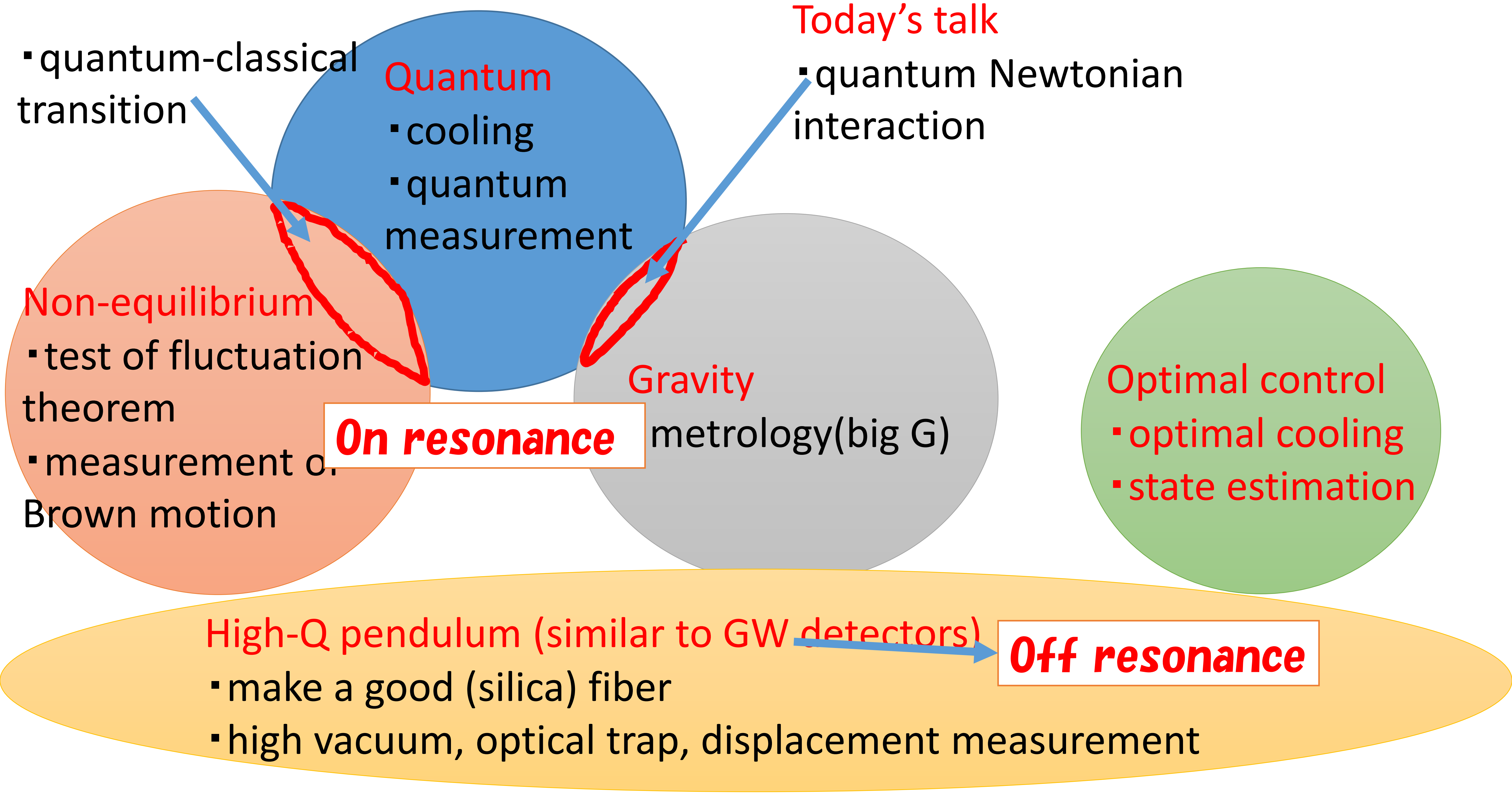
[3]*JST, PRESTO, Kawaguchi, Saitama 332-0012, Japan*
[4]*Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[5]*National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[6]*Department of Astronomical Science, SOKENDAI (The Graduate University for Advanced Studies), Mitaka, Tokyo 181-8588, Japan*


・quantum-classical transition
Quantum
・cooling
・quantum measurement
Today's talk
・quantum Newtonian interaction
Non-equilibrium
・test of fluctuation theorem
・measurement of Brown motion
Gravity
・metrology(big G)
Optimal control
・optimal cooling
・state estimation
High-Q pendulum (similar to GW detectors)
・make a good (silica) fiber
・high vacuum, optical trap, displacement measurement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Outline

- Gravity experiments

➢ What is special about gravity?

➢ Is gravity classical or quantum?

➢ Experimental approach so far

➢ Our approach

If there's time

- Test of non-equilibrium thermodynamics
- What is fluctuation theorem?

What is special about gravity?

(Following is more suitable document)
https://member.ipmu.jp/yuji.tachikawa/transp/colloq.pdf

↓

Is gravity classical or quantum?

↓

Experimental approach so far

↓

Our approach

High energy limit

- (Classical) Einstein equation

→black hole

e.g., Schwarzschild radius: $\frac{2GM}{c^2} \sim 1\ \mathrm{cm}\left(\frac{6\times 10^{24}\ \mathrm{kg}}{M}\right)$

M: mass, G: Newton's constant, c: speed of light

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- black hole uniqueness theorem

For 4-dimensional black hole, only mass, charge, and angular momentum are necessary to determine its state.

$\Rightarrow W = 1, W$:number of states

Laws of black hole thermodynamics

- First law

$$dM = \frac{\kappa}{8\pi G} dA + \frac{\Phi}{c^2} dQ$$

Second law

$$\frac{dA}{dt} \geq 0$$

A: the area of the event horizon,
Φ: electrostatic potential, Q: electric charge

Laws of black hole thermodynamics

- First law

$$dM = \frac{\kappa}{8\pi G} dA + \frac{\Phi}{c^2} dQ$$

⇩ Hawking radiation
(photons are considered under classical gravity fields made by black hole)

$$dE = T dS + \Phi dQ$$

Second law

$$\frac{dA}{dt} \geq 0$$

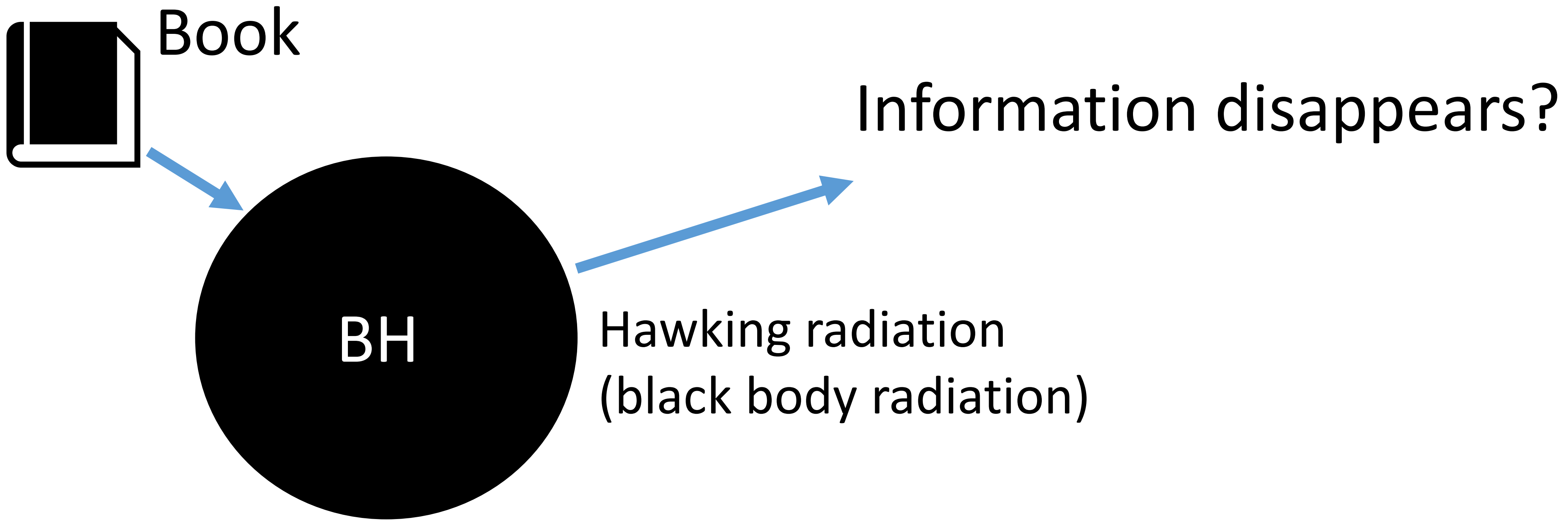
A: the area of the event horizon,
Φ: electrostatic potential, Q: electric charge

$$T = \frac{\hbar}{k_B c} \frac{\kappa}{2\pi} \sim 0.02\ \mathrm{K} \left(\frac{6 \times 10^{24}\ \mathrm{kg}}{M} \right), S = \frac{k_B A}{4 l_p^2} \to 1\ \mathrm{bit} \left(\frac{M}{10\ \mu\mathrm{g}} \right)$$

Black hole seems to have entropy, which is not consistent with the (classical) prediction

Information Paradox

- Gravity should be treated as quantum? But,...
- Black hole seems to have temperature because it radiates as a black body.



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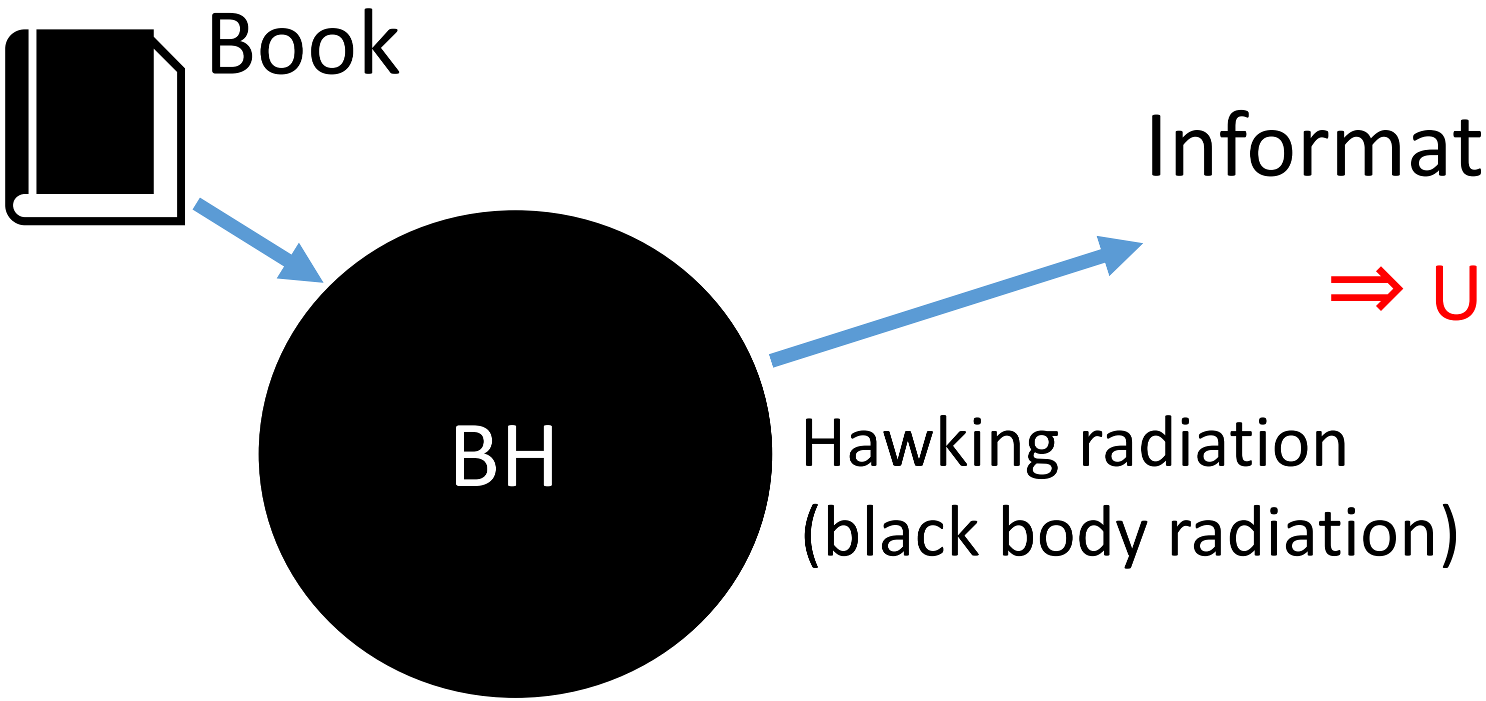

Information disappears?

⇒ Unitarity is broken?

What is special about gravity?

↓

Is gravity classical or quantum?

↓

Experimental approach so far

↓

Our approach

- Low energy limit: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

This can be quantized, which includes graviton (GWs) and a longitudinal Newtonian component

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For 2-oscillators system interacting with gravity is

$$H = \sum\left(\frac{p_i^2}{2m} + \frac{1}{2}m\omega^2 x_i^2\right) - \frac{Gm^2}{|d-(x_1-x_2)|}$$

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⇩ Taylor expansion

$$H_{int} = -\hbar\lambda_g \frac{x_1}{x_{zpf}} \frac{x_2}{x_{zpf}}$$

(zeroth order⇒overall constant, first order⇒equilibrium position, part of second order⇒oscillator frequency)

$$\lambda_g = \frac{Gm^2 x_{zpf}^2}{\hbar d^3} = \frac{Gm}{\omega d^3} \sim 5 \times 10^{-8}\ \mathrm{Hz} \left(\frac{m}{5\ \mathrm{mg}} \right) \left(\frac{1\ \mathrm{Hz}}{\omega/2\pi} \right) \left(\frac{1\ \mathrm{mm}}{d} \right)^3$$

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For 2-

$H = \Sigma$

Requirement to test the quantum Newtonian potential

$$\lambda_g > \bar{n}_{th}\gamma \sim 4 \times 10^{-8}\ \mathrm{Hz}\left(\frac{300\ K}{T}\right)\left(\frac{10^{21}}{Q}\right)$$

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- Newtonian interaction can be easily quantized under low energy limit
- Is it possible to test it?

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- Is it possible to test it?

If possible, then experimentally

- Newtonian interaction is quantum

⇒gravity is quantum even in high energy scale?

- Not quantum

⇒suspicious result! Should be evaluated in many ways.

What is special about gravity?

↓

Is gravity classical or quantum?

↓

Experimental approach so far

↓

Our approach

- No experiments have been done.

- No experiments have been done. But recently some proposals have been made.

PRL **119,** 240401 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew A. Geraci,[6] Peter F. Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]

PRL **119,** 240402 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

C. Marletto[1] and V. Vedral[1,2]

Quantum correlation of light mediated by gravity arXiv:1901.05827 (2019)

Haixing Miao,[1,*] Denis Martynov,[1,†] and Huan Yang[2,3,‡]

[1]*School of Physics and Astronomy, and Institute for Gravitational Wave Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2L2Y5, Canada*
[3]*University of Guelph, Guelph, ON N2L3G1, Canada*

We consider using the quantum correlation of light in two optomechanical cavities, which are coupled to each other through the gravitational interaction of their end mirrors, to probe the quantum nature of gravity. The optomechanical interaction coherently amplifies the correlation signal, and a unity signal-to-noise ratio can be achieved within one-year integration time by using high-quality-factor, low-frequency mechanical oscillators.

- Spin systems (Stern-Gerlach interferometers)
- Matter interferometer
- Suspended mirror + FP cavity

- Test of the quantum Newtonian interaction:
- $H_{int} = -\hbar\lambda_g \frac{x_1}{x_{zpf}} \frac{x_2}{x_{zpf}}$

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- One comment:

Graviton (GWs)⇒true dofs

Newtonian ⇒pure gauge (Newtonian term depends only on the matter dofs)

Is it interesting to probe Newtonian in quantum regime?

arXiv:1804.11315v2 [quant-ph] 13 Nov 2018

- Test of the qu
- $H_{int} = -\hbar\lambda_g$

Comment on "A Spin Entanglement Witness for Quantum Gravity" and on "Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity"

C. Anastopoulos[1] and B. L. Hu[2]

[1] *Department of Physics, University of Patras, 26500 Patras, Greece. and*

[2] *Maryland Center for Fundamental Physics and Joint Quantum Institute, University of Maryland, College Park, Maryland 20742-4111 U.S.A.* *

- One commen

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Rejected

APPENDIX

To further the extent and depth of discussions on the central theme, namely, whether the experiments proposed in the two PRL papers we commented upon can provide a test to the quantum nature of gravity, we have collected the exchanges with the authors of the two PRL papers and the two negative referee reports on our Comment and our replies. We deem this useful for researchers, especially students, who are interested in laboratory tests of the quantum nature of gravity to hear both sides of the arguments, and, in passing, see the editorial practice of PRL in action.

1. While the discussion about the dynamical degrees of freedom in GR is correct, I disagree with the belief expressed in the Comment that it is of no interest to examine whether non-dynamical metric components can be treated quantum mechanically. Indeed, an example of interest is actually provided in the context of cosmology, as the Comment authors reference. In the standard inflationary picture, the Sasaki-Mukhanov variable is what is canonically quantized when examining the scalar perturbations. This variable is a combination of metric and inflaton fields but does not involve the dynamical tensor degrees of freedom in the metric, but rather non-dynamical metric components that are "slaves" to the inflaton. While classically this is a simple field redefinition, if the metric was a purely classical field while matter was quantized then quantization of such a combination could not be straightforwardly done. For a discussion on this point and the possible ramifications see [22]. Hence it is of interest to ask about the other metric components, even if they are non-dynamical.

Referee comment ⇒ how do you think?

In my opinion, in short, it is possible to test

$$\hat{H}_{int} = -\hbar\lambda_g \frac{\hat{x}_1}{x_{zpf}} \frac{\hat{x}_2}{x_{zpf}}, \text{or} \ -\hbar\lambda_g \frac{\langle\hat{x}_1\rangle}{x_{zpf}} \frac{\langle\hat{x}_2\rangle}{x_{zpf}}$$

What is special about gravity?

↓

Is gravity classical or quantum?

↓

Experimental approach so far

↓

Our approach

Quantum correlation of light mediated by gravity

Haixing Miao,[1,*] Denis Martynov,[1,†] and Huan Yang[2,3,‡]
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$$H_{int} = \sum \hbar G_i \hat{a}_i \hat{X}_i - \hbar \lambda_g \hat{X}_1 \hat{X}_2$$

$\hat{a}$ ($\hat{b}$): amplitude (phase) quadrature of the cavity mode
G: optomechanical coupling strength
$i = 1 \; or \; 2$
$\hat{X}_1$ ($\hat{X}_2$): normalized position operator

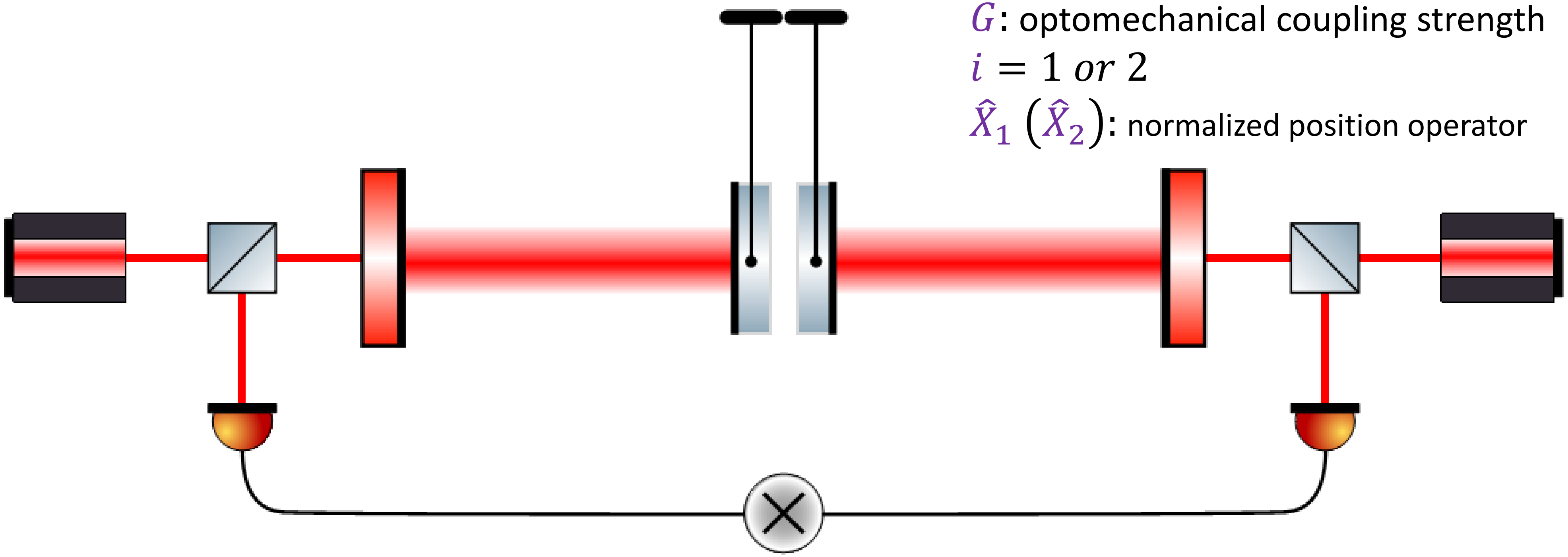

FIG. 1. Schematics showing the setup of two optomechanical cavities with their end mirrors coupled to each other through gravity. The quantum correlation of light is inferred by cross-correlating the readouts of two photodiodes.

- In the frequency domain, input-output relation for cavity 1 (similar for cavity 2)

$$\hat{a}_1^{out}(\omega) = \hat{a}_1^{in}(\omega)$$

$$\hat{b}_1^{out}(\omega) = \hat{b}_1^{in}(\omega) + \sqrt{\frac{2}{\kappa}}\, G_1 \hat{X}_1(\omega)$$

κ: cavity bandwidth

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κ: cavity bandwidth

- The position of oscillator 1 (similar for oscillator 2)

$$\hat{X}_1 = \chi\left[\sqrt{\frac{\kappa}{2}}\, G_1 \hat{a}_1^{in} - \lambda_g \hat{X}_2 + 2\sqrt{\gamma}\hat{Q}_1^{th}\right]$$

χ: mechanical susceptibility

γ: mechanical damping rate

- In the frequency domain, total input-output relation

$$\begin{pmatrix} \hat{a}_1^{out} \\ \hat{b}_1^{out} \\ \hat{a}_2^{out} \\ \hat{b}_2^{out} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -\frac{4G_1^2\chi}{\gamma} & 1 & \mathcal{G} & 0 \\ 1 & 0 & 1 & 0 \\ \mathcal{G} & 0 & -\frac{4G_2^2\chi}{\gamma} & 1 \end{pmatrix} \begin{pmatrix} \hat{a}_1^{in} \\ \hat{b}_1^{in} \\ \hat{a}_2^{in} \\ \hat{b}_2^{in} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 2\sqrt{\frac{2\gamma}{\kappa}}G_1\chi & 2\sqrt{\frac{2\gamma}{\kappa}}G_1\chi^2\lambda_g \\ 0 & 0 \\ 2\sqrt{\frac{2\gamma}{\kappa}}G_2\chi^2\lambda_g & 2\sqrt{\frac{2\gamma}{\kappa}}G_2\chi \end{pmatrix} \begin{pmatrix} \hat{Q}_1^{th} \\ \hat{Q}_2^{th} \end{pmatrix}$$

$$\mathcal{G} \equiv \frac{4G^2\lambda_g\chi^2}{\gamma} \rightarrow_{\omega=\omega_m} 2C\frac{\lambda_g}{\gamma_m}, C \equiv \frac{2G^2}{\kappa\gamma}$$

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$$\mathcal{G}\equiv\frac{4G^2\lambda_g\chi^2}{\gamma}\rightarrow_{\omega=\omega_m}2C\frac{\lambda_g}{\gamma_m},\ C\equiv\frac{2G^2}{\kappa\gamma}$$

Cross correlation⇒to infer quantum correlation by gravity

$$\int\int_{-\frac{\tau}{2}}^{\frac{\tau}{2}}dtdt'\hat{a}_1^{out}(t)\mathcal{F}(t-t')\hat{b}_2^{out}(t')\ ,\mathrm{SNR}=\left[\frac{\tau C Q_m\lambda_g^2}{2(\bar{n}_{th}+1)\omega_m}\right]^{1/2}$$

Requirement to test the quantum Newtonian potential

Only mechanics $\Rightarrow \lambda_g > \bar{n}_{th}\gamma \sim 4 \times 10^{-8}\ \mathrm{Hz} \left(\frac{300\ K}{T}\right)\left(\frac{10^{21}}{Q}\right)$

Optomechanics $\Rightarrow \lambda_g > \left(\frac{\bar{n}_{th}\gamma}{C\tau}\right)^{0.5} \sim 4 \times 10^{-8}\ \mathrm{Hz} \left[\left(\frac{C/\bar{n}_{th}}{200}\right)\left(\frac{10^{8}}{Q}\right)\left(\frac{2\ \mathrm{day}}{\tau}\right)\left(\frac{\omega_m/2\pi}{1\ \mathrm{Hz}}\right)\right]^{0.5}$

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$$\tau \sim 2\ day \left(\frac{C/\bar{n}_{th}}{200}\right)^{-1}\left(\frac{\omega_m/2\pi}{1\ \mathrm{Hz}}\right)\left(\frac{10^{8}}{Q}\right)\left(\frac{2\ \mathrm{g/cm^3}}{\rho}\right)^{2}$$

Gold mirror（~20 g/cm^3）、resonance of 100 Hz is more suitable

Coating on gold is possible？

（structure damping、optical spring）

$$\frac{C}{\bar{n}_{th}} \sim 200 \left(\frac{5\ \mathrm{mg}}{m}\right)\left(\frac{2\ \mathrm{kW}}{P_c}\right)\left(\frac{\mathrm{Finesse}}{10000}\right)\left(\frac{300\ \mathrm{K}}{T}\right)$$

- What is $\frac{C}{n_{th}}$?

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GW detector $\Rightarrow$ it is (radiation pressure noise) / (thermal noise)

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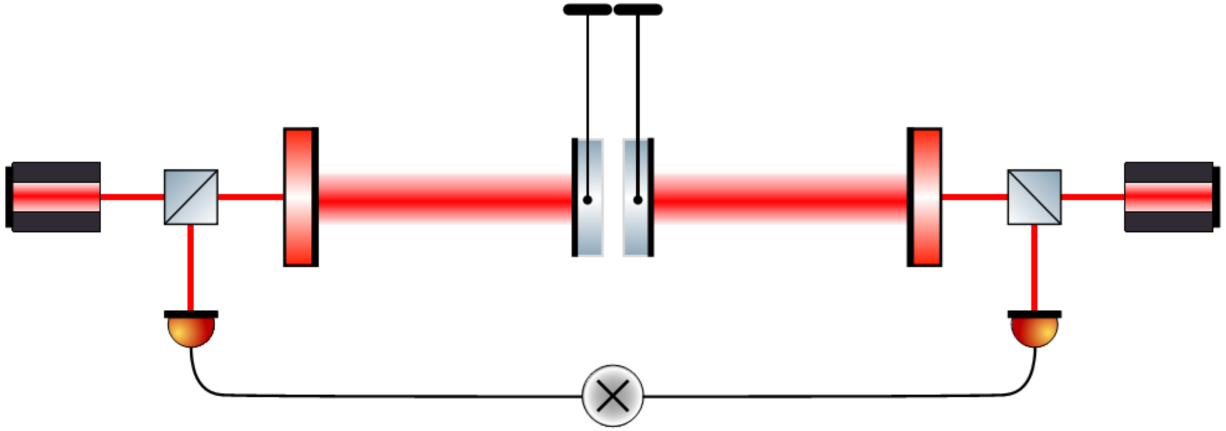
Active cooling $\Rightarrow \frac{C}{\bar{n}_{th}} > 1 \Leftrightarrow$ measurement rate > decoherence rate

- What is $\frac{C}{n_{th}}$?

GW detector ⇒ it is (radiation pressure noise) / (thermal noise)

Active cooling ⇒ $\frac{C}{\bar{n}_{th}} > 1$ ⇔ measurement rate > decoherence rate

- Gravity measurements between two (possibly cooled) oscillators



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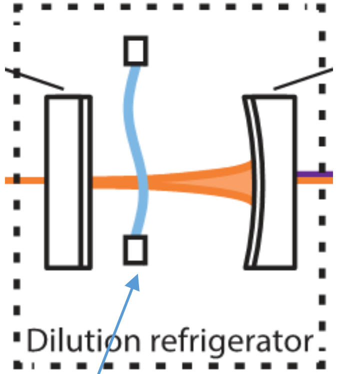
- The most massive oscillator that has been used to realized its motional ground state is

PRL **116,** 063601 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Laser Cooling of a Micromechanical Membrane to the Quantum Backaction Limit

R. W. Peterson,[1,2] T. P. Purdy,[1,2,*] N. S. Kampel,[1,2] R. W. Andrews,[1,2] P.-L. Yu,[1,2,†] K. W. Lehnert,[1,2,3] and C. A. Regal[1,2,‡]
[1]*JILA, University of Colorado and NIST, Boulder, Colorado 80309, USA*
[2]*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[3]*National Institute of Standards and Technology (NIST), Boulder, Colorado 80305, USA*
(Received 8 October 2015; published 8 February 2016)



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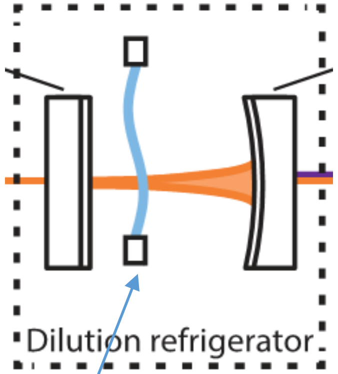

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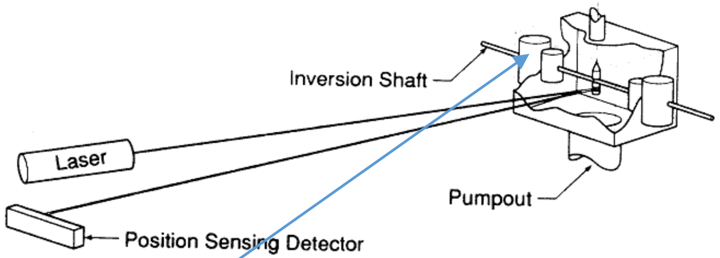
- The smallest source mass that has been used to produce a measurable gravitational force is

PHYSICAL REVIEW D VOLUME 42, NUMBER 4 15 AUGU

Experimental test of equivalence principle with polarized masses

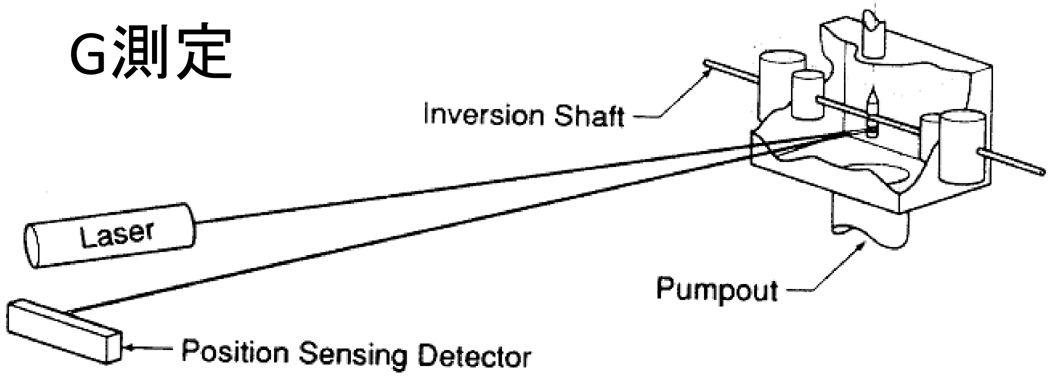
Rogers C. Ritter, Charles E. Goldblum,* Wei-Tou Ni,† George T. Gillies,‡ and Clive C. Speake§
Department of Physics, University of Virginia, Charlottesville, Virginia 22901
(Received 27 November 1989)



90 g

Gravity & quantum

G測定



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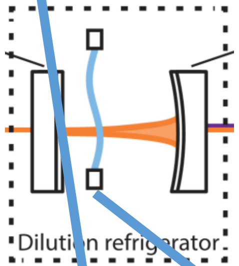
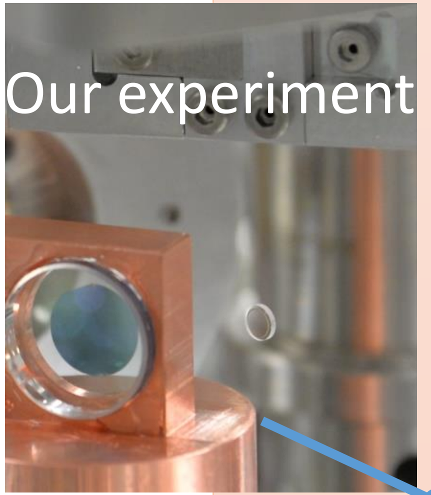
Test of quantum nature of Newtonian interaction

Ground state





ag fg pg ng ug mg g kg Mass

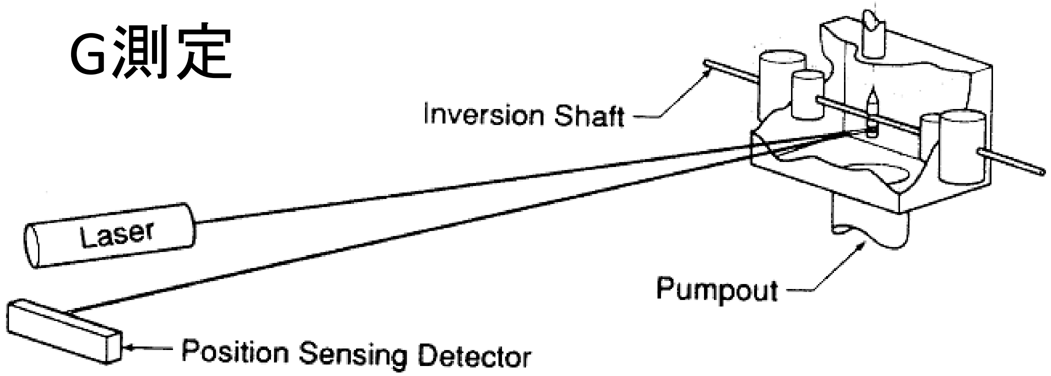
Gravity &

PRL **119,** 240401 (2017) PHYS

Spin Entangle

Sougato Bose,[1] Anupam Mazur
Mauro Paternostro,[5] Andrew A.

G測定



PHYSICAL REVIEW LETTERS **122,** 071101 (2019)

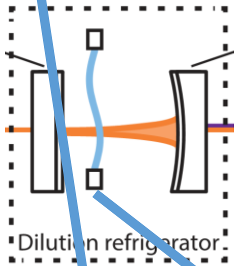
Featured in Physics

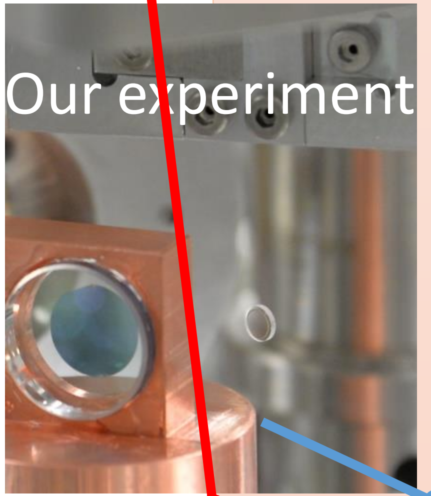
Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements

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]
[1]*Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai 980-8578, Japan*
[2]*Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan*
[3]*JST, PRESTO, Kawaguchi, Saitama 332-0012, Japan*
[4]*Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[5]*National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[6]*Department of Astronomical Science, SOKENDAI (The Graduate University for Advanced Studies), Mitaka, Tokyo 181-8588, Japan*

Test of quan
of Newtonia

Ground state





ag fg pg ng ug mg g kg Mass

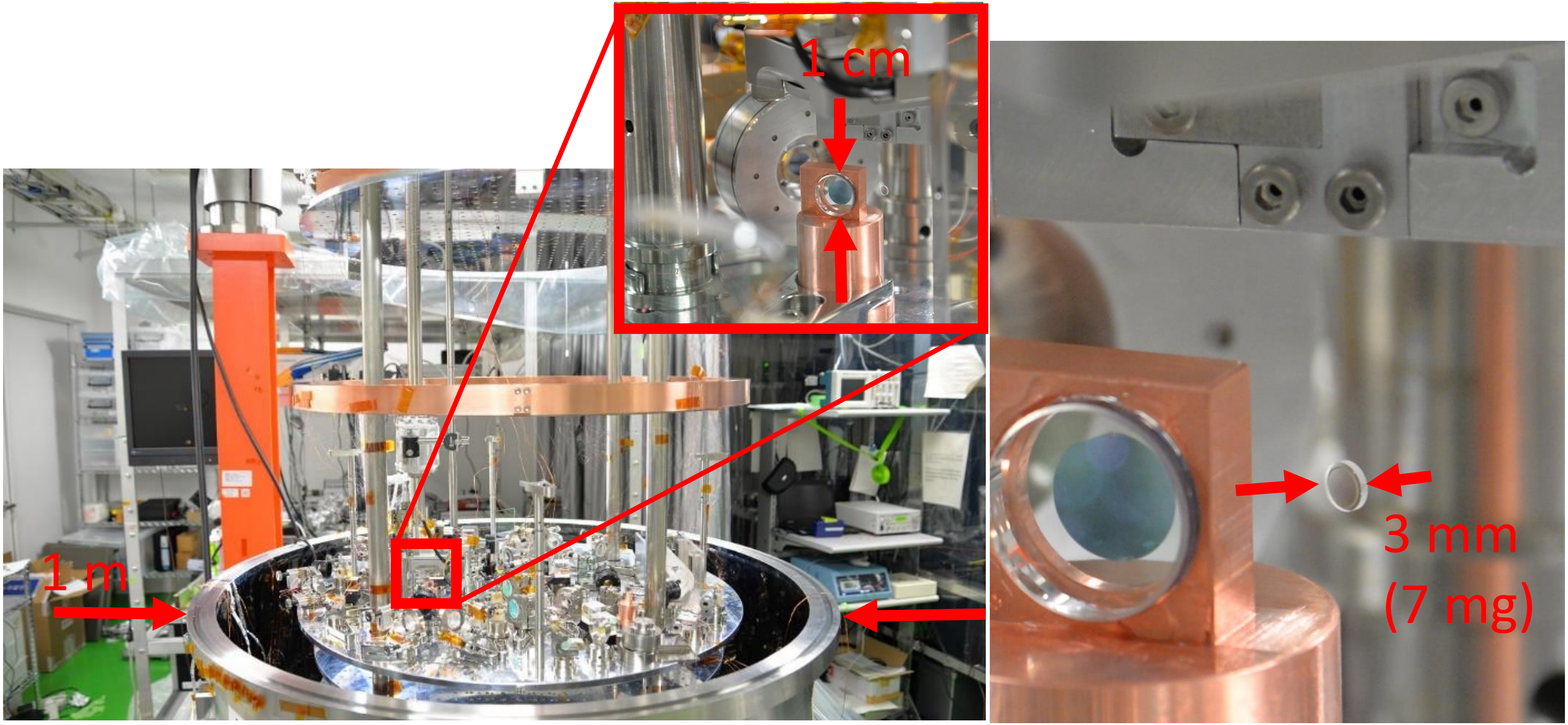
OPEN ACCESS
IOP Publishing
Classical and Quantum Gravity
Class. Quantum Grav. 33 (2016) 125031 (19pp)
doi:10.1088/0264-9381/33/12/125031

A micromechanical proof-of-principle experiment for measuring the gravitational force of milligram masses

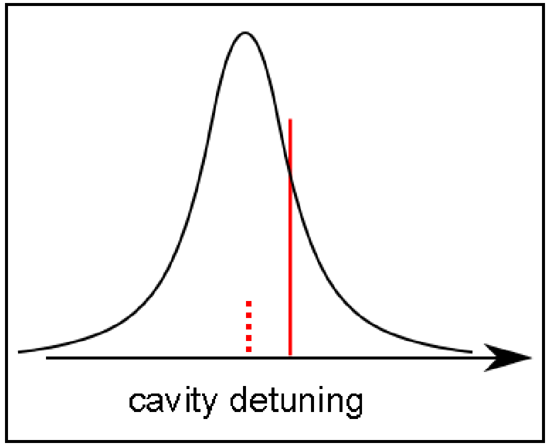
Jonas Schmöle, Mathias Dragosits, Hans Hepach and Markus Aspelmeyer

ag tg pg ng ug mg g kg Mass

Our experiment



Opt-mechanical cavity (design)



Optical freq.

$$\frac{\omega_c}{2\pi} = 280\ \mathrm{THz}$$

Input power

$P_{in} = 10$ mW (trap)

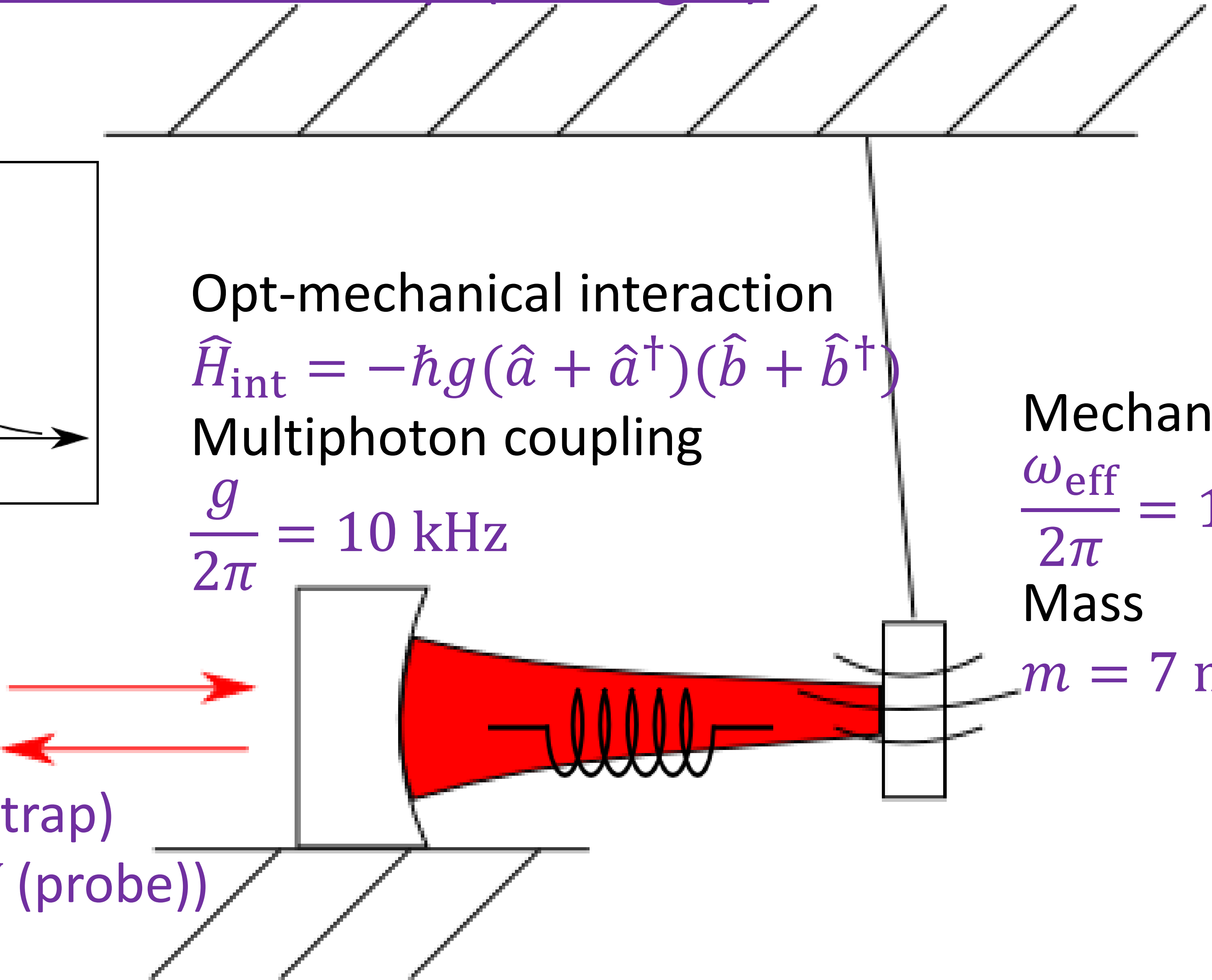
(= 0.3 mW (probe))

Opt-mechanical interaction

$$\hat{H}_{int} = -\hbar g(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

Multiphoton coupling

$$\frac{g}{2\pi} = 10\ \mathrm{kHz}$$



Mechanical freq.

$$\frac{\omega_{eff}}{2\pi} = 1\ \mathrm{kHz}$$

Mass

$m = 7$ mg

Towards quantum control of **low freq.** oscillators

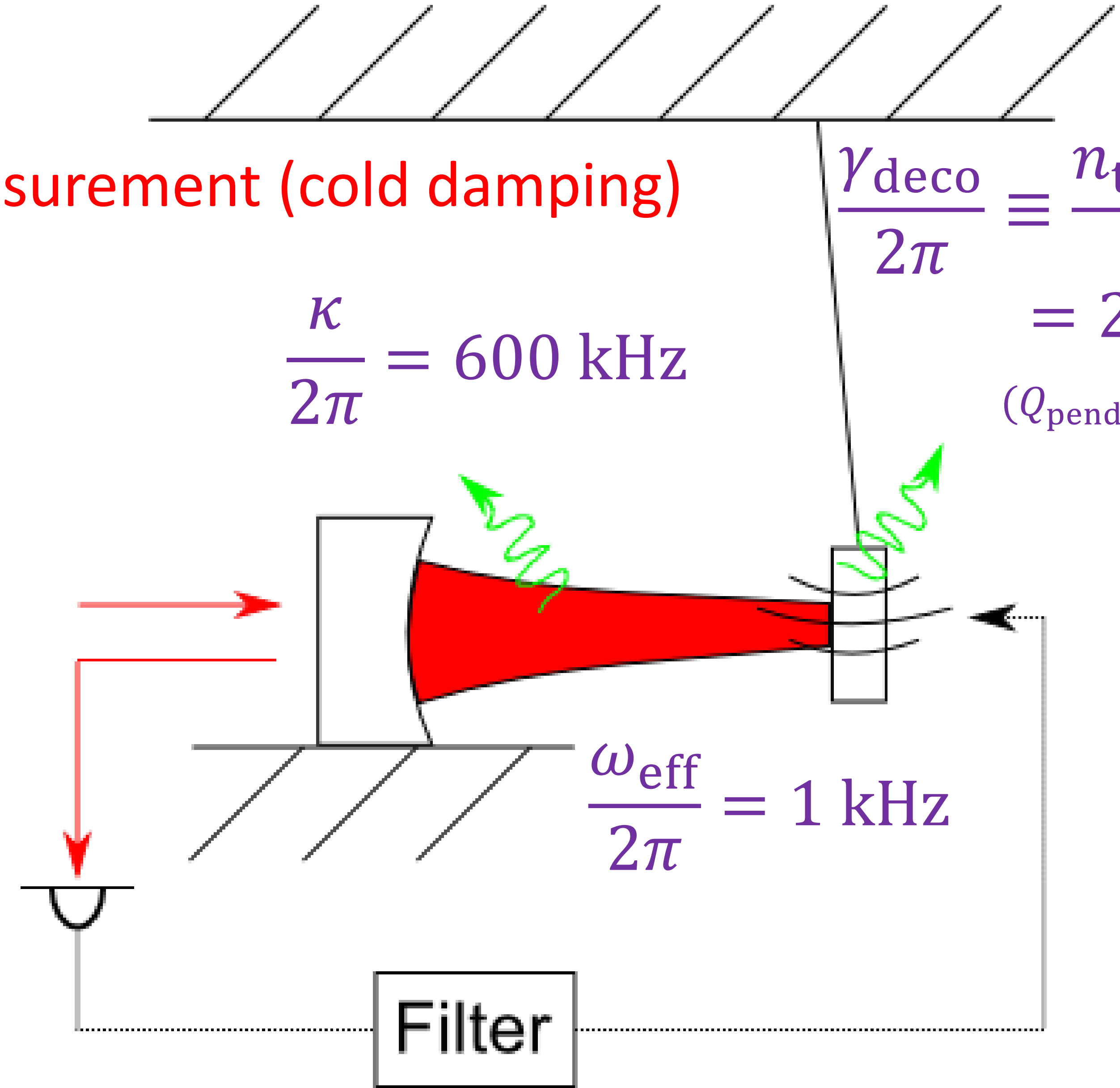
- Ground state cooling based on measurement (cold damping)

$\gamma_{\mathrm{meas}} > \gamma_{\mathrm{deco}}$

- Thermal decoherence

$\omega_{\mathrm{eff}} > \gamma_{\mathrm{deco}}$

$$\gamma_{\mathrm{meas}} \equiv \frac{x_{zp}^2}{S_{XX}^{\mathrm{shot}}} = \frac{4g^2}{\kappa} = 2\pi 40\ \mathrm{Hz}$$



$$\frac{\kappa}{2\pi} = 600\ \mathrm{kHz}$$

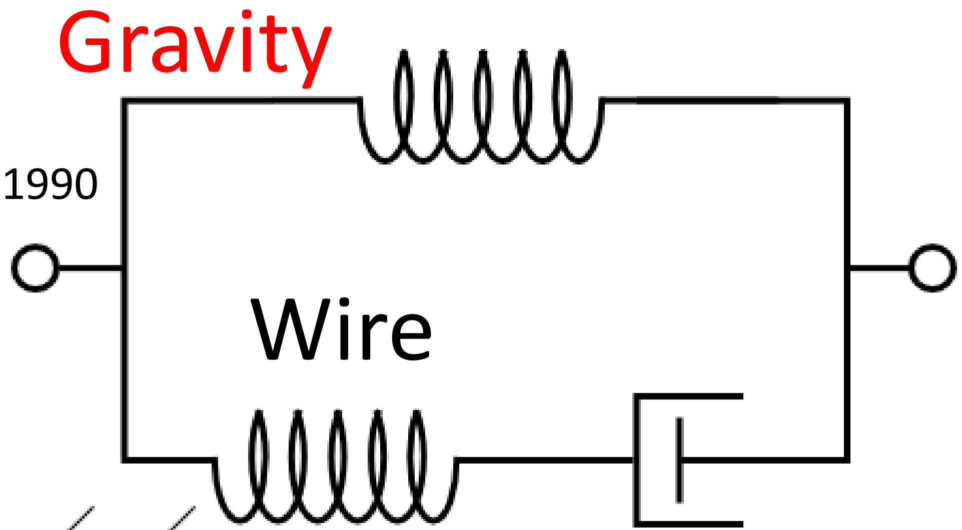
$$\frac{\gamma_{\mathrm{deco}}}{2\pi} \equiv \frac{n_{\mathrm{th}}\gamma_{\mathrm{eff}}}{2\pi} = 20\ \mathrm{Hz}$$

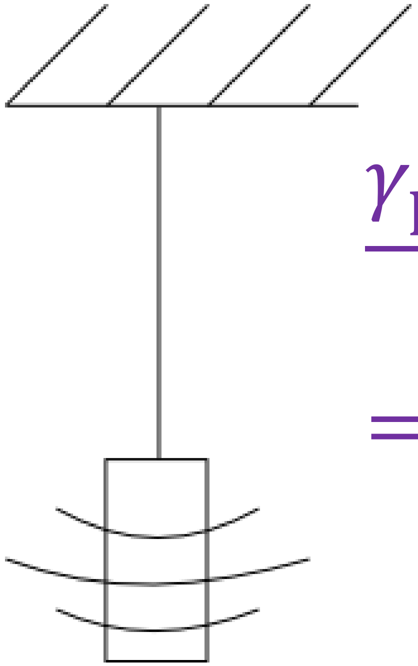
$(Q_{\mathrm{pend}} = 10^6)$

$$\frac{\omega_{\mathrm{eff}}}{2\pi} = 1\ \mathrm{kHz}$$

Mechanical oscillators: pendulum/levitation

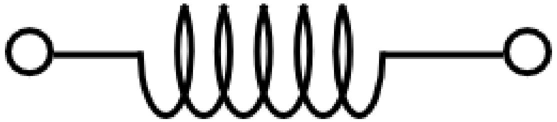
c.f. Saulson 1990





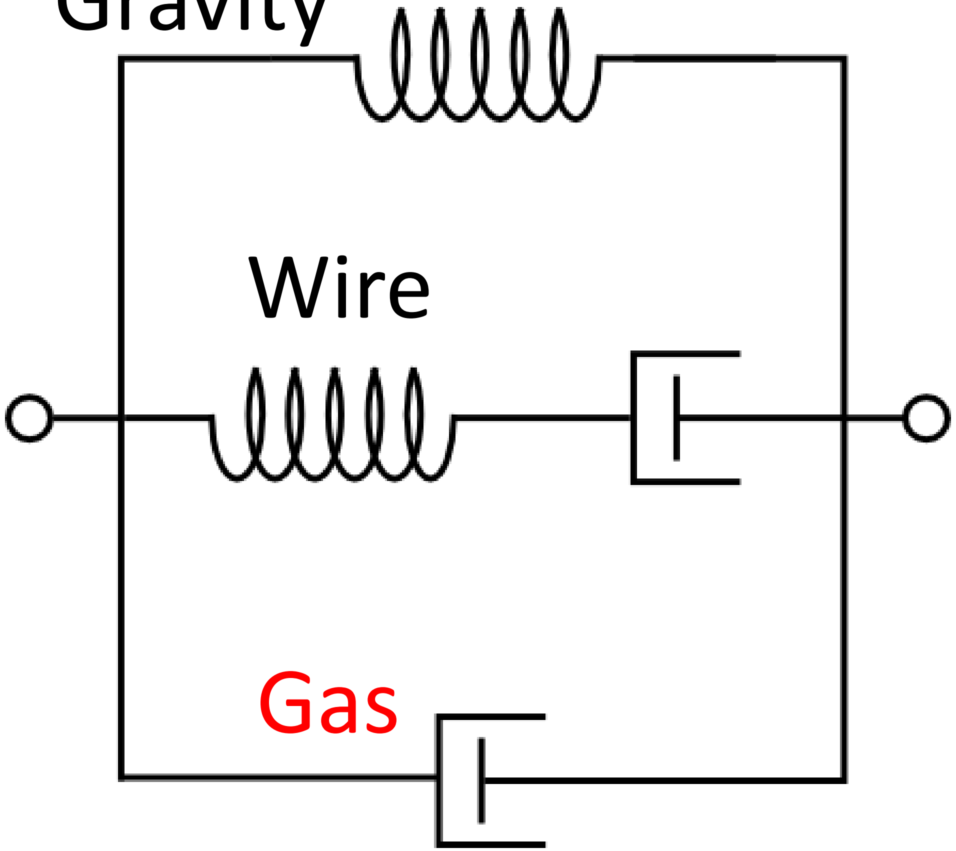
$$\frac{\gamma_{\mathrm{pend}}}{2\pi} = 4.4 \times 10^{-6} \left(\frac{\omega_{\mathrm{pend}}}{\omega}\right) \mathrm{Hz}$$

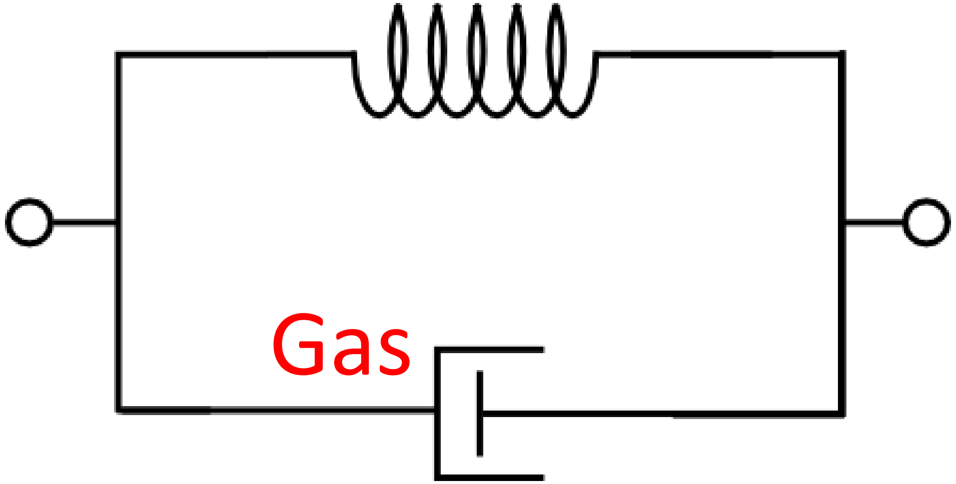
e.g. Optical spring



$$\gamma_{\mathrm{tot}} = 0$$

Mechanical oscillators: pendulum/levitation





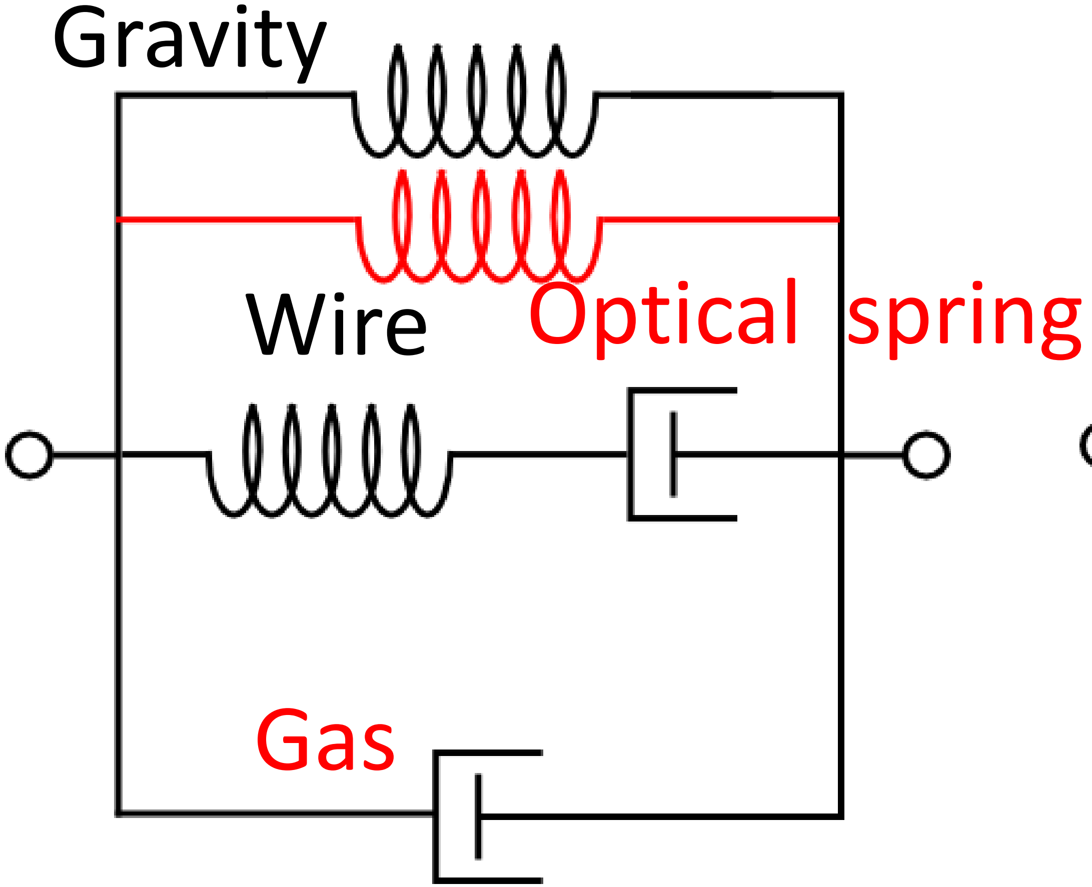
$\gamma_{\text{tot}} = \gamma_{\text{gas}} = 2\pi 3.9\ \text{nHz}$

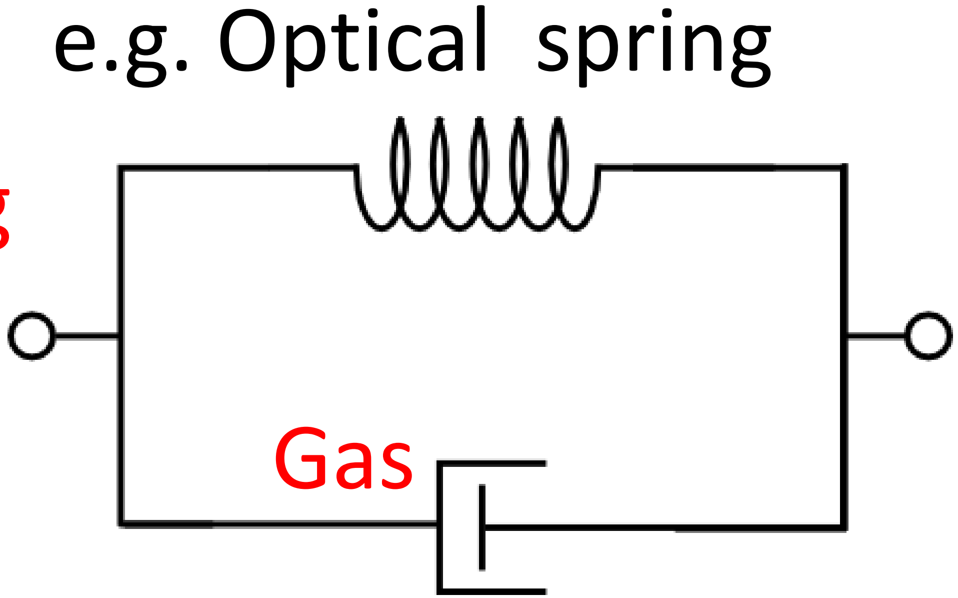
(Pressure = 10^-5 Pa,
Mirror's diameter = 3 mm)

$\gamma_{\text{tot}} = \gamma_{\text{pend}}(f) + \gamma_{\text{gas}}$

$\rightarrow \gamma_{\text{gas}}$@~kHz but ω_{pend} is small

Mechanical oscillators: pendulum/levitation

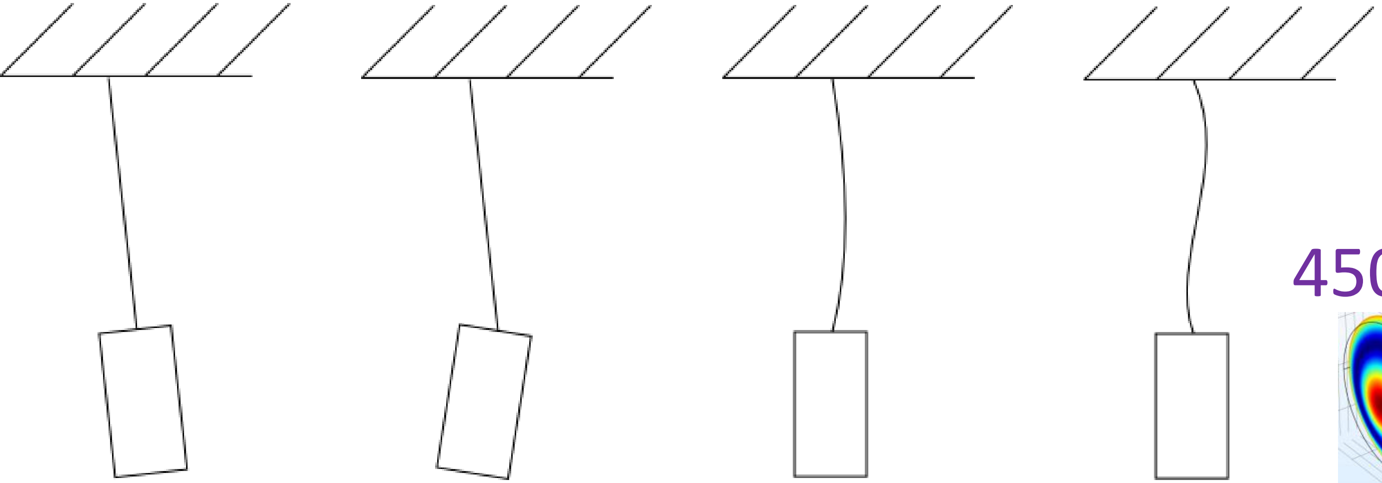




$\gamma_{\mathrm{tot}} \rightarrow \gamma_{\mathrm{gas}} @ \omega = \omega_{\mathrm{eff}}$

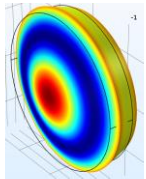
$\gamma_{\mathrm{tot}} = \gamma_{\mathrm{gas}}$

Limit of dissipation dilution : higher frequency modes



pendulum pitch 1-st violin 2-nd violin

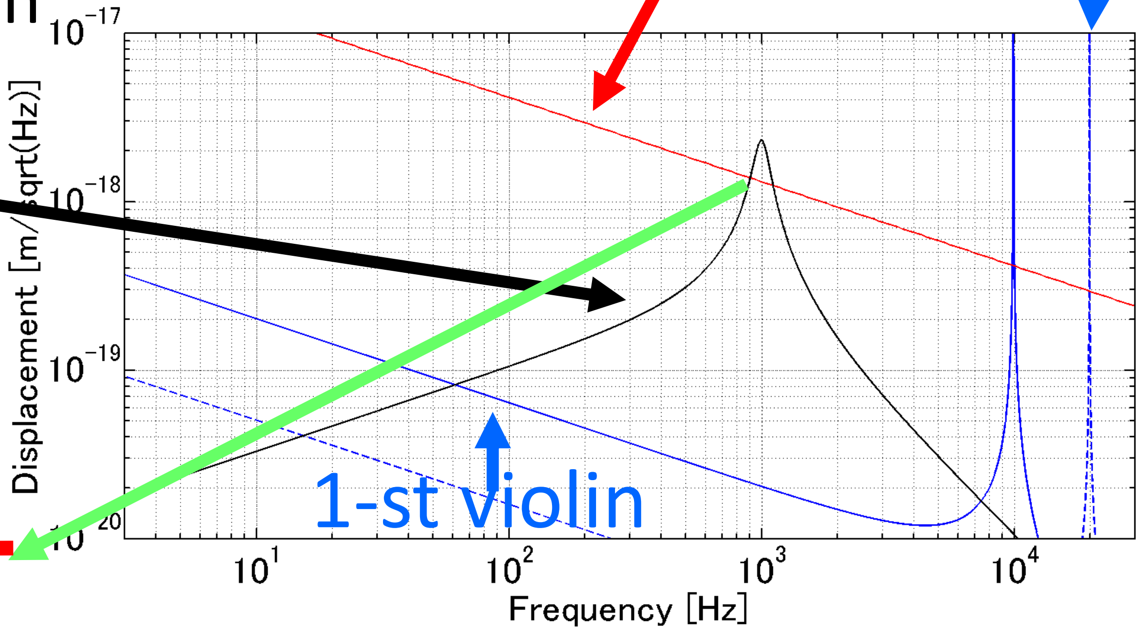
450 kHz



Mirror
(contribution:70 % coating)

(1) Increase thermal noise at optically trapped COM frequency

2-nd violin



Pendulum's zero point fluc.

$Q_{\mathrm{eff}} = 5$
$Q_{\mathrm{violin}} = 2 \times 10^4$
$Q_{\mathrm{dielectric}} = 2500\ (SiO_2/Ta_2O_5)$
beam radii = 300 um

$\frac{\gamma_{\mathrm{meas}}}{2\pi} =$ ~~40 Hz~~ 20 Hz

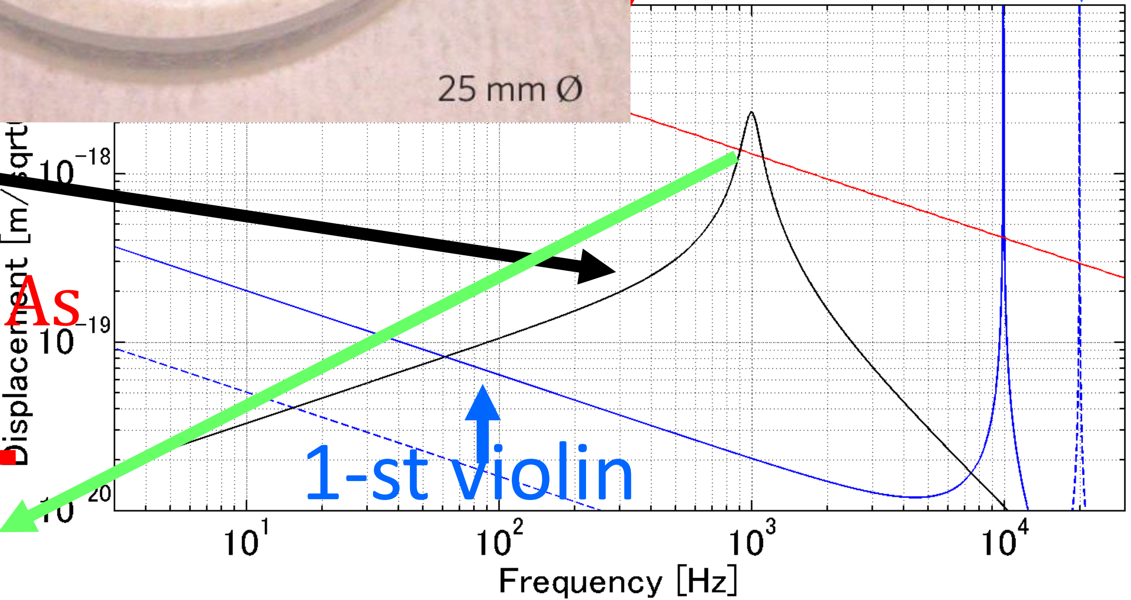
dilution : higher frequency modes

ease thermal noise
ally trapped COM
cy

2-nd violin

0 % coating)

oint fluc.



1-st violin

$Q_{\mathrm{violin}} = 2 \times 10^4$ 10^4

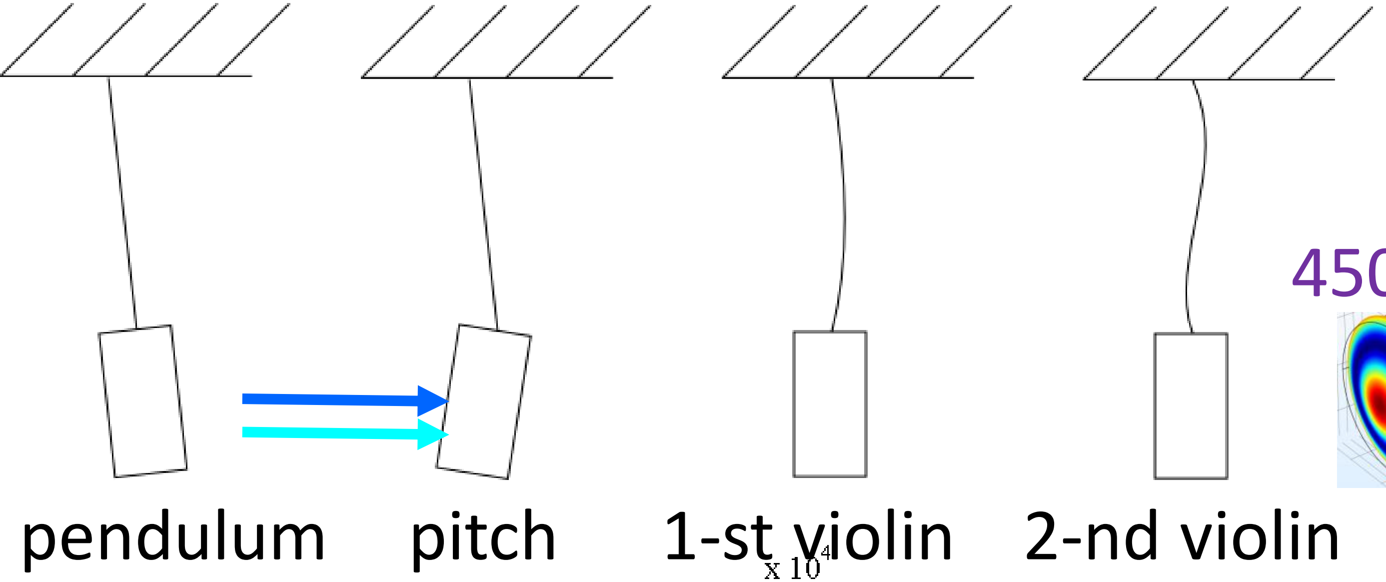
$GaAs/Al_{0.92}Ga_{0.08}As$

$Q_{\mathrm{dielectric}} = \sout{2500}\ (\sout{SiO_2/Ta_2O_5})$

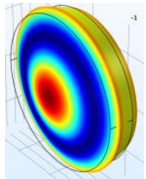
beam radii = 300 um

$\frac{\gamma_{\mathrm{meas}}}{2\pi} = \sout{20\ \mathrm{Hz}}\ 40\ \mathrm{Hz}$

Limit of dissipation dilution : higher frequency modes



450 kHz



(1) Increase thermal noise at optically trapped COM frequency

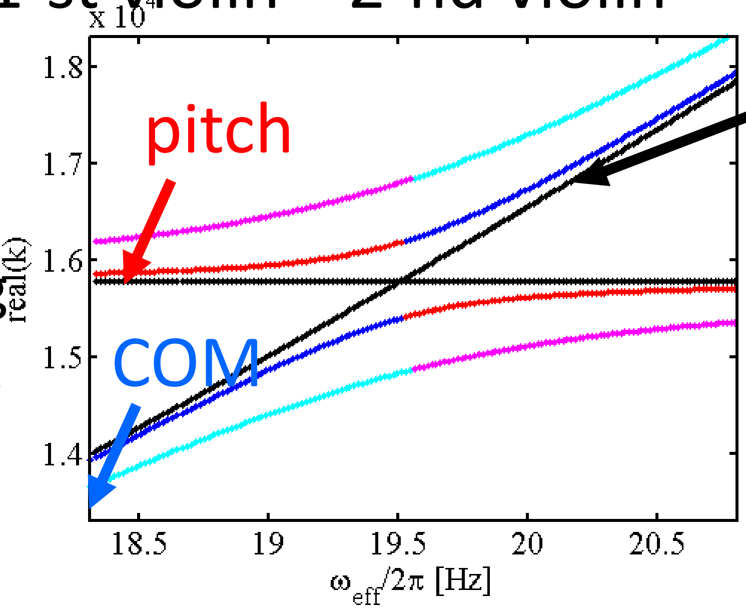
c.f. PRL108,214302 (2012)

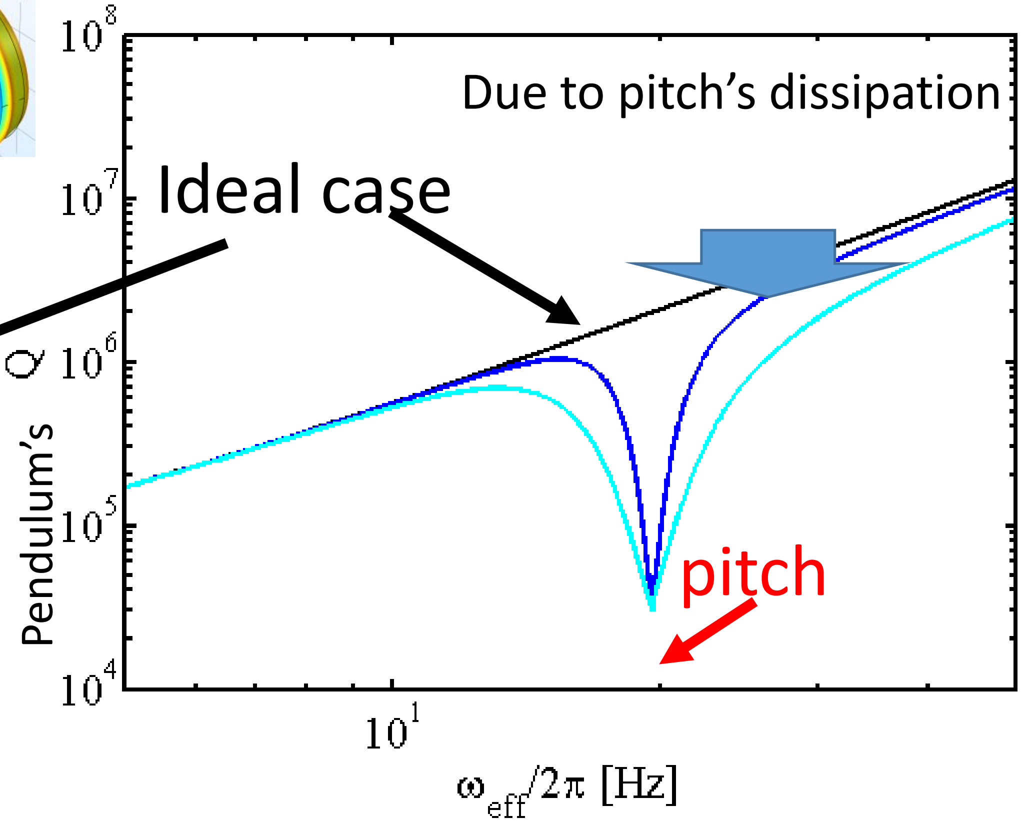
(2)Mode mixing

pendulum-pitch coupling

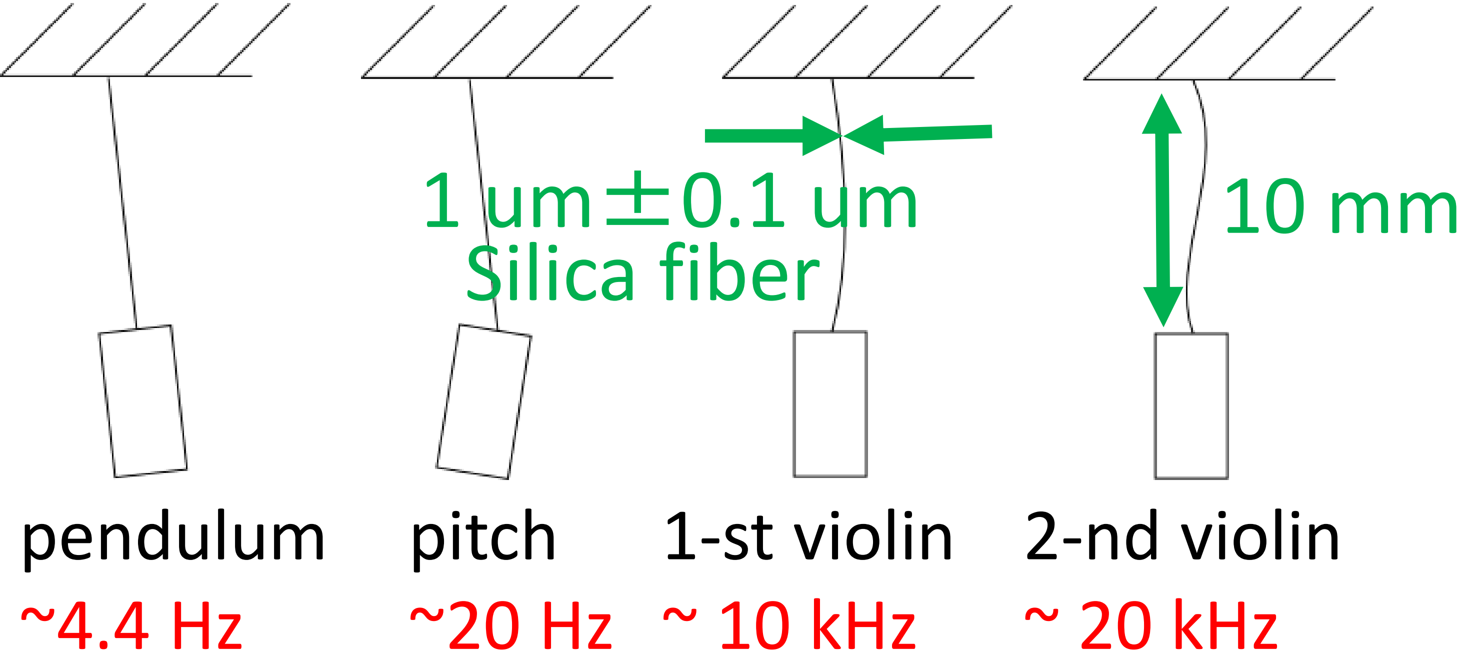
Beam miss-centering

5e-5 m, 2e-5 m



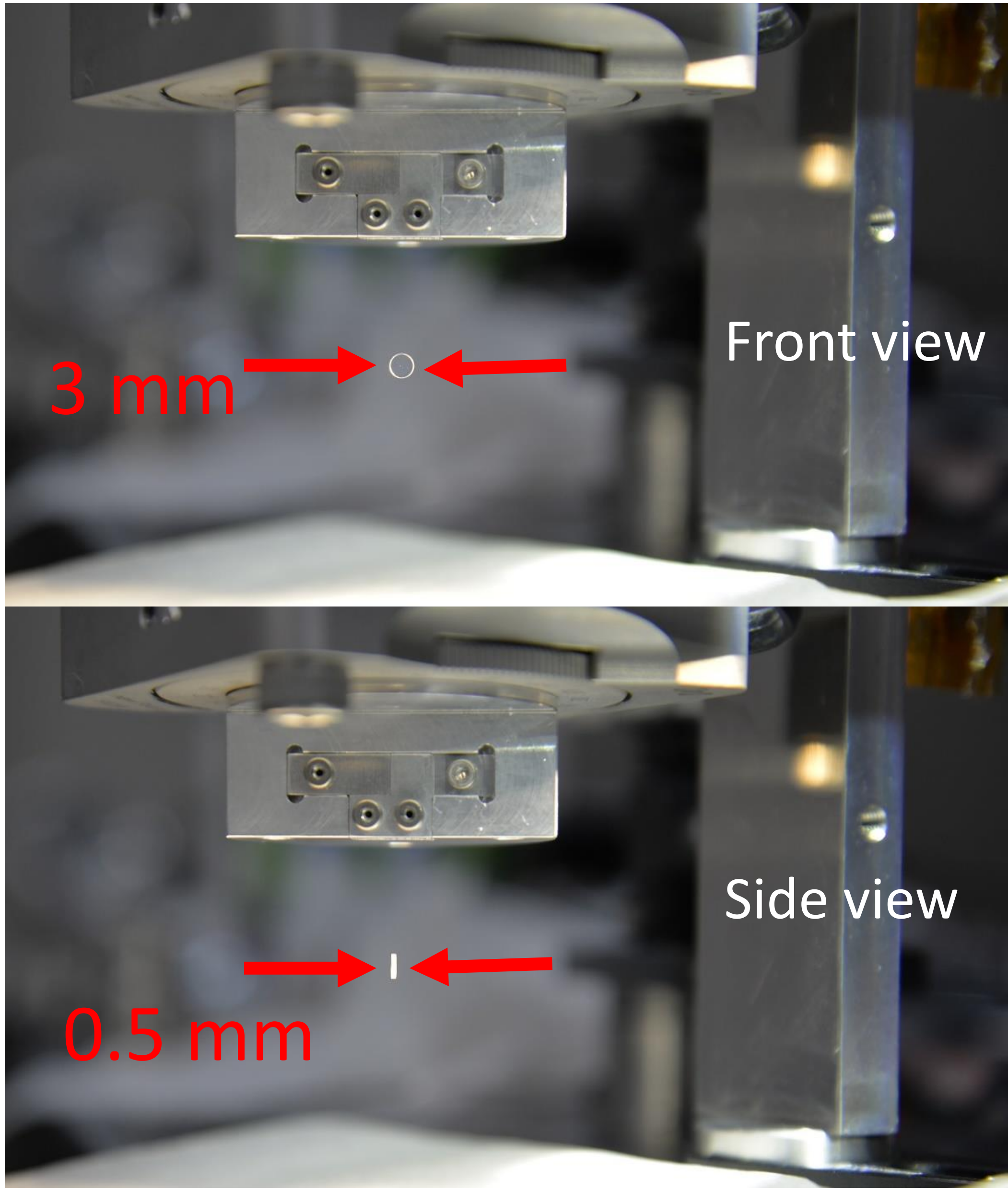


Current status of our pendulum

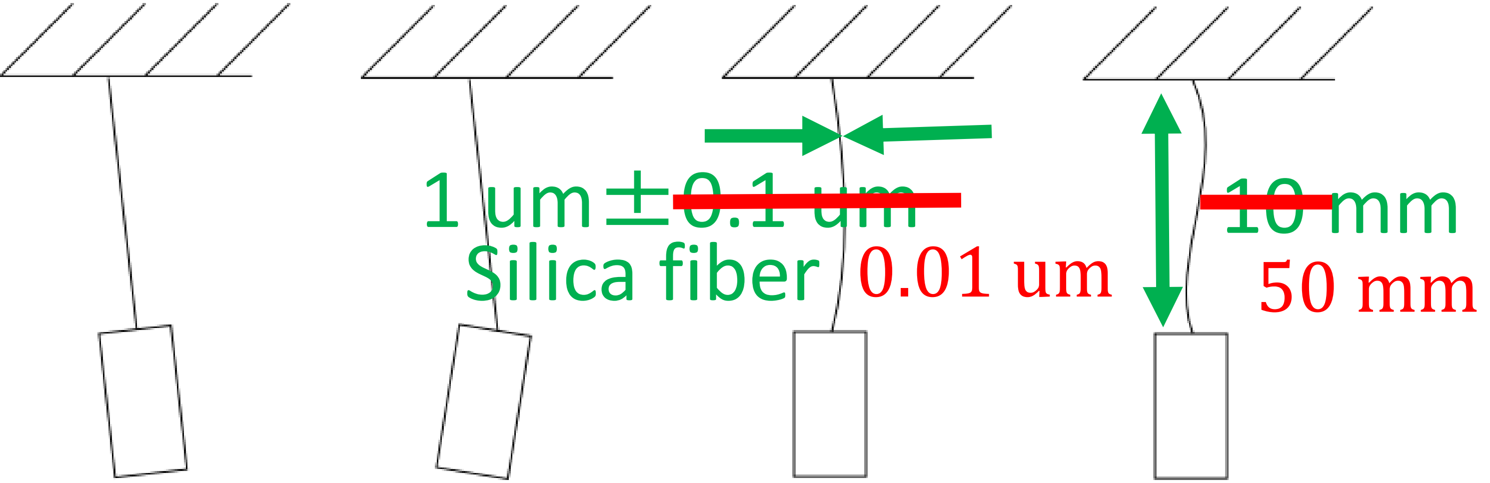


$$Q_{\text{pend}} \simeq 10^5$$

$$\frac{\gamma_{\text{deco}}}{2\pi} = 1\,\text{kHz}\ \left(\frac{\omega_{\text{eff}}}{2\pi} = 1\,\text{kHz}\right)$$



Next goal: long silica fiber for enhancing dilution

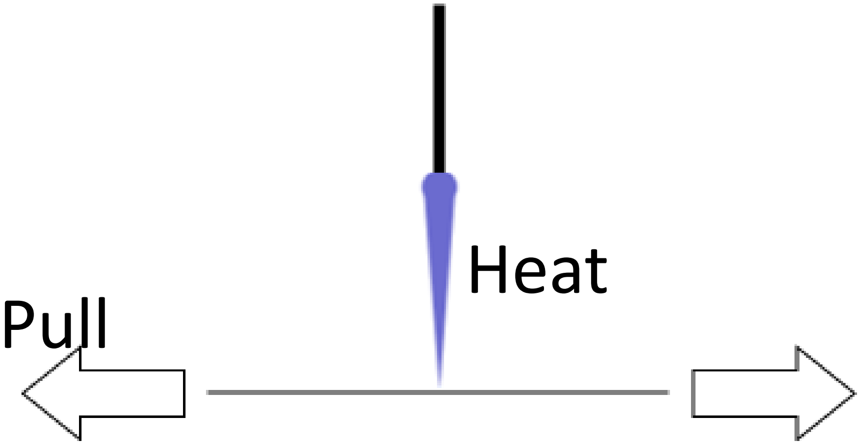


$$Q_{\mathrm{pend}} \simeq 10^5 > 10^6$$

$$\frac{\gamma_{\mathrm{deco}}}{2\pi} = 1\,\mathrm{kHz} \left(\frac{\omega_{\mathrm{eff}}}{2\pi} = 1\,\mathrm{kHz}\right)$$

20 Hz < measurement rate

Heat & pull method



For increasing wire length,
Pull length 10 cm→30 cm

For reducing surface roughness,
Gas flow is stabilized

- 5 cm fiber（直径1 um）作ったよ
- 写真は間に合いませんでした

Siddels-Sigg (angular) instability in a linear cavity

- Pendulum + optical spring (detuned cavity)

✓Low mechanical dissipation

✓Prevents higher modes

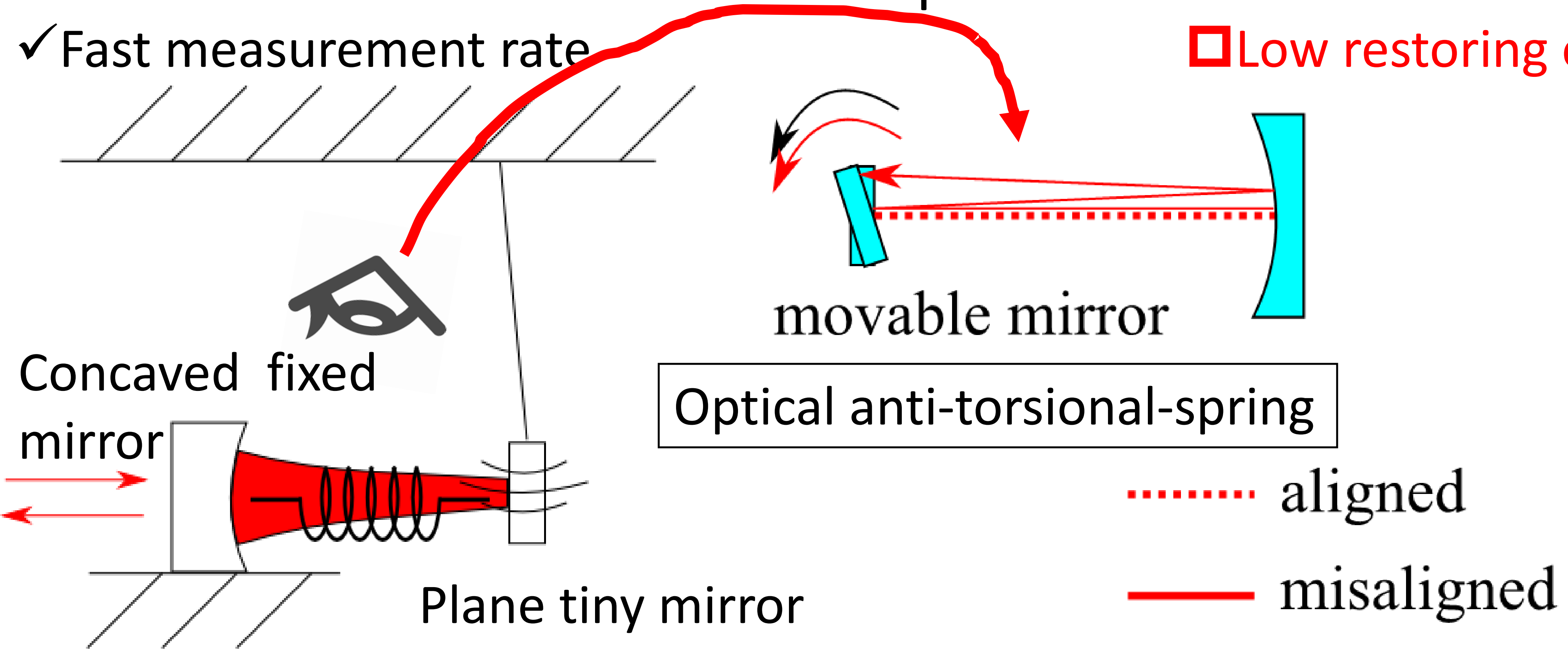
✓Fast measurement rate

- A thin fiber for suspension

✓High gravitational dilution

✓Ignoring violin modes

☐Low restoring of YAW



Siddels-Sigg (angular) instability in a linear cavity

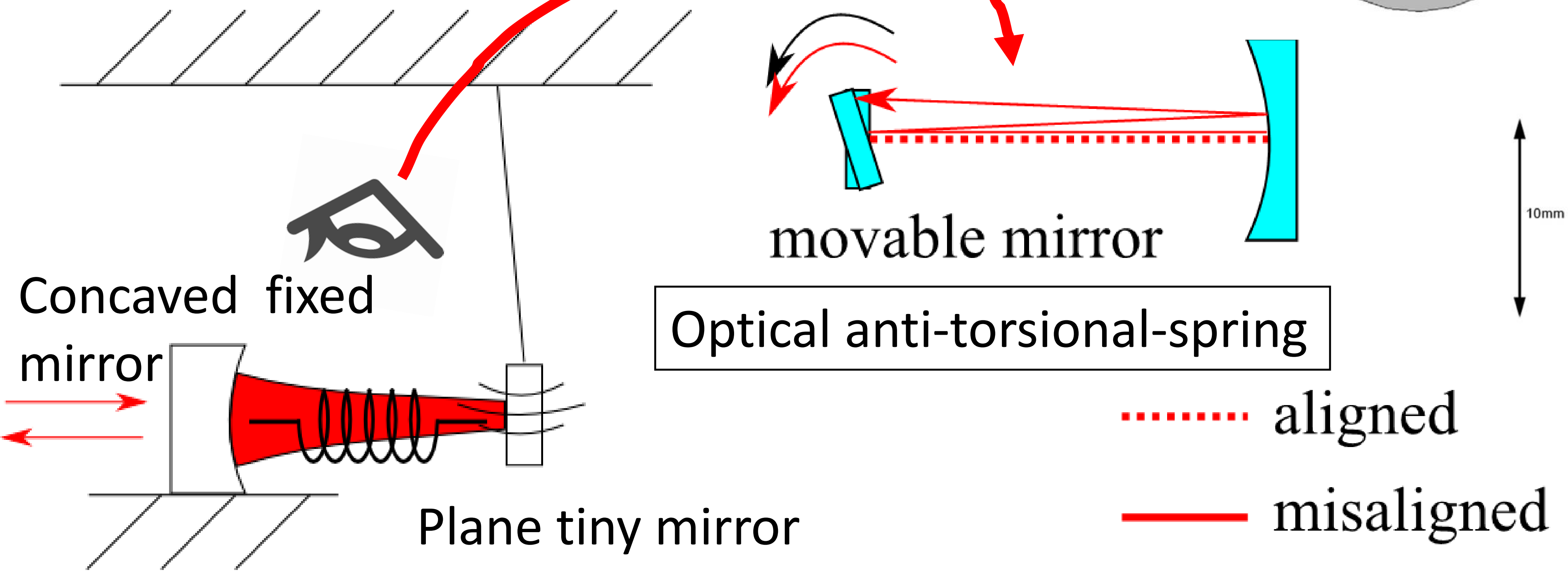
New Journal of Physics 14 (2012) 115008

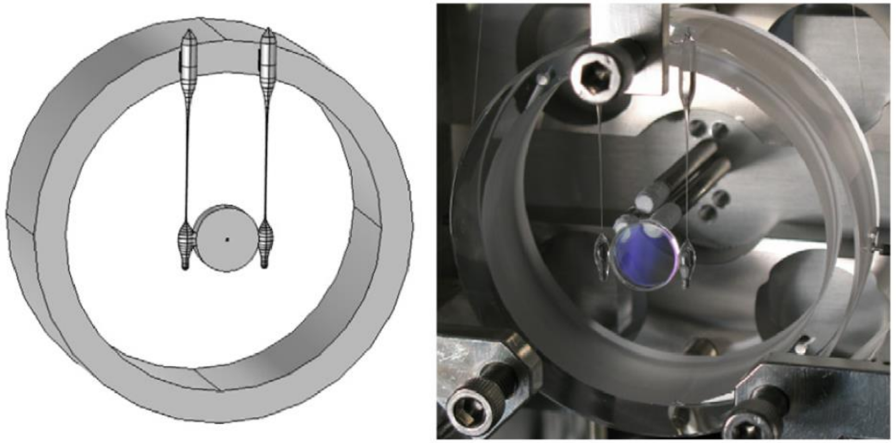
- Pendulum + optical spring (detuned cavity)

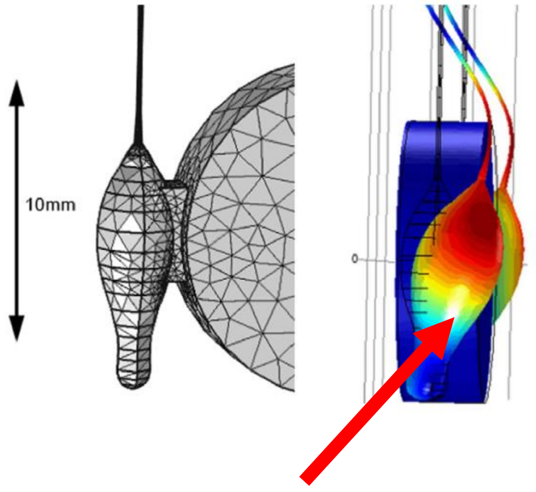
✓Low mechanical dissipation

✓Prevents higher modes

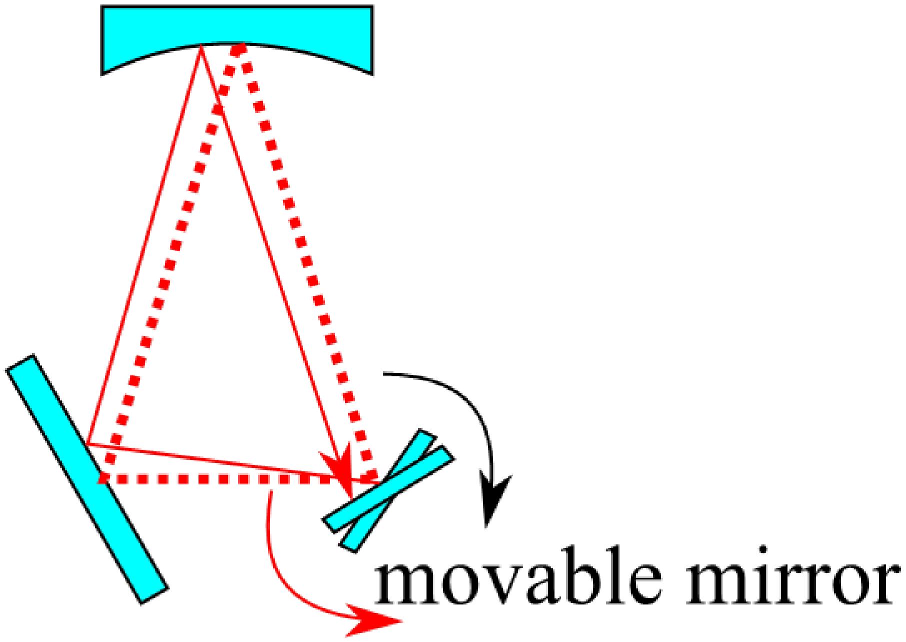
✓Fast measurement rate







Optical torsional spring



Opt. express 22, 12915–12923 (2014)

Simple pendulum + optical spring

+ optical torsional spring

→almost levitated system??

✓Low mechanical dissipation (gas limit)

✓Prevents higher frequency modes

✓Fast measurement rate

✓Passive stabilization

✓simple!

Coating thermal noise is main issue.

Setup

- Laser source

(1064 nm/500 mW)

- In-vac.

(1e-5 Pa)&

on-vibration-isolated

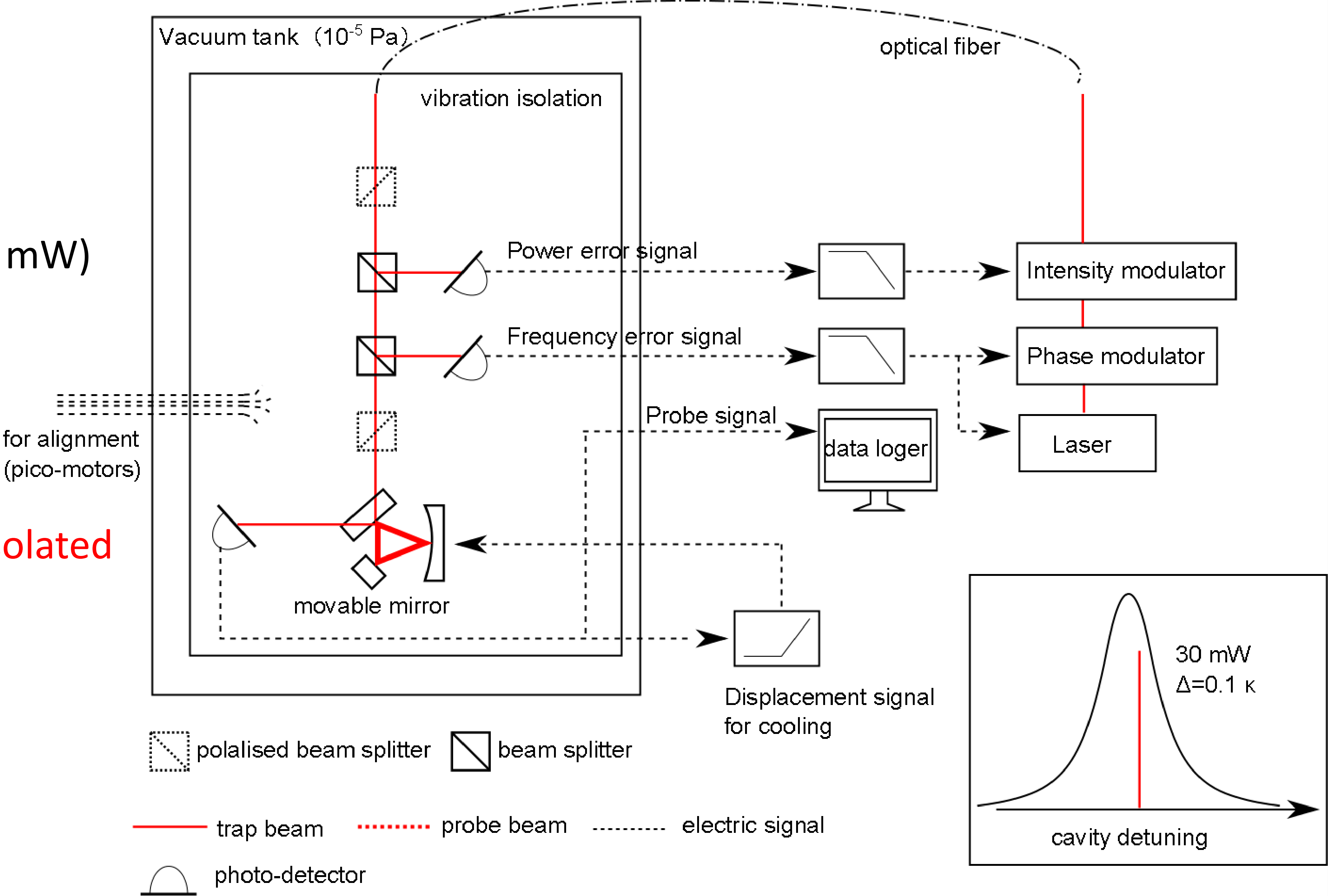
system

➢Int. stab.

➢Freq. stab.

➢Cooling

➢Probe



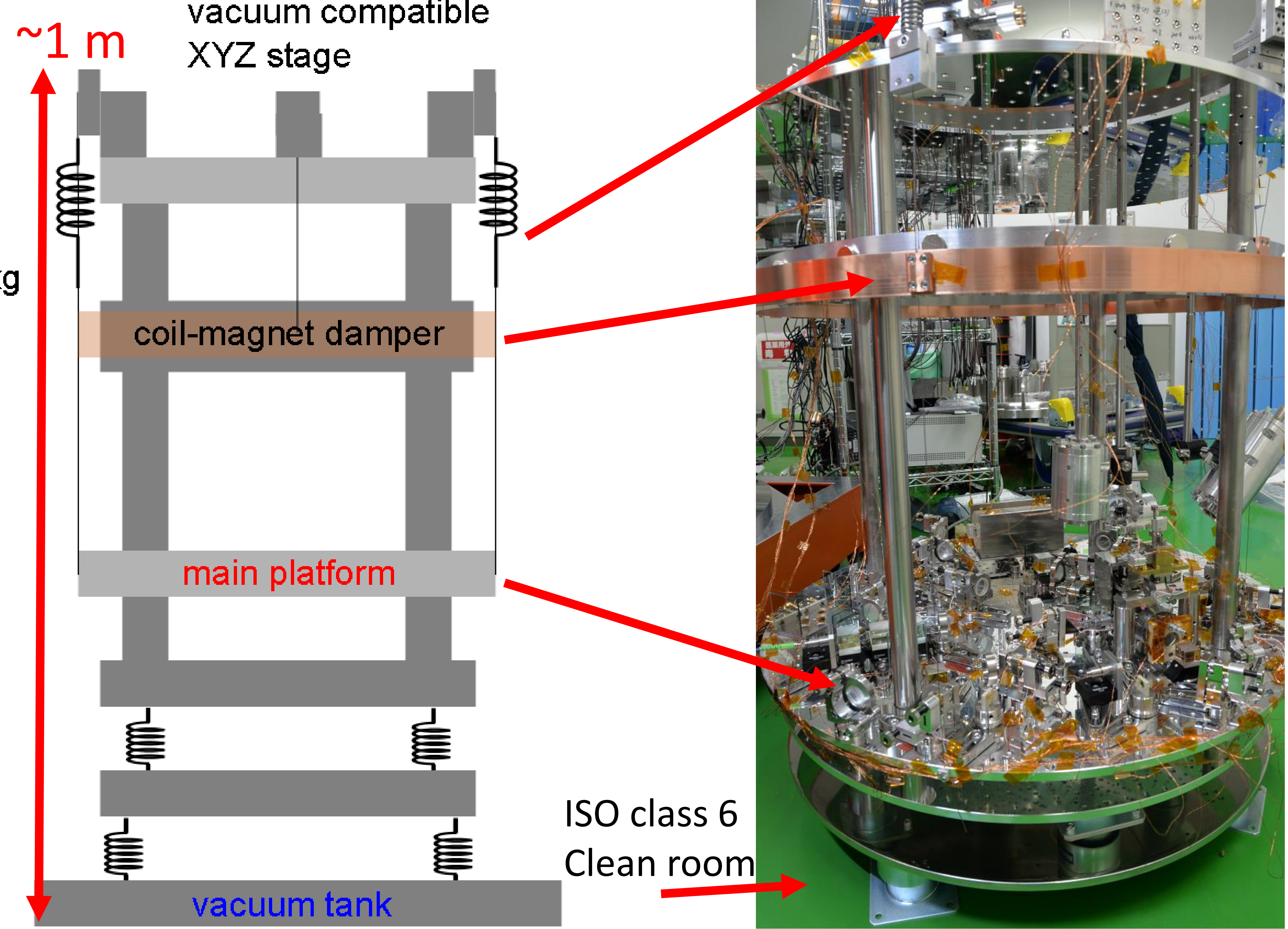
Setup

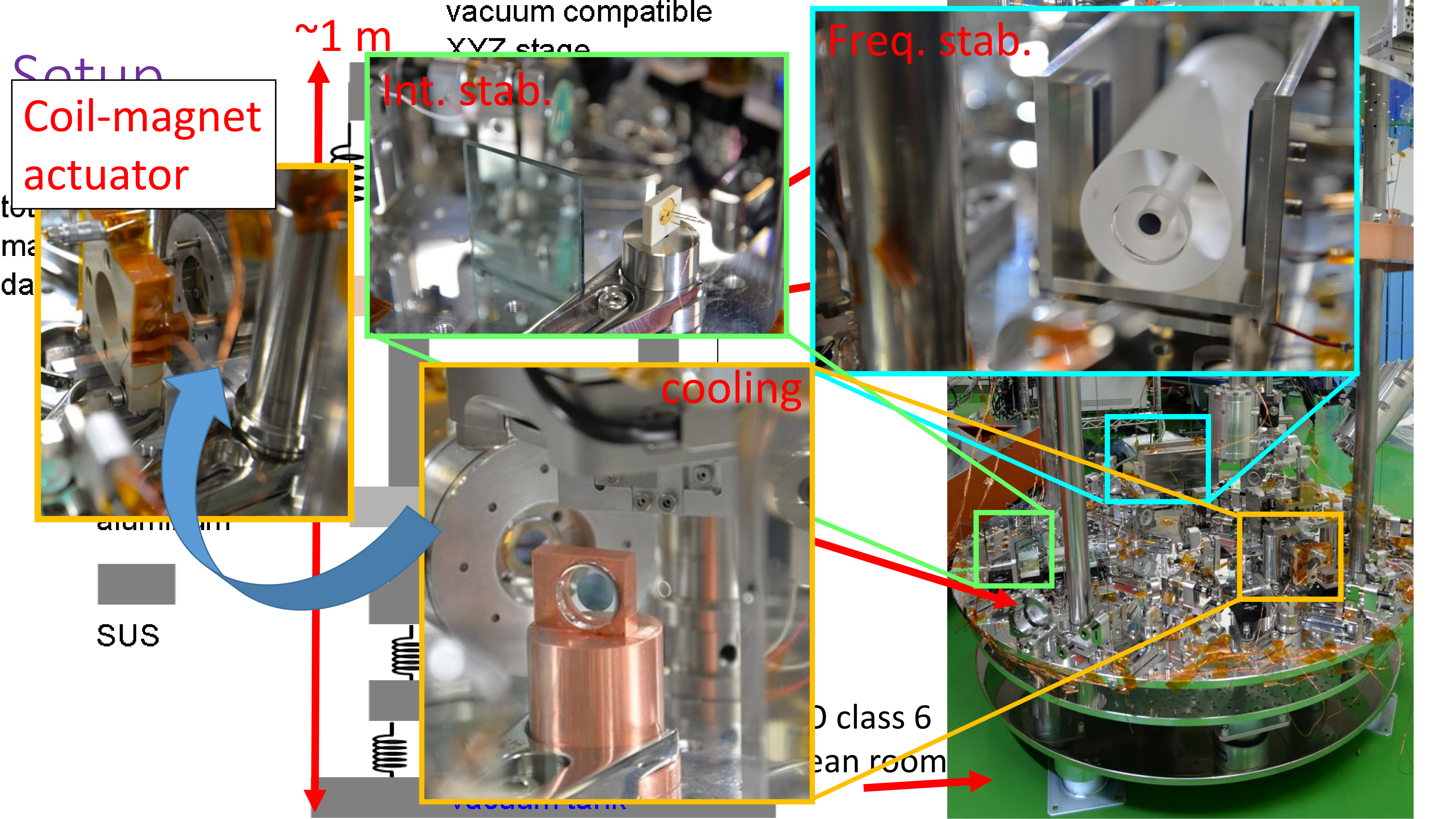
total mass ~ 120 kg
main platform ~ 20 kg
damper ~ 10 kg × 2

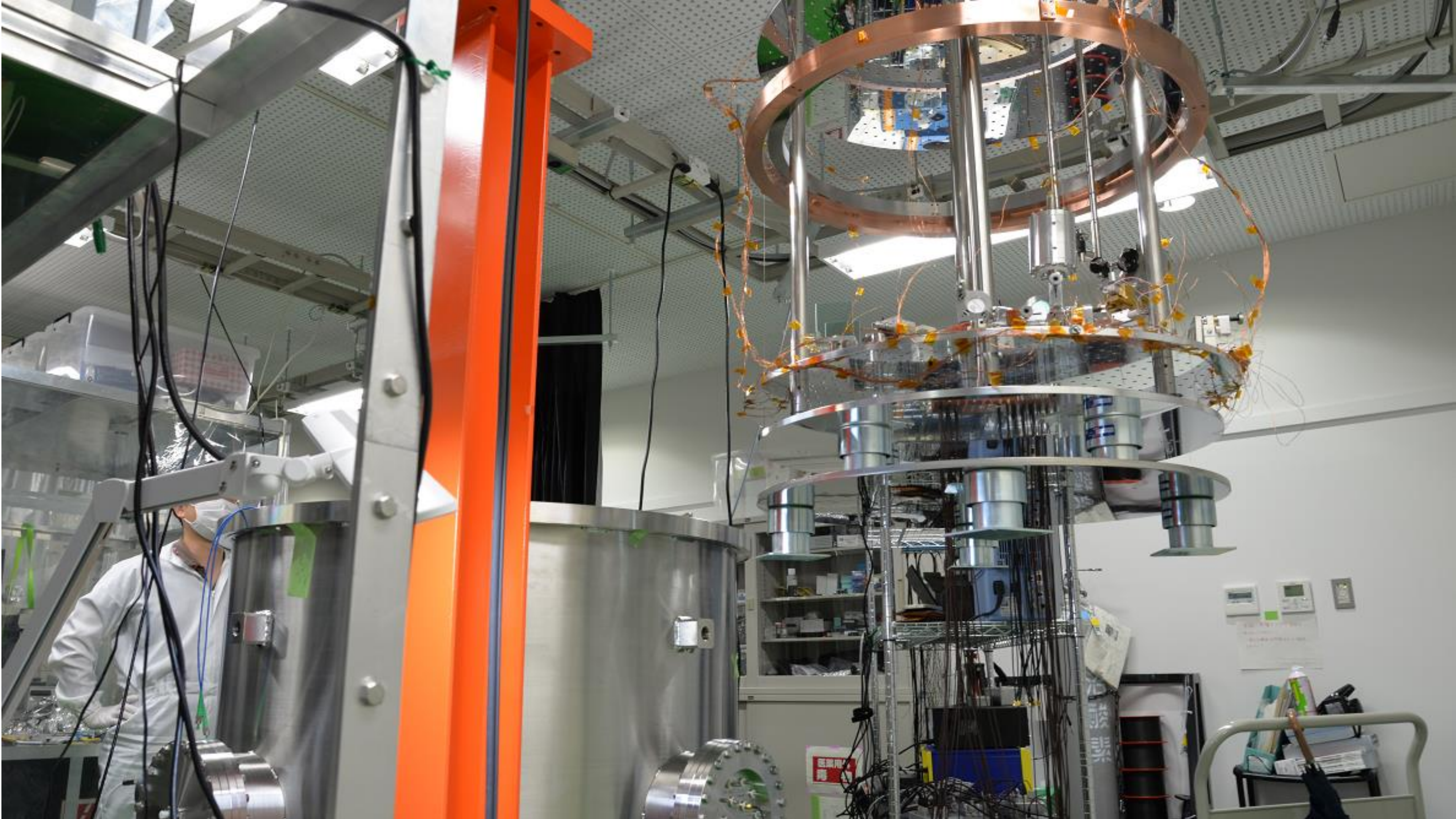
copper

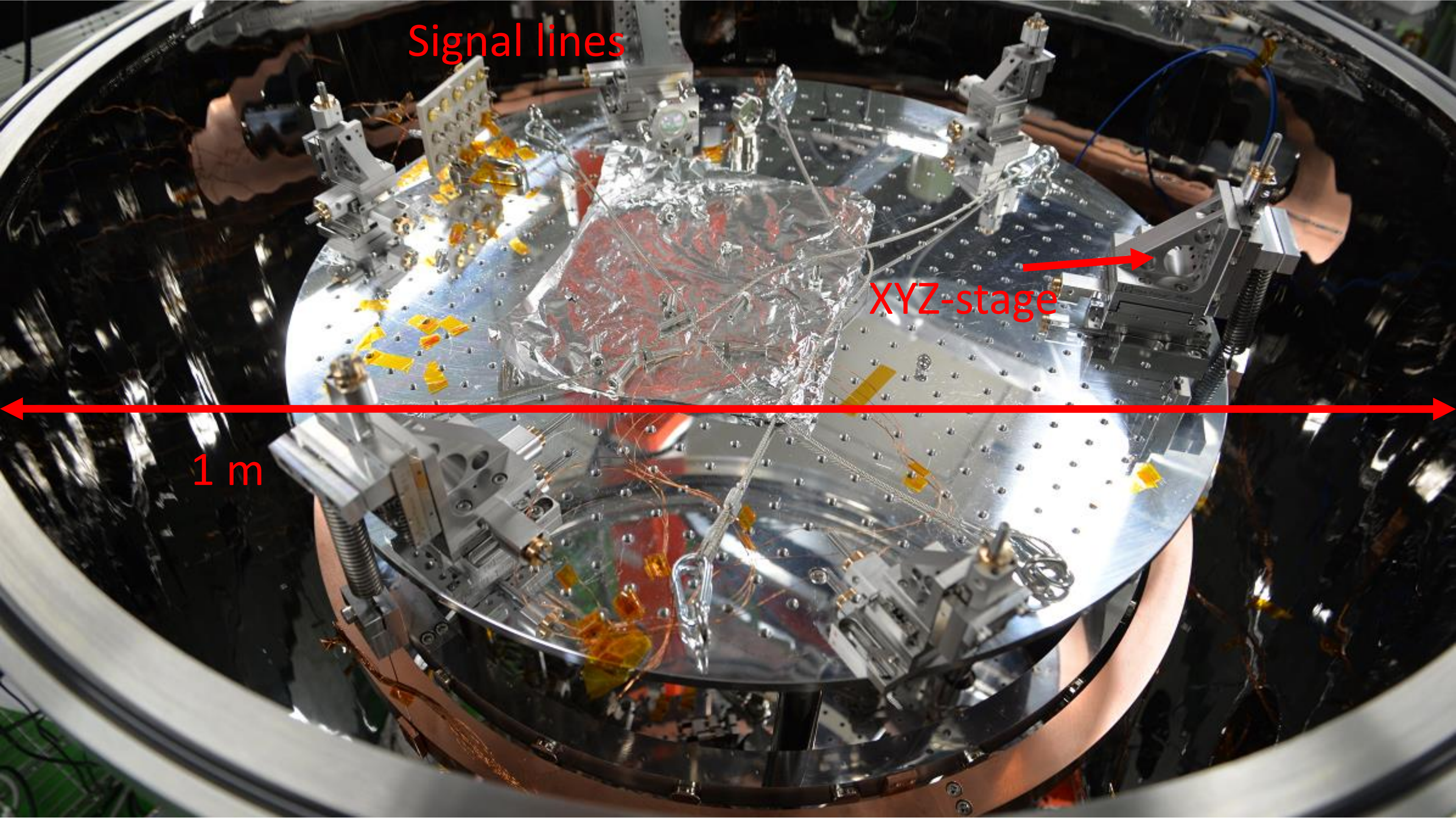
aluminum

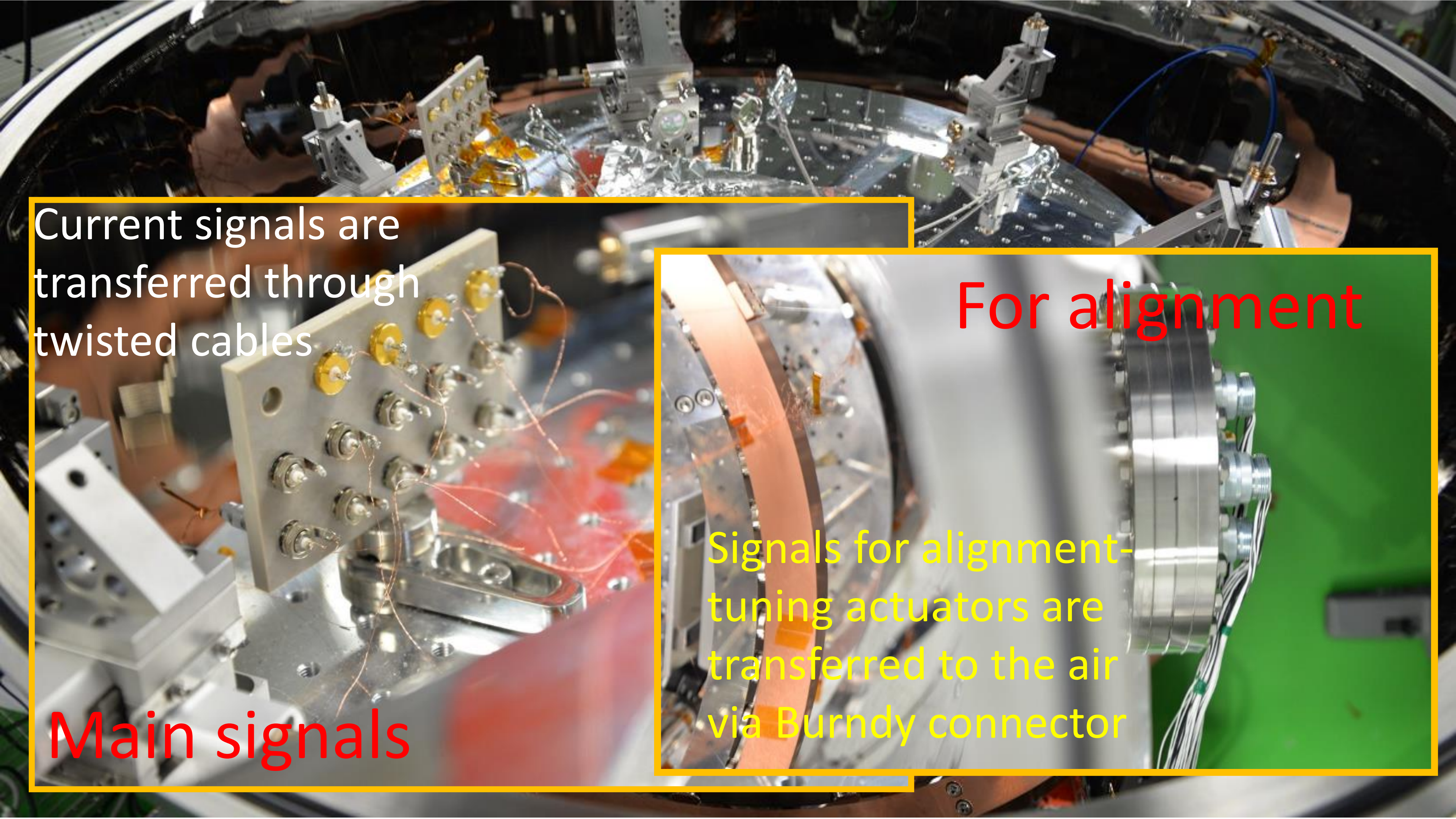
SUS

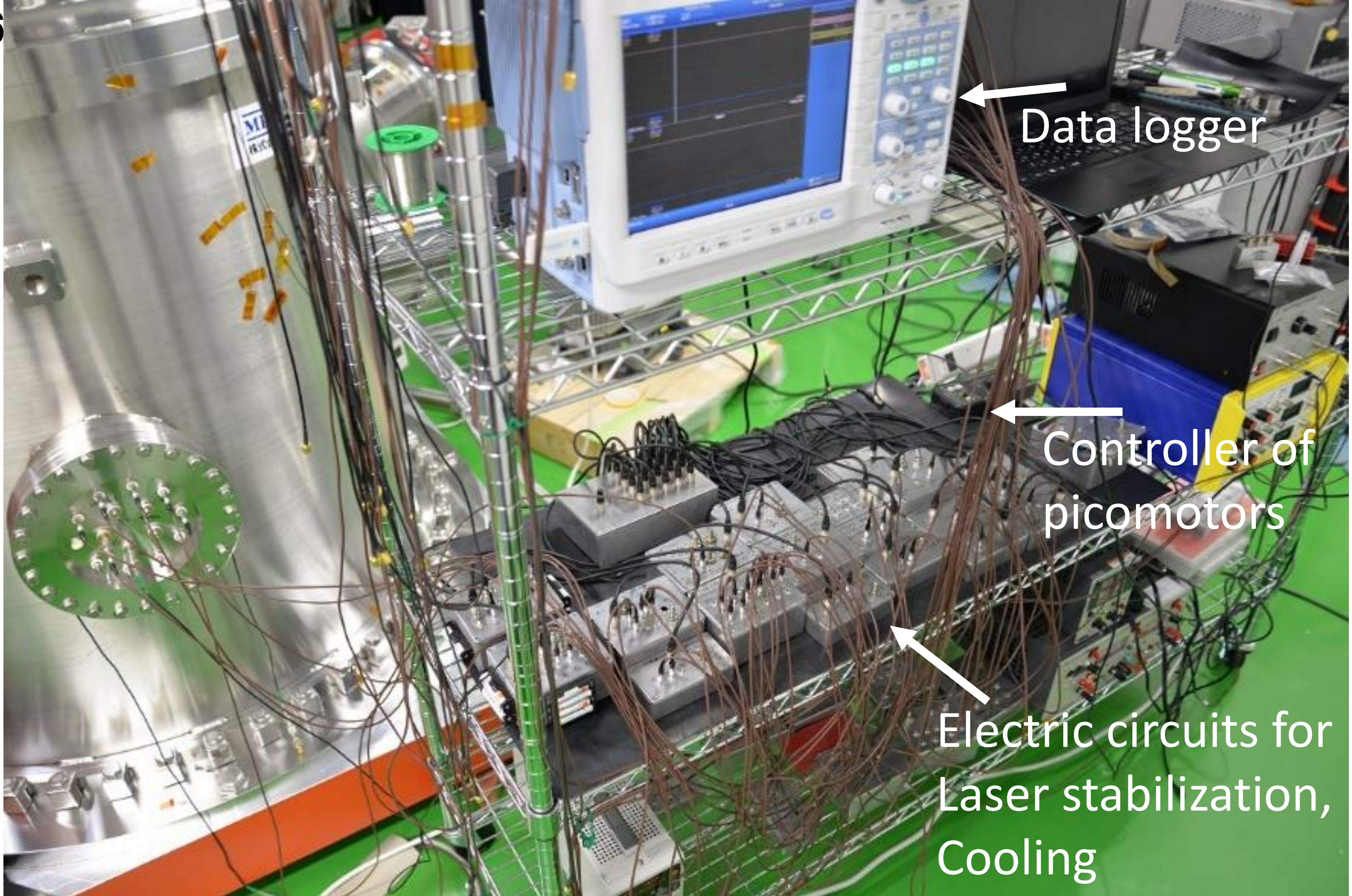



vacuum compatible
~1 m
Coil-magnet actuator
Int. stab.
Freq. stab.
cooling
SUS
class 6

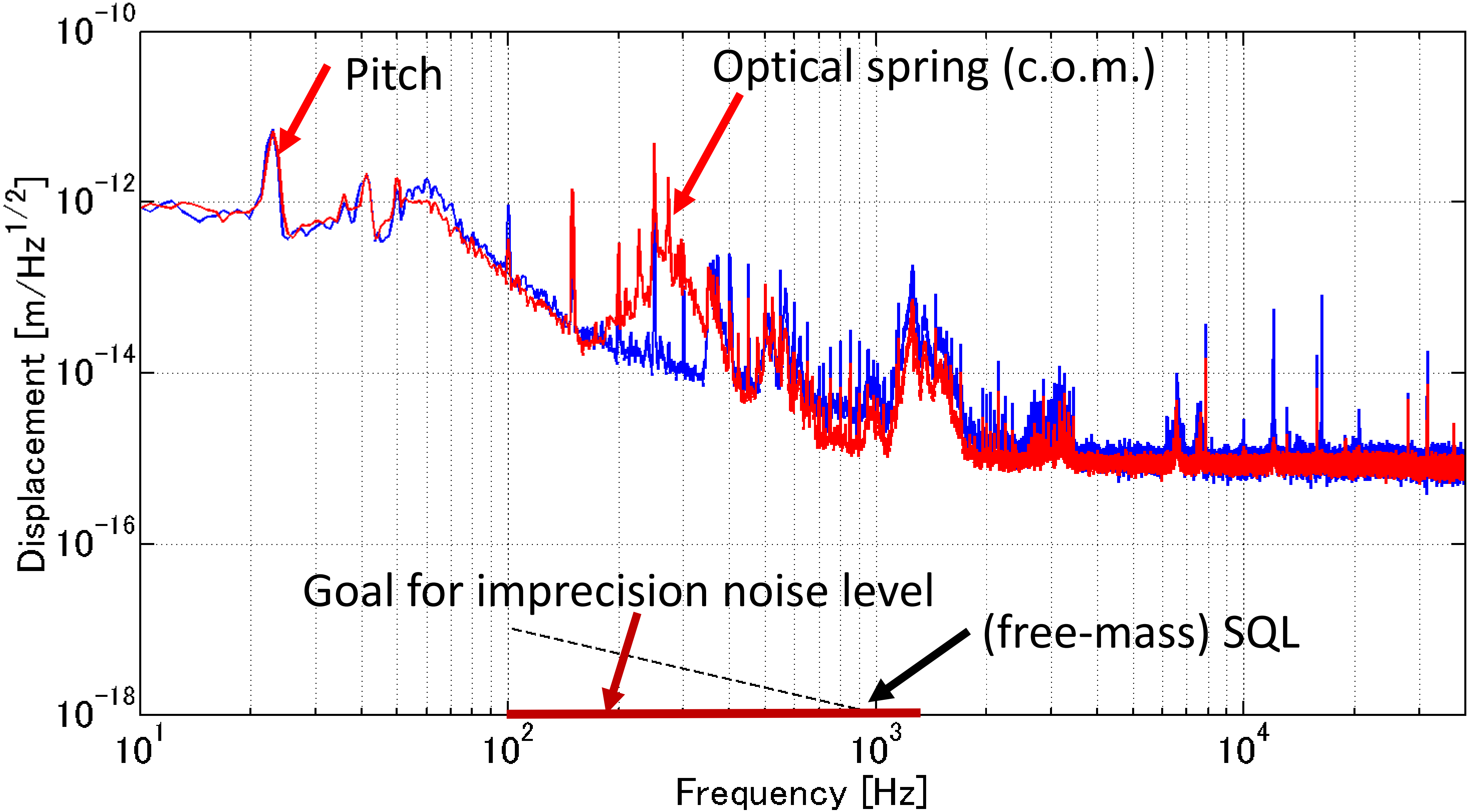



Signal lines
XYZ-stage
1 m

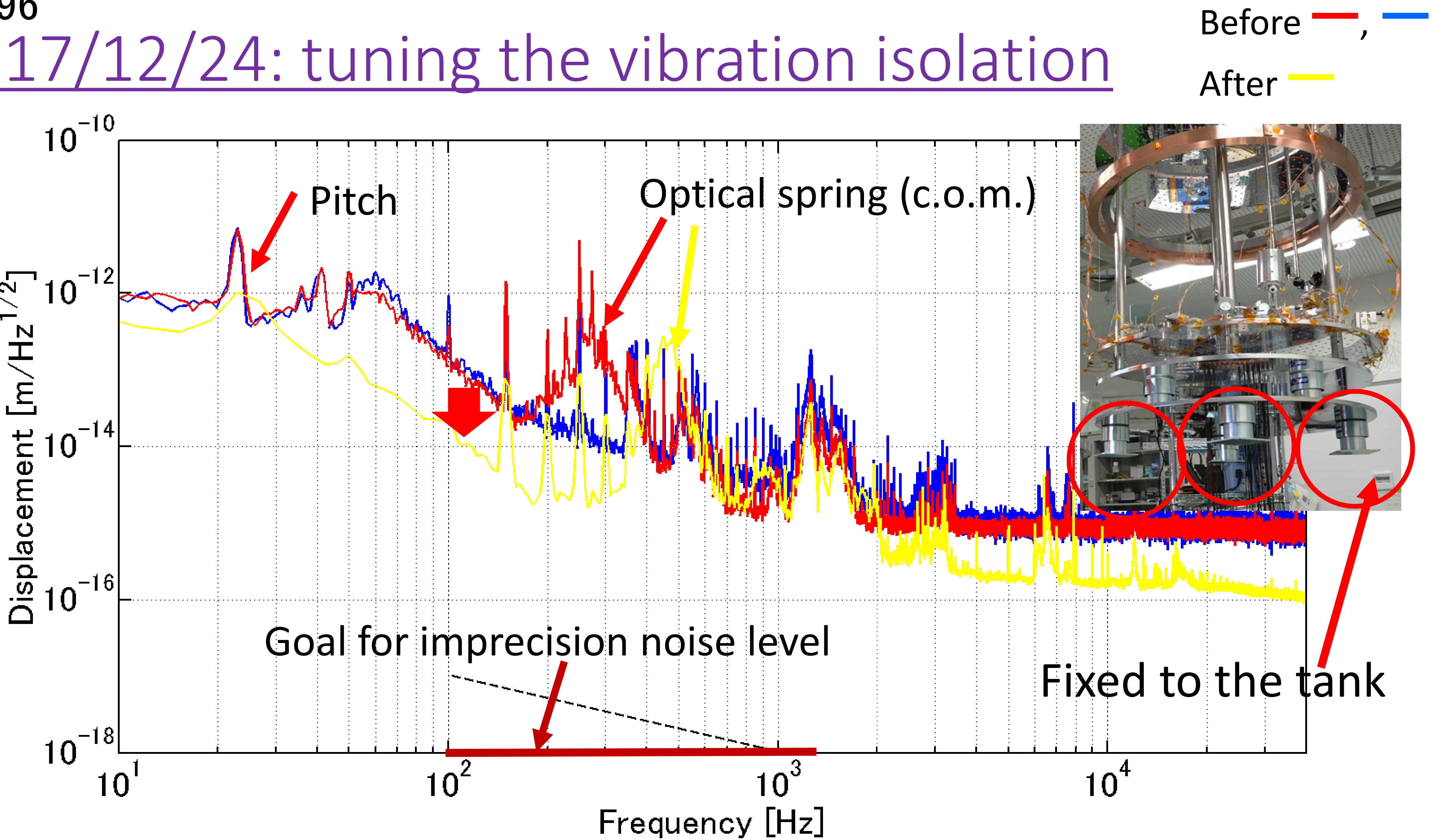

Current signals are transferred through twisted cables
Main signals
For alignment
Signals for alignment-tuning actuators are transferred to the air via Burndy connector


Data logger
Controller of picomotors
Electric circuits for Laser stabilization, Cooling

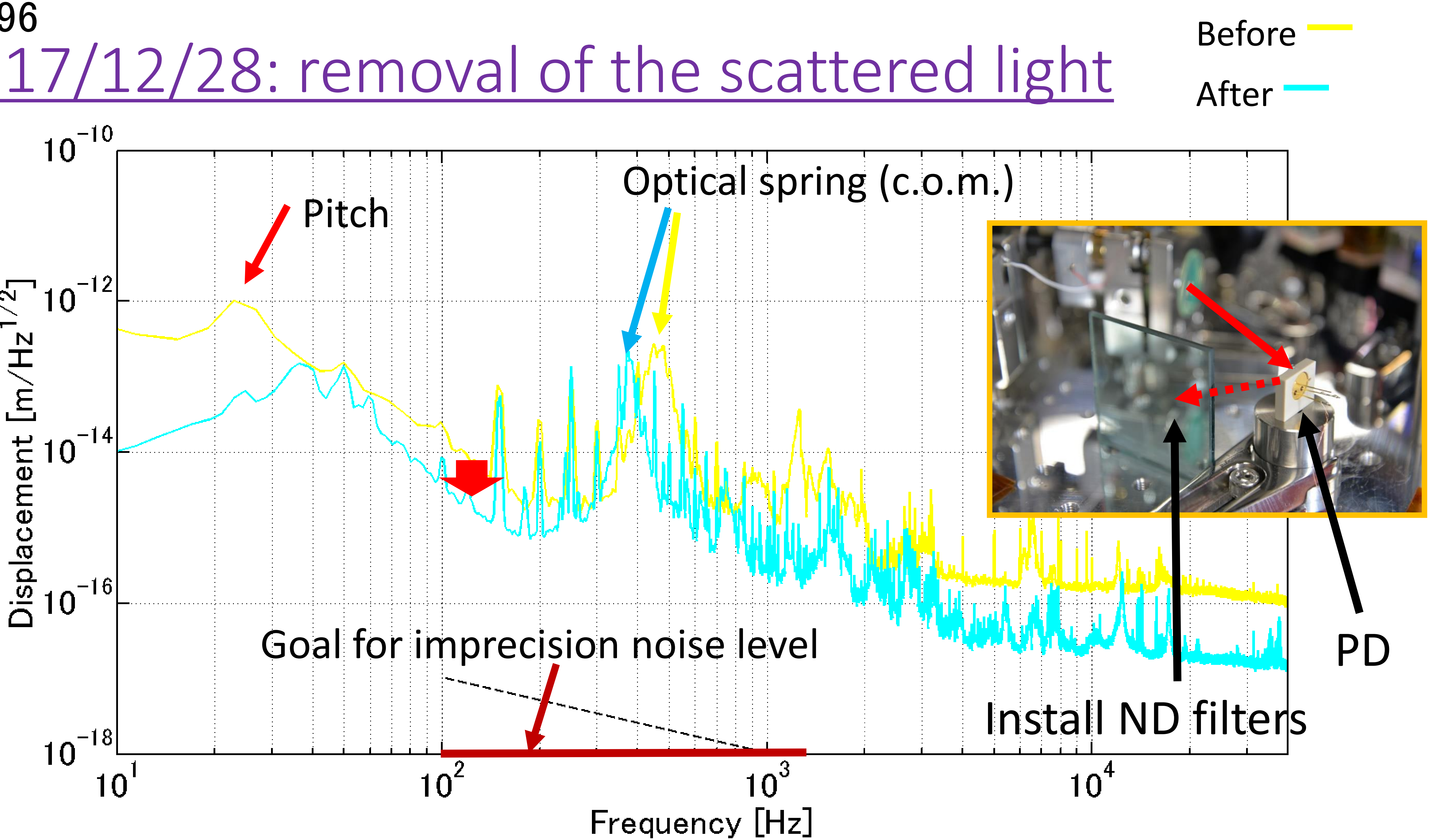
2017/12/19: first measurement using current setup



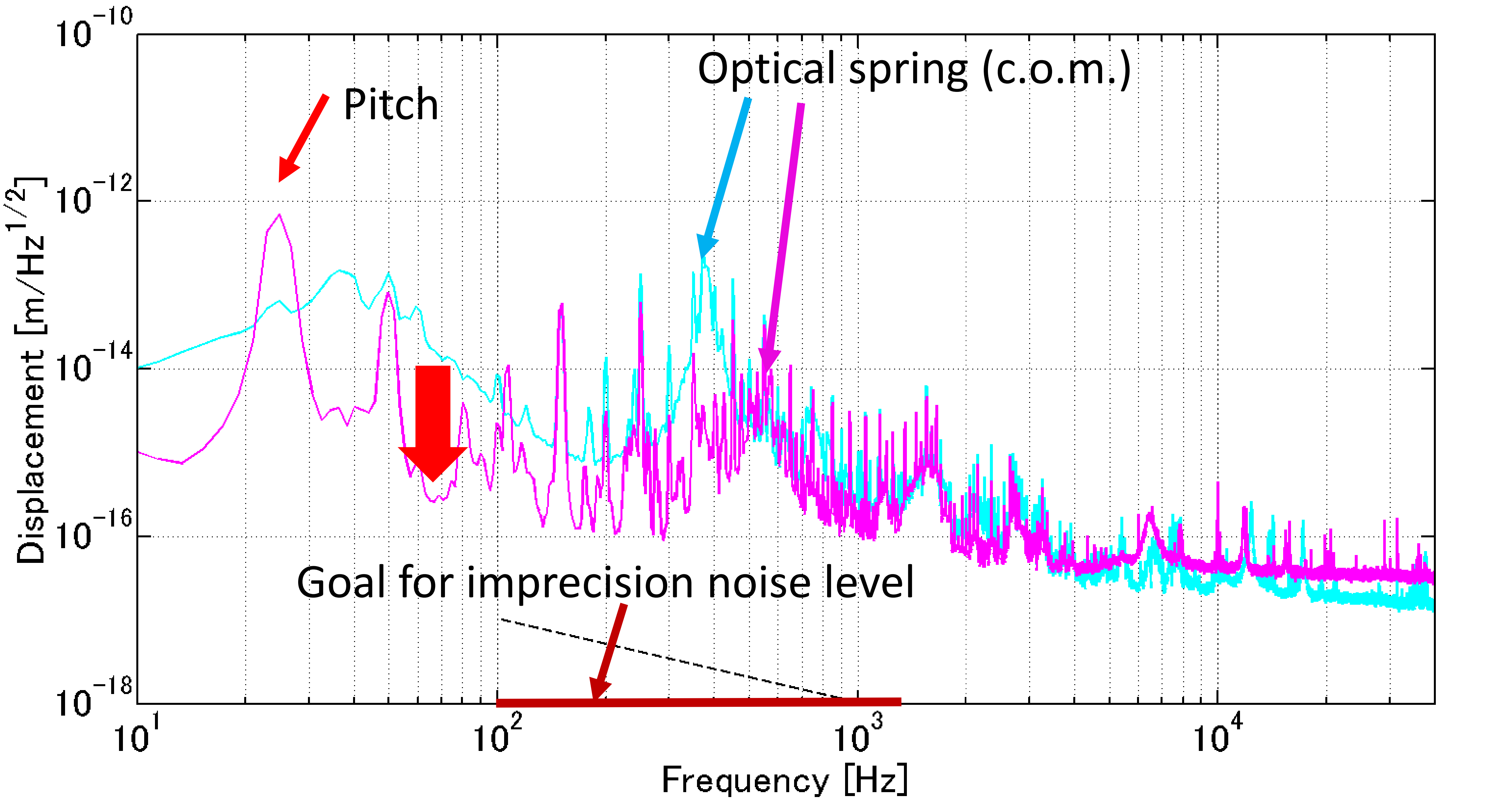
2017/12/24: tuning the vibration isolation



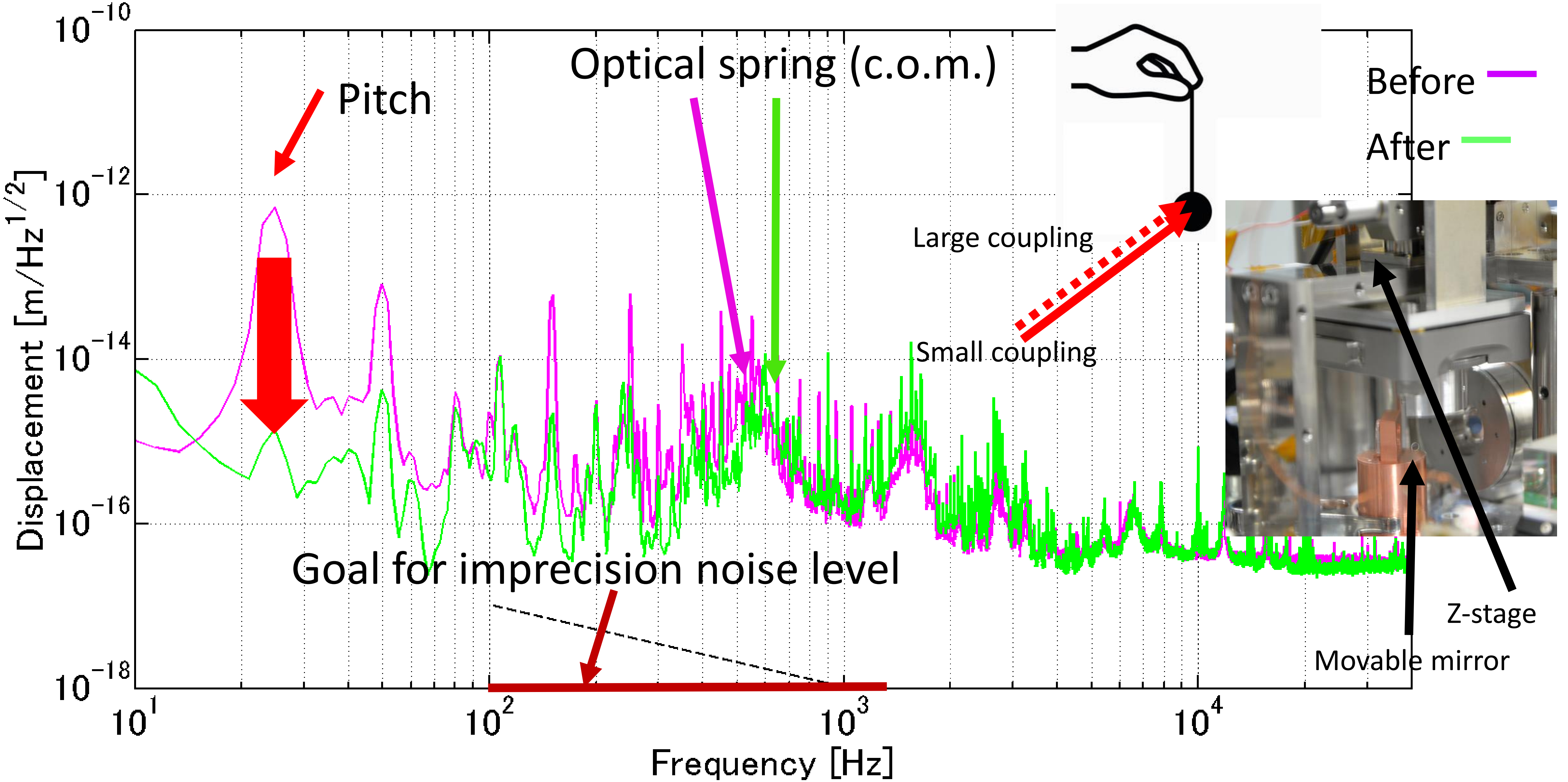
2017/12/28: removal of the scattered light



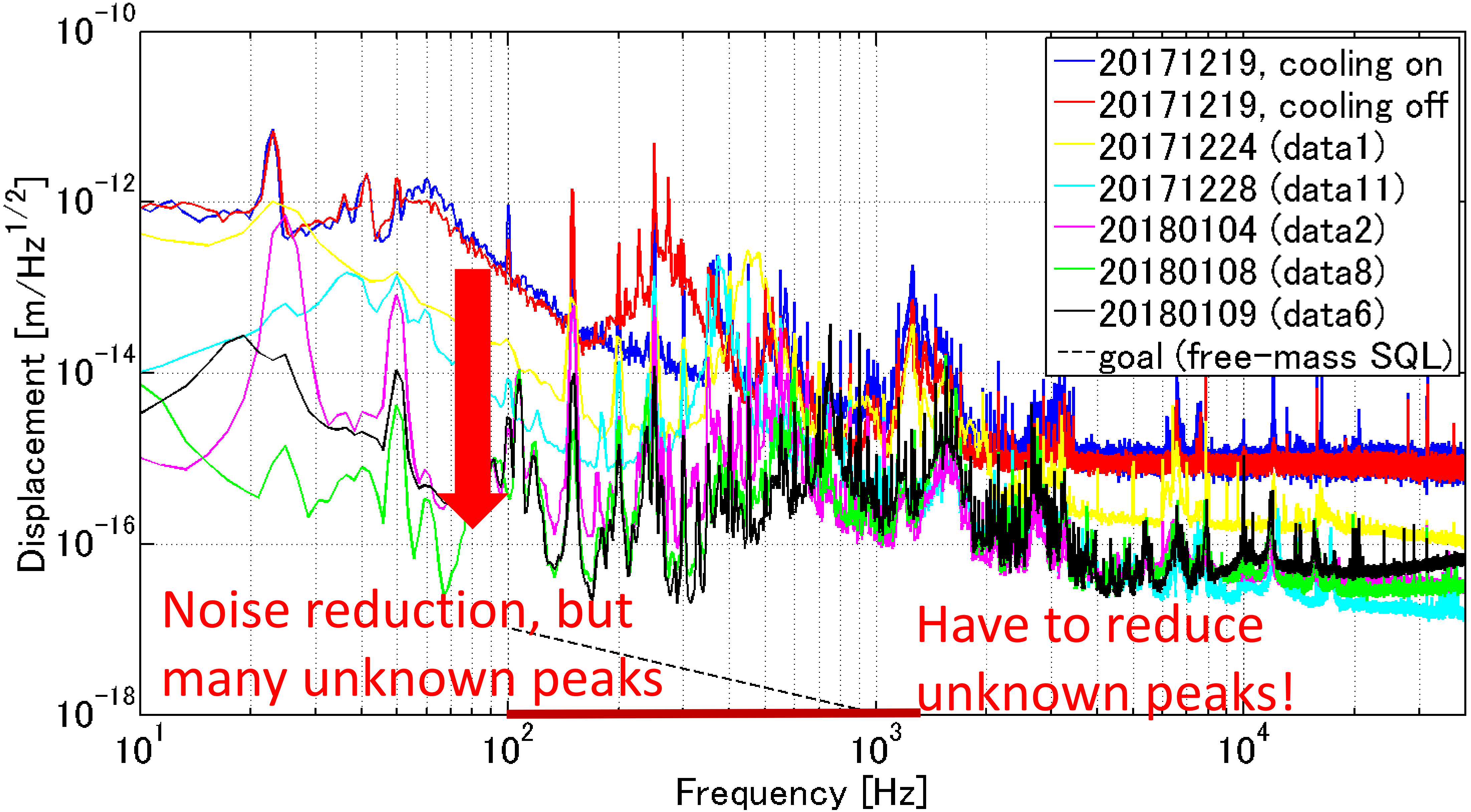
2018/01/04: stabilize laser source

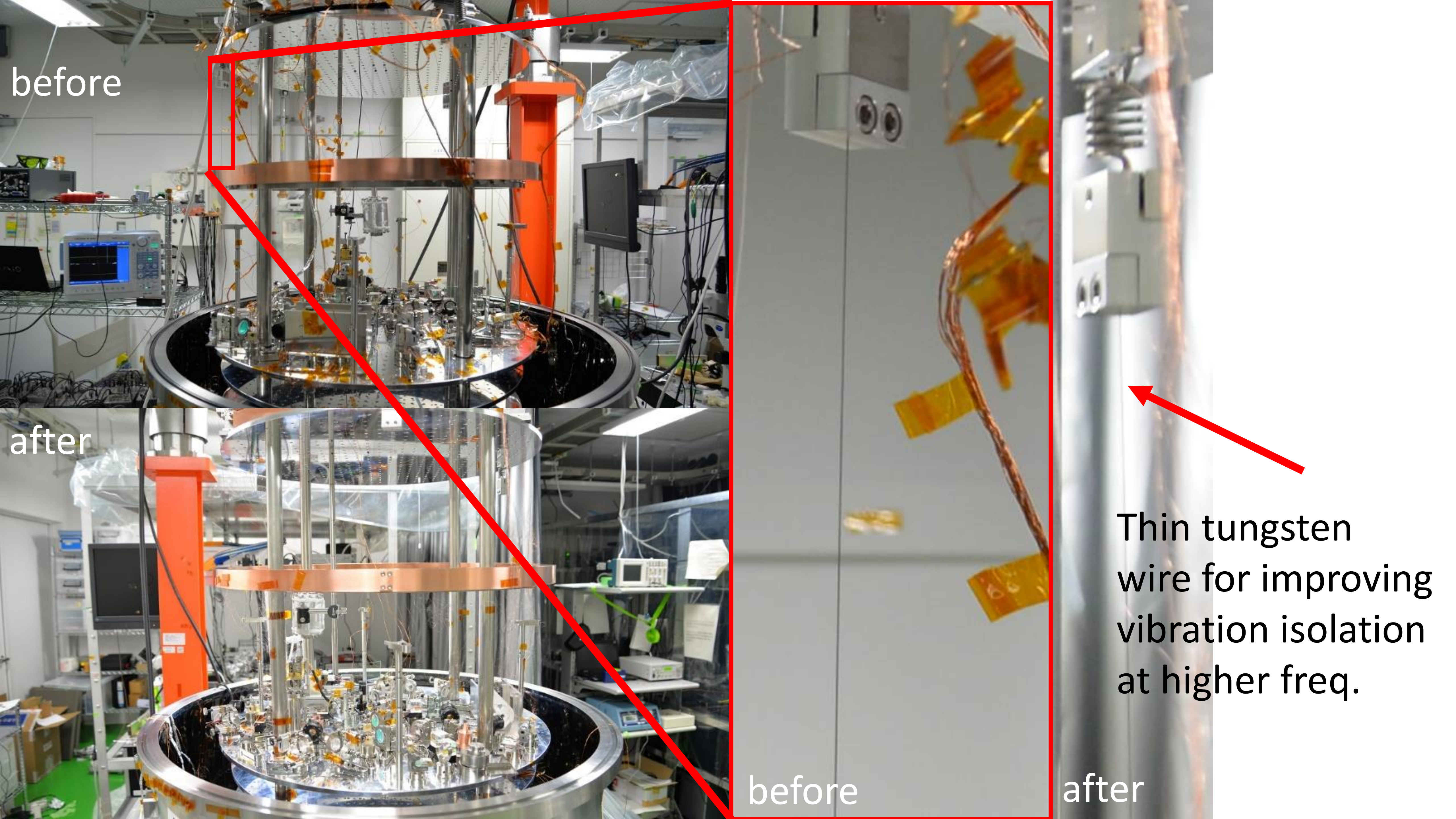


2018/01/08: reduction of pitch-pendulum coupling

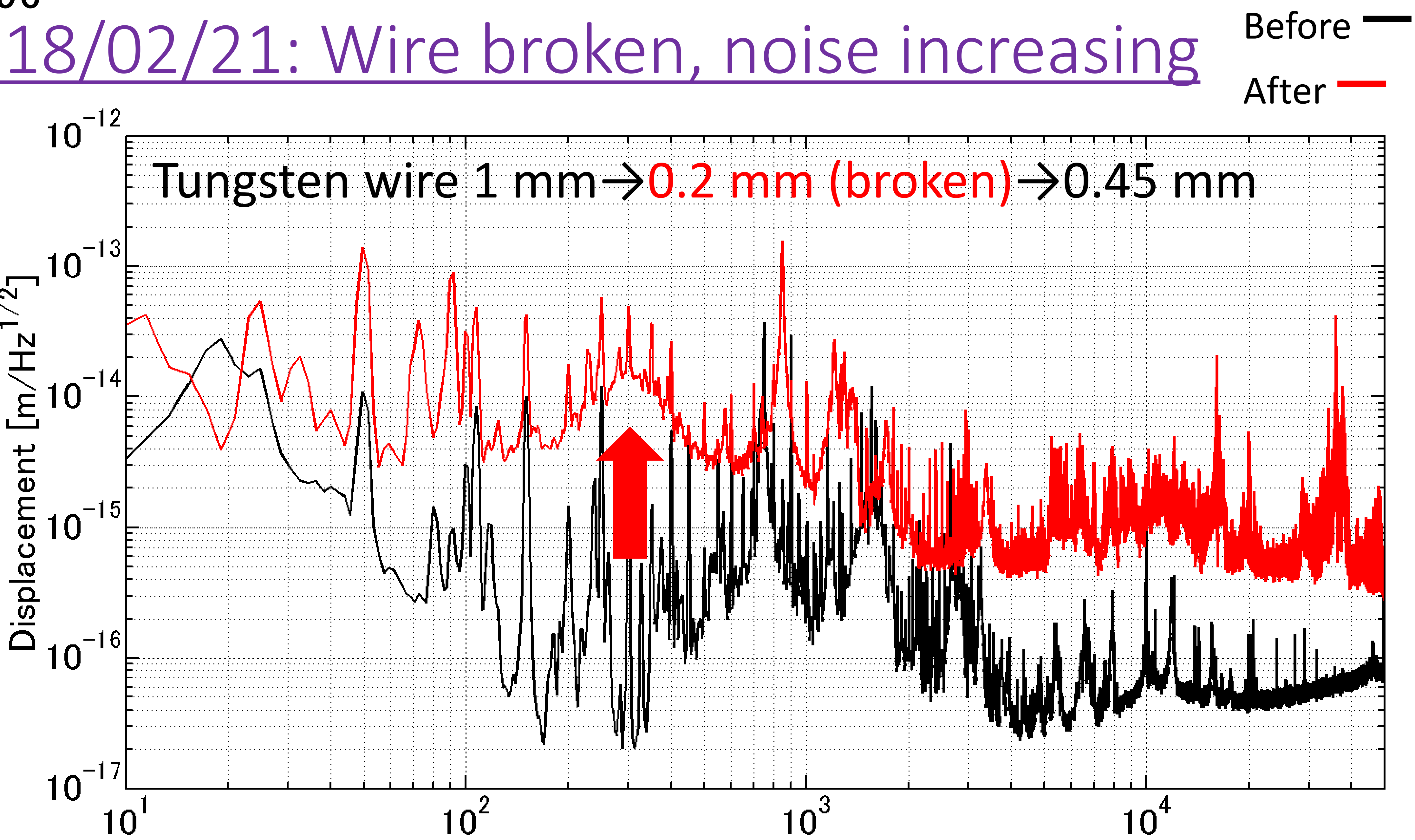


Summary from 2017/12/19 to 2018/01/09

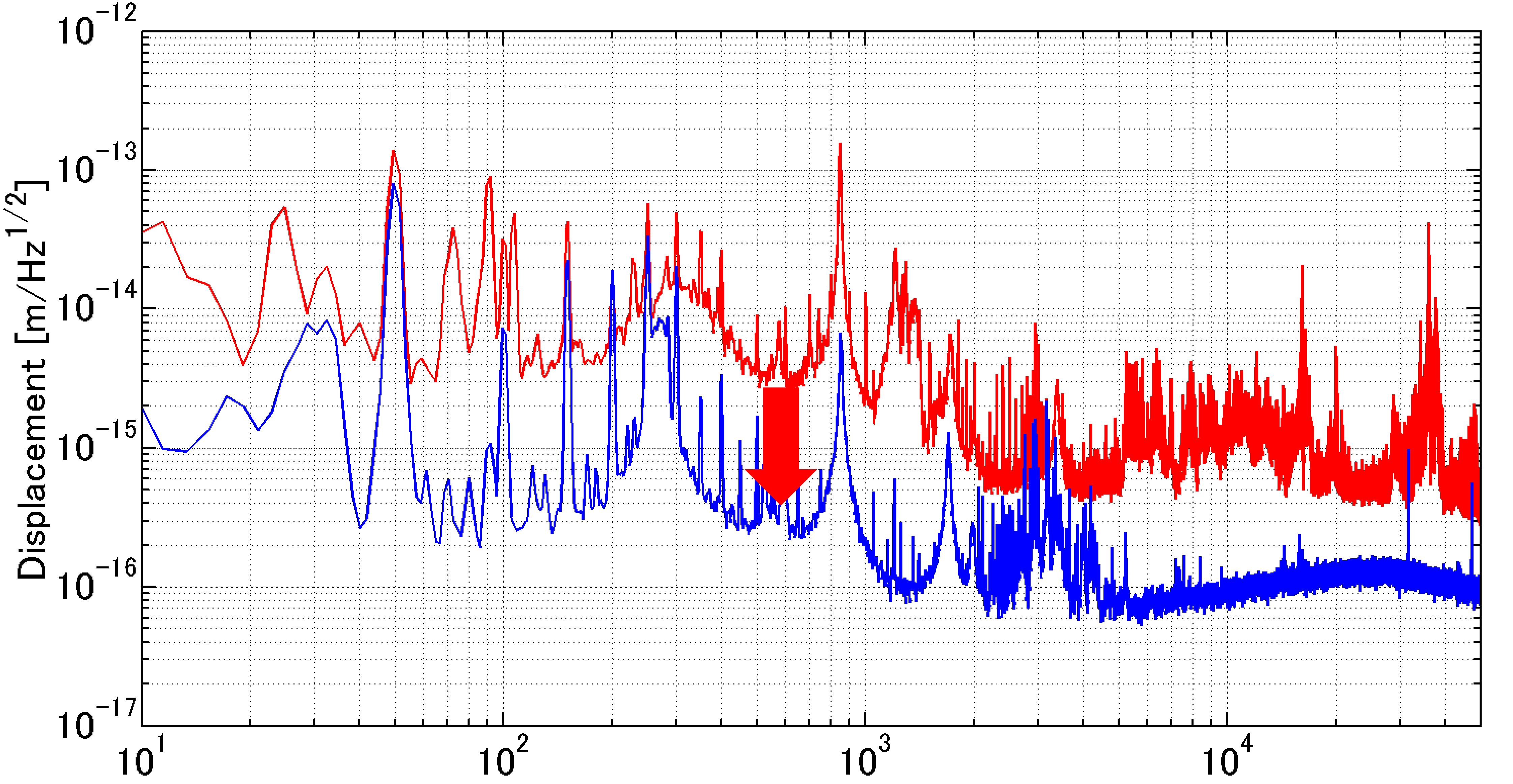



before
after
before
after
Thin tungsten
wire for improving
vibration isolation
at higher freq.

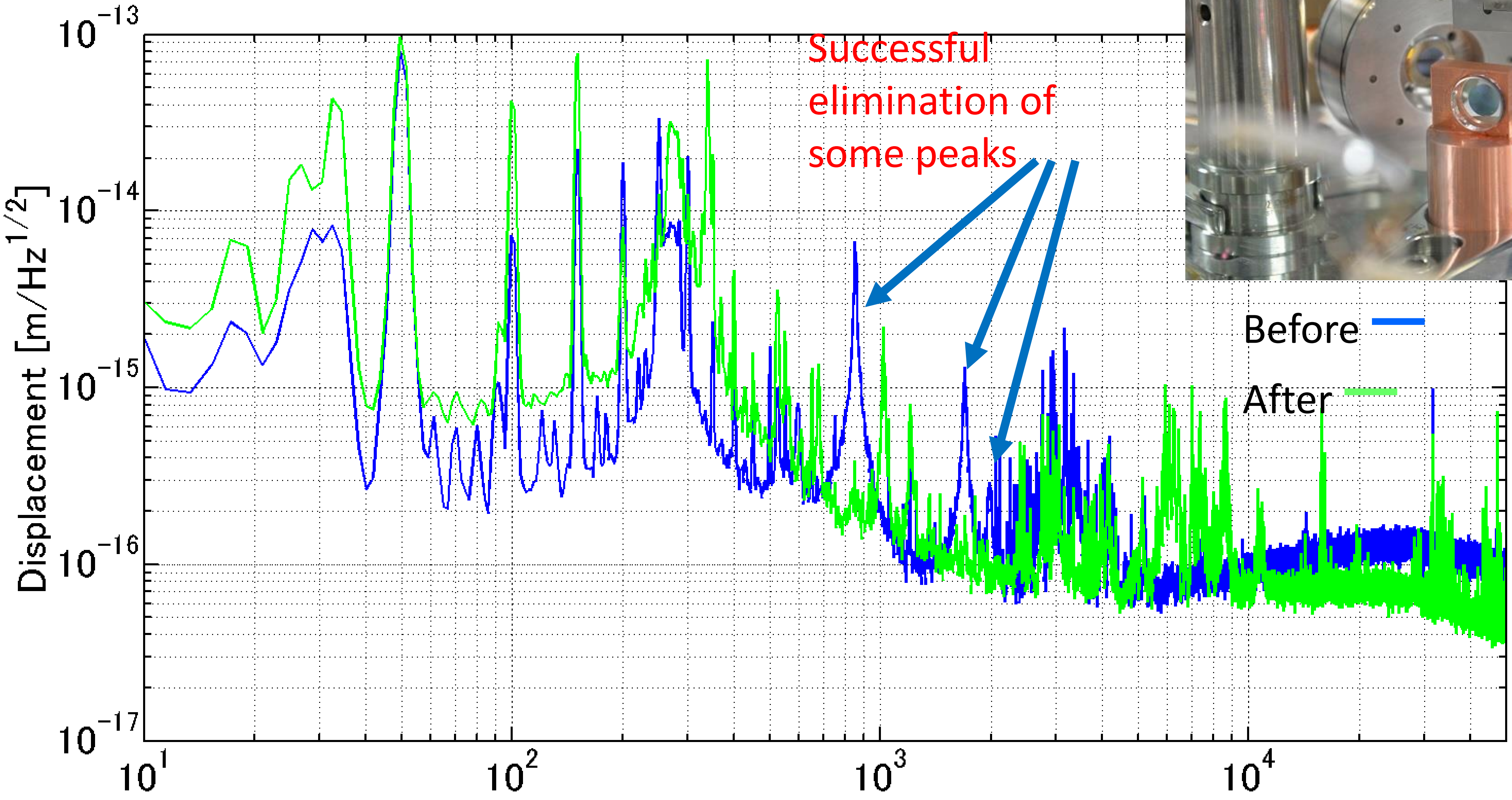
2018/02/21: Wire broken, noise increasing

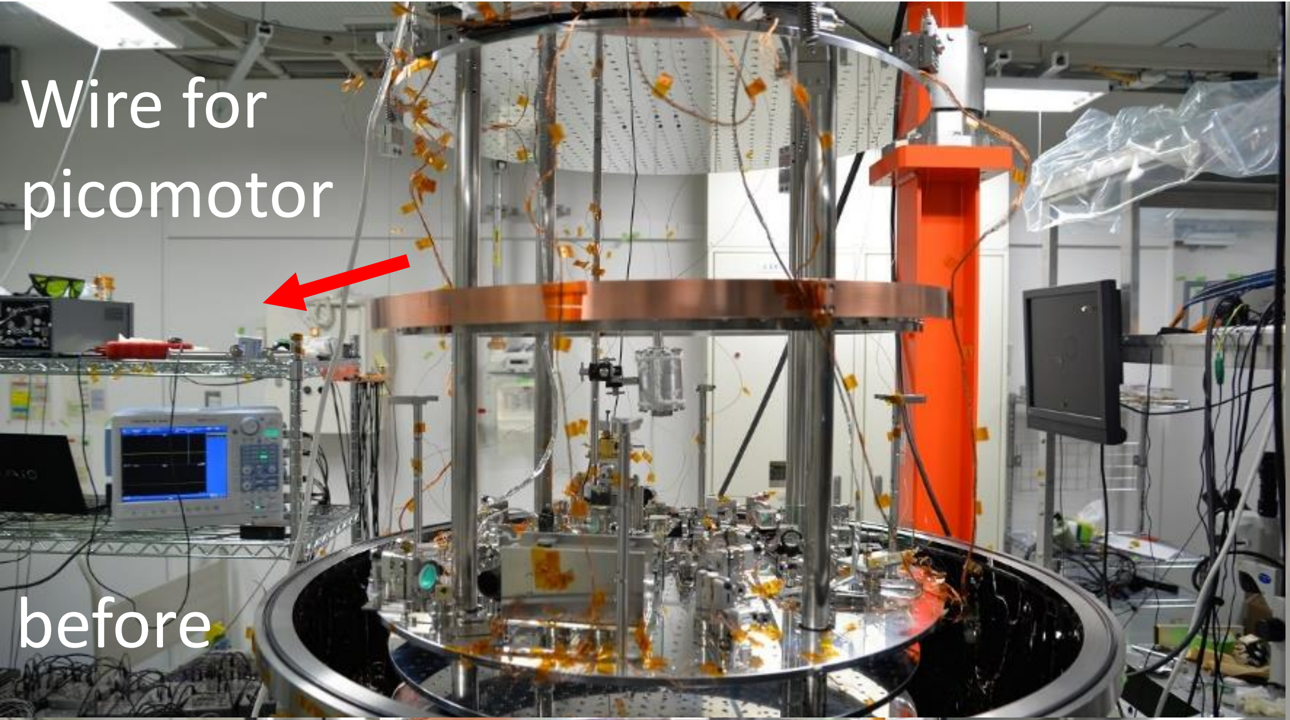


2018/03/21: Noise reduction again!



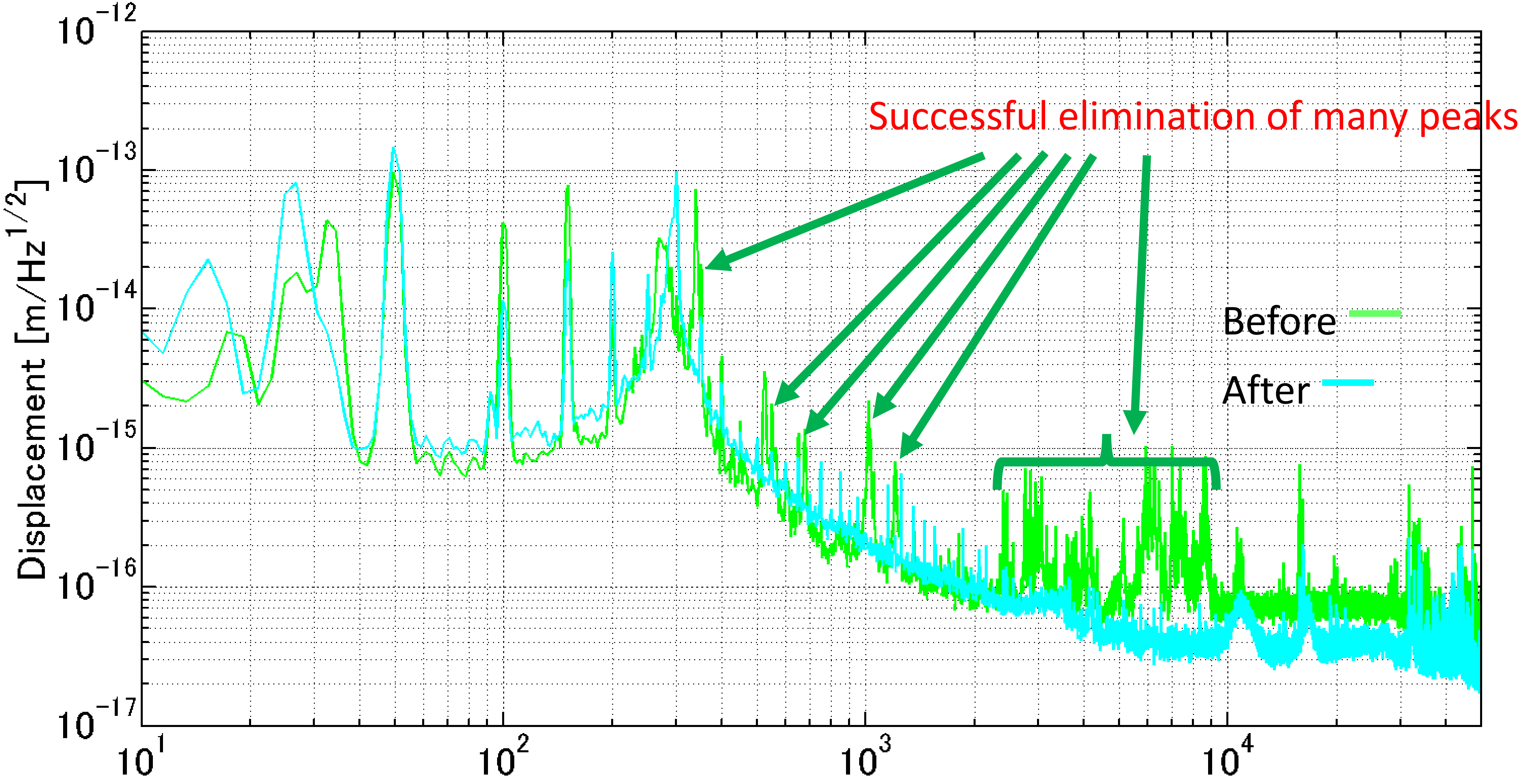
2018/03/21: monolithic mirror holder



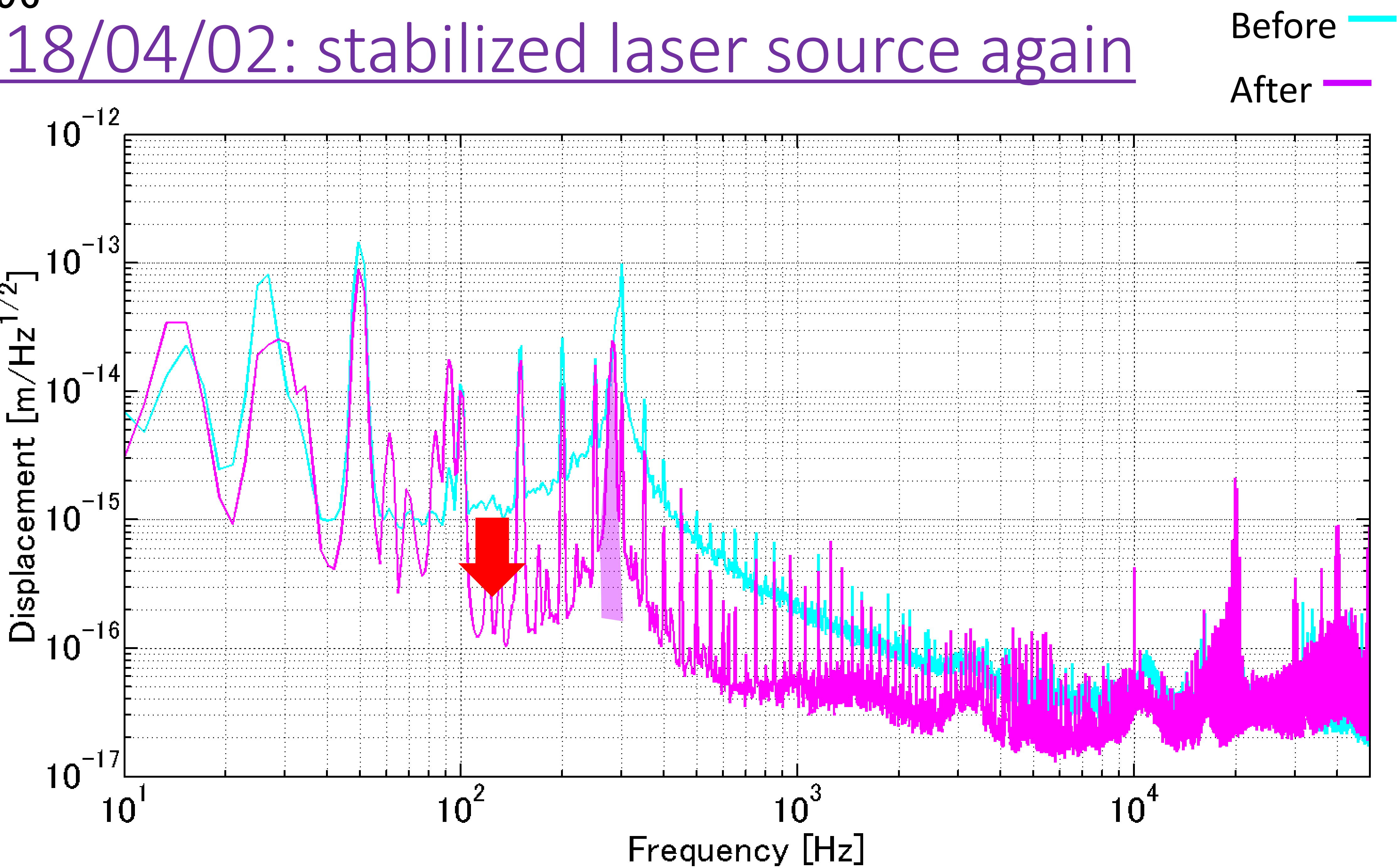


Use thin wire

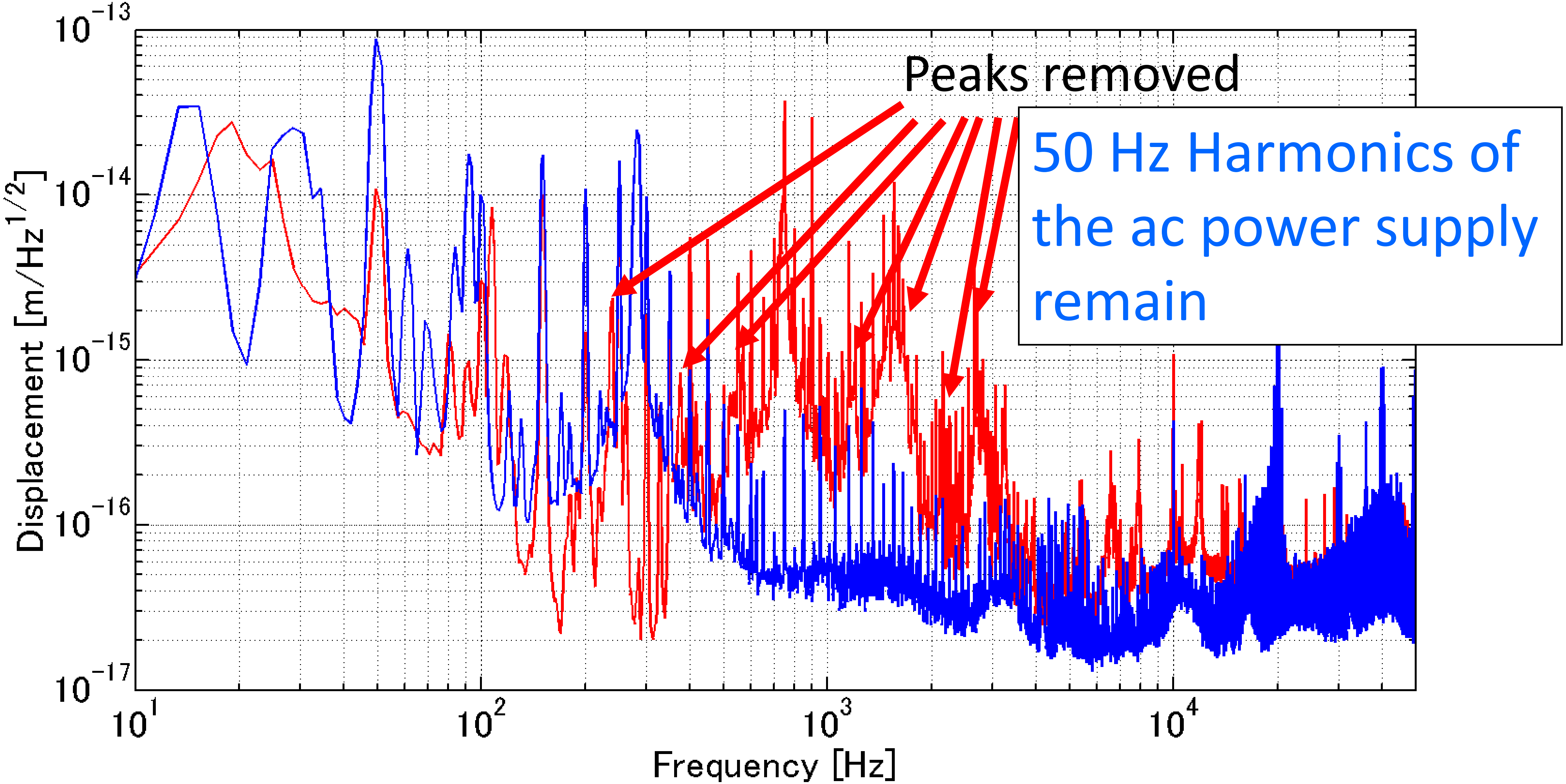
2018/04/01: thinner wire (250 um→50~100 um)



2018/04/02: stabilized laser source again

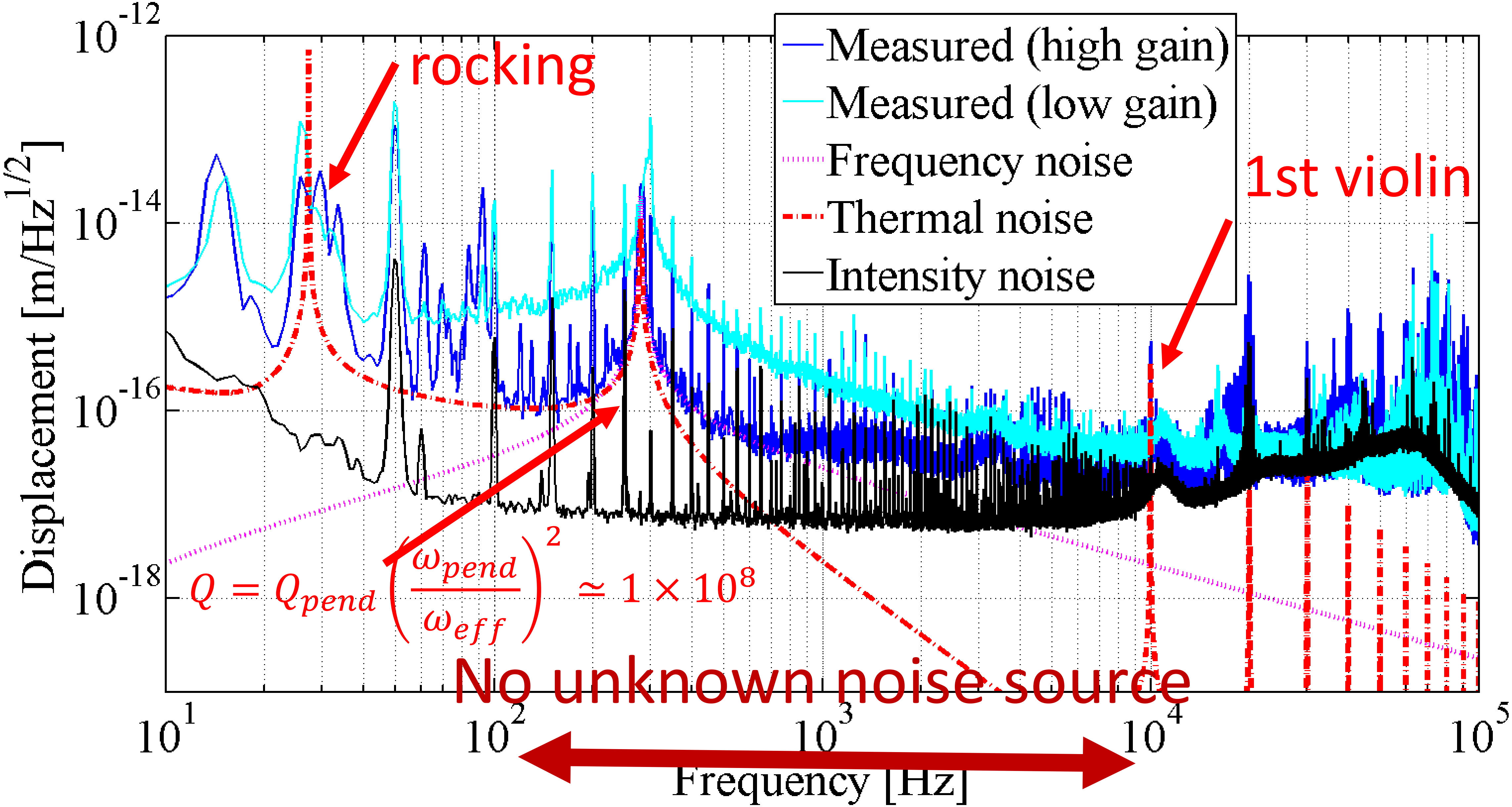


Comparison with 2018/01/09



Current states: noise budget

arXiv: 1809.05081



• To demonstrate gravity measurement between mg-scale masses,
we firstly try to use a simple cantilever for source mass (not suspended mirror).

Development of a milligram-scale source mass for applications in mg-mm-scale gravity measurements

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Background-Source Masses in Gravity Experiments

- Traditionally, large source masses are used in gravity measurements because this increases the strength of the signal.
  - Hardest part for a *precision measurement* (big G measurement) is locating and aligning the centers of mass of the interacting bodies.
- ***Reducing the dimensions and integration time*** would allow to reduce systematic errors in measurement and explore new regimes of gravity (quantum nature of gravity?).
- What is the smallest measured interaction to date?
  - DyFe–cylinders ~100 g in torsion balance experiment [1]
  - Experiment time of >2.5 hours!
- How much smaller can we go?
  - **~100 mg**

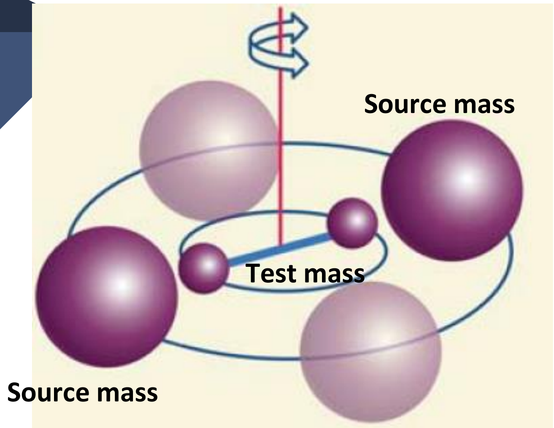


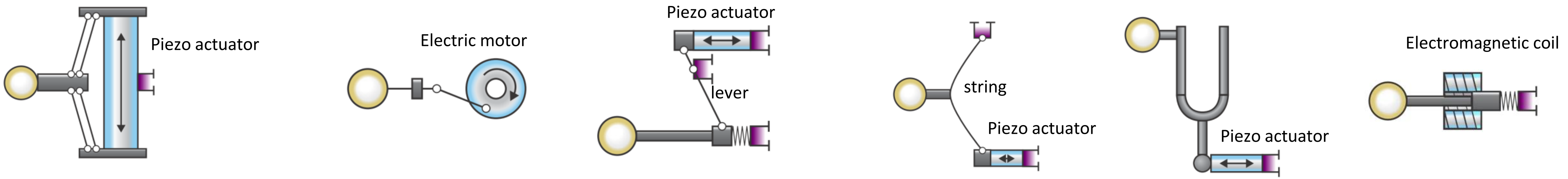
Fig. 1 Time-of-swing experiment[3].

[1]**Ritter R. C. et al.1989.** *Experimental test of equivalence principle with polarized masses.* **Physical Review D 42.4.**
[2]**Matsumoto N., et al. 2019** *Demonstrations of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements.* **PRL. 122, 071101.**

[3]**Speake C., et al. 2014.** *The Search for Newton's Constant.* **Physics Today 67, 7, 27.**

Micro-Mechanical Approach

- Scaling down brings advantages, but the fabrication and driving become difficult in a modulated gravity scheme.



- **Can we meet the necessary requirements with a simple cantilever?**
  - **Easiest to fabricate**
- **What are the limiting factors?**

Schoele Jonas. **2017**. *Development of a micromechanical proof-of-principle experiment for measuring the gravitational forcé of milligram masses*, **Doctoral thesis, University of Vienna.**

Requirements and Constraints for a Modulated Gravity Experiment

- Material
- Driving amplitude → ~1 mm optimal
- Resonance frequency→ ~280 Hz
- Q_{source} > Q_{test} ~250
- Coupling noise
  - EM noise
  - Mechanical coupling

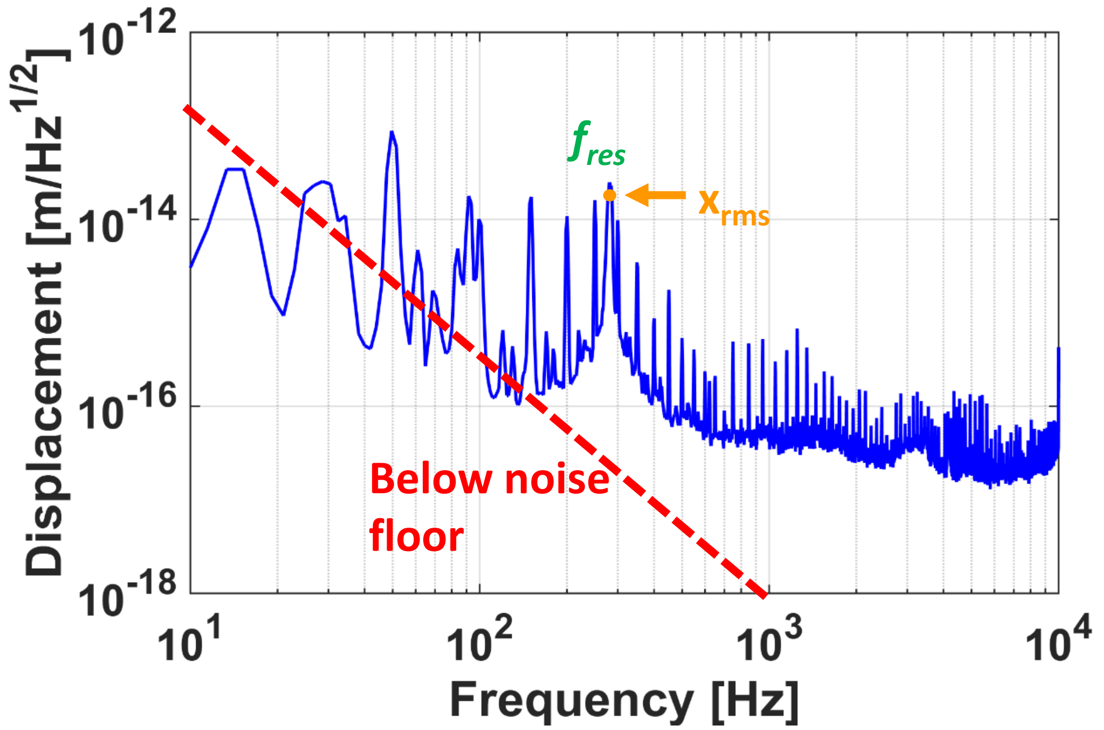
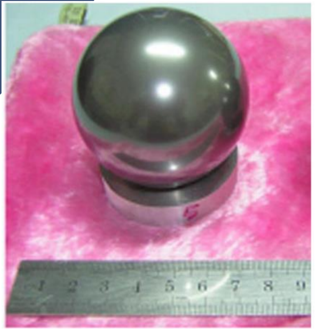


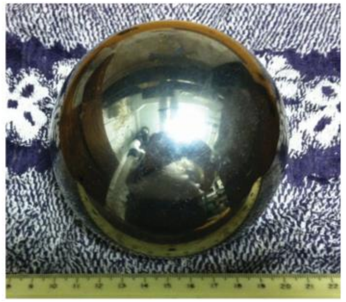
Fig. 2 Noise power spectral density of test mass

Choice of Materials

- Gold, platinum, tungsten…
  - Dense materials (19 , 21… [g/cm3]) , good conductors, low magnetic susceptibility (~−1e−5)
  - Hard to manufacture with a good grade
- Type 316 Stainless Steel
  - Not so dense (8 [g/cm3]), low magnetic susceptibility (~2e−3)
  - Easier to manufacture with better precision (< grade 100)
  - ***<u>Commercially available</u>***



SS316 5 cm source mass[1]



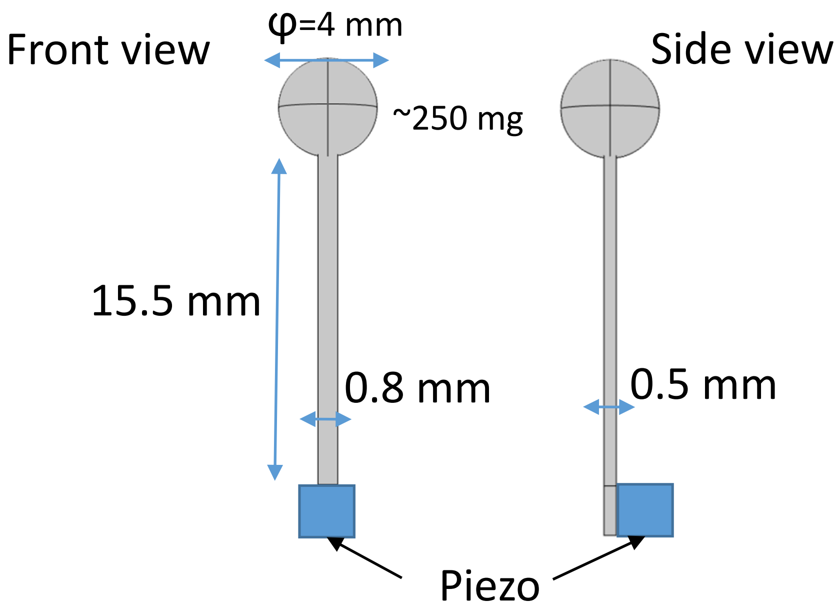
Tungsten 10 cm source mass[2]

[1]**Tu L-C, et al. 2010.** *New determination of the gravitational constant G with time-of-swing method*. **Phys. Rev. D** 82, 022001, 2010

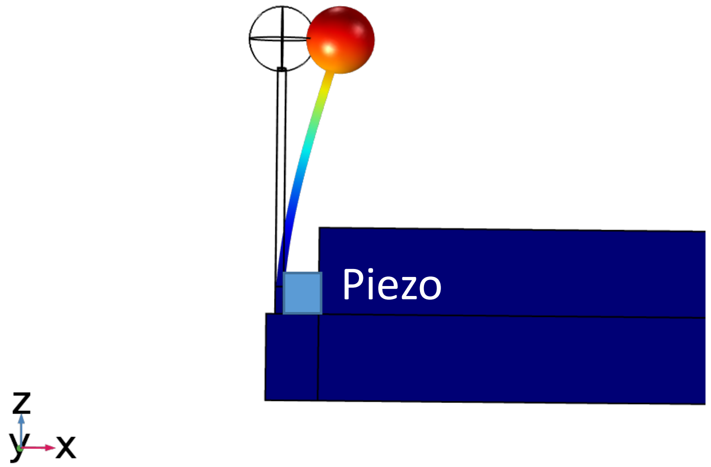
[2]**G.T. Gillies, et al. 2014**. *The attracting masses in measurements of G: an overview of physical characteristics and performance*. **Phil. Trans. R. Soc**. A 372 20140022

First Design

- Geometry of cantilever determines resonant frequency and mode shape of oscillation.



Total displacement (mode shape)



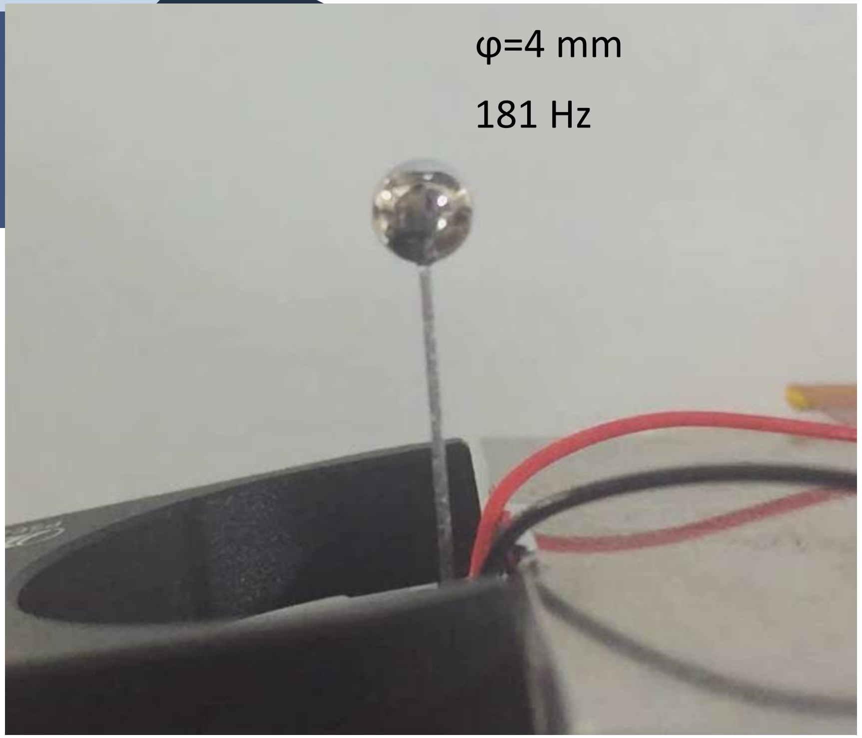
- *Aluminum cantilever* 15.5 x 0.8 x 0.5 mm^3 and SS316 ball.

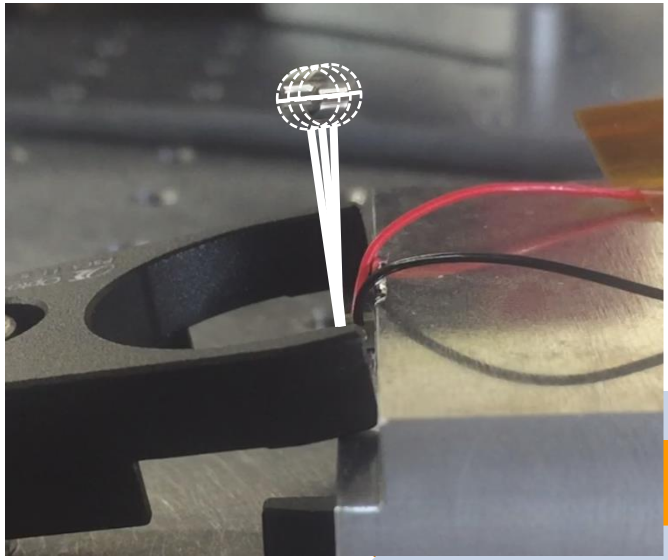
Resonant frequency at **~177 Hz**

Driving

- Gravitational signal scales linearly with driving amplitude.
- Achieved with a piezo actuator.

- Driving amplitude of **~0.7 mm** at resonant frequency



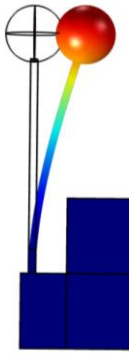


Q factor

- Q factor of the source mass ***should be significantly smaller*** than that of the test mass (Q_{source}>Q_{test}) to achieve resonant excitation.

- Q factor >100 possibly limited by material damping.

- Glue affecting?
  - Mode shape suggests dissipation comes from the material.



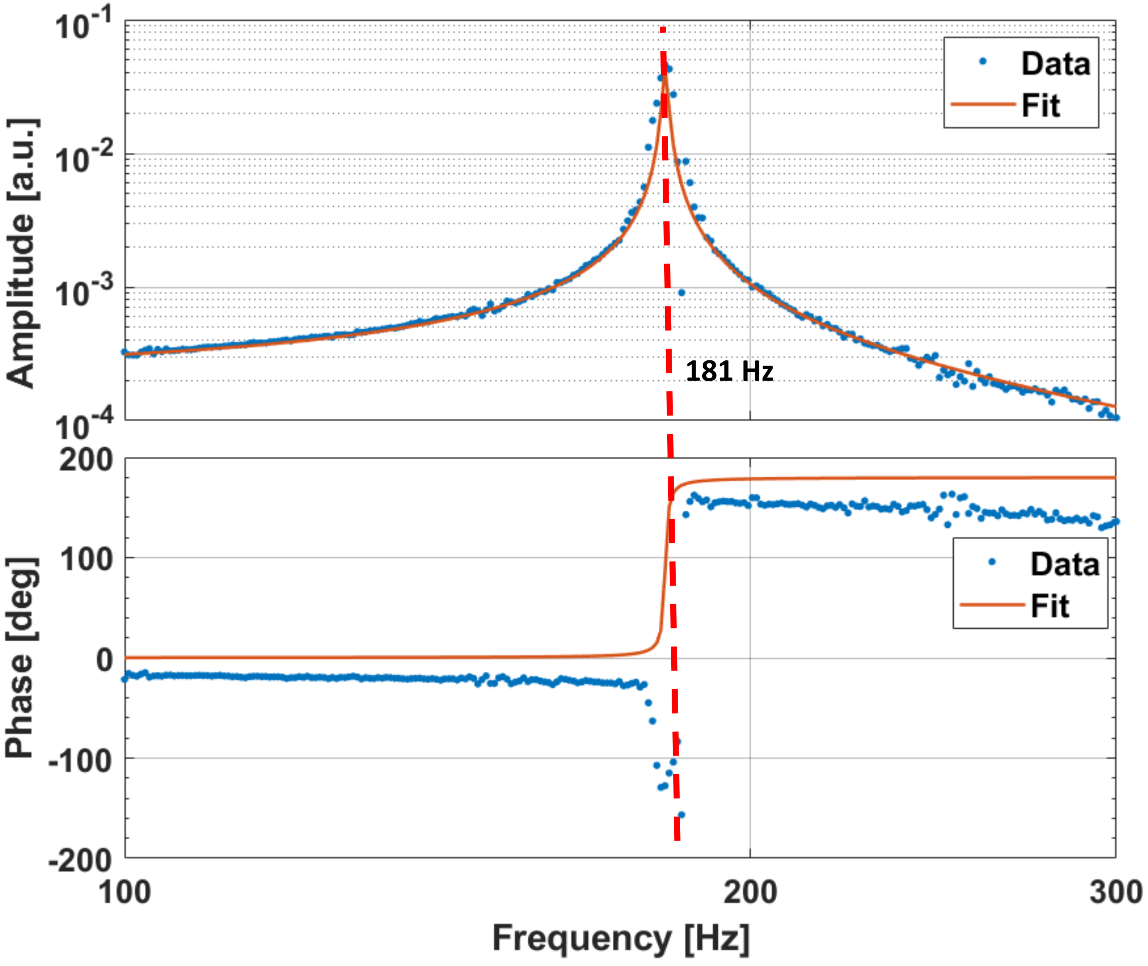


Fig. 3 Mechanical transfer function of cantilever, measured at 10 Pa

EM Shielding

- Attenuate the effect of *stray fields* acting at the driving frequency (frequency of detection) and *stray charges* on the masses.

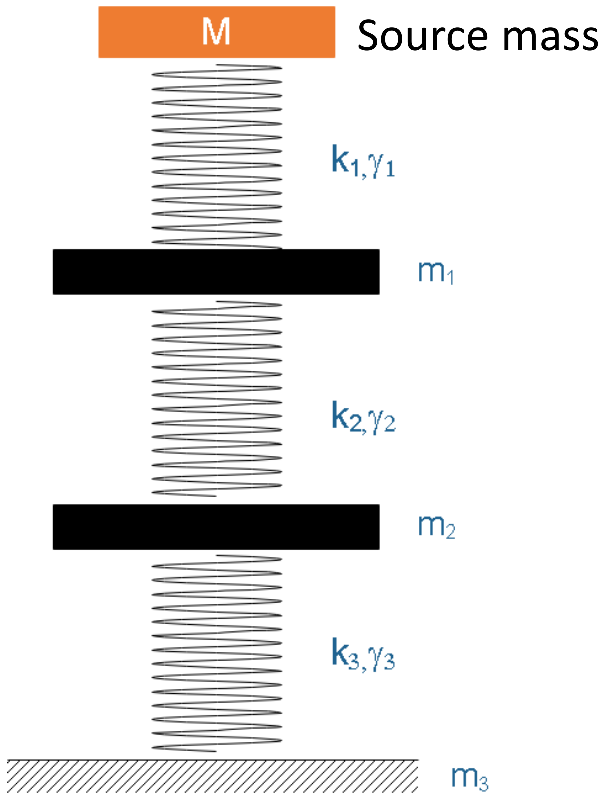
  - Electrical charges should be discharged from probe and source mass (conductor)

  - Mu-metal has a skin depth of ~100um at 180 Hz. *A cage of ~1.5 mm is proposed.*

  - Transmitted power attenuated by a factor of ~200dB between the two masses.

Mechanical coupling

- 3 step vibration-isolation model suffices to reduce vibrations by a factor of 10^-10



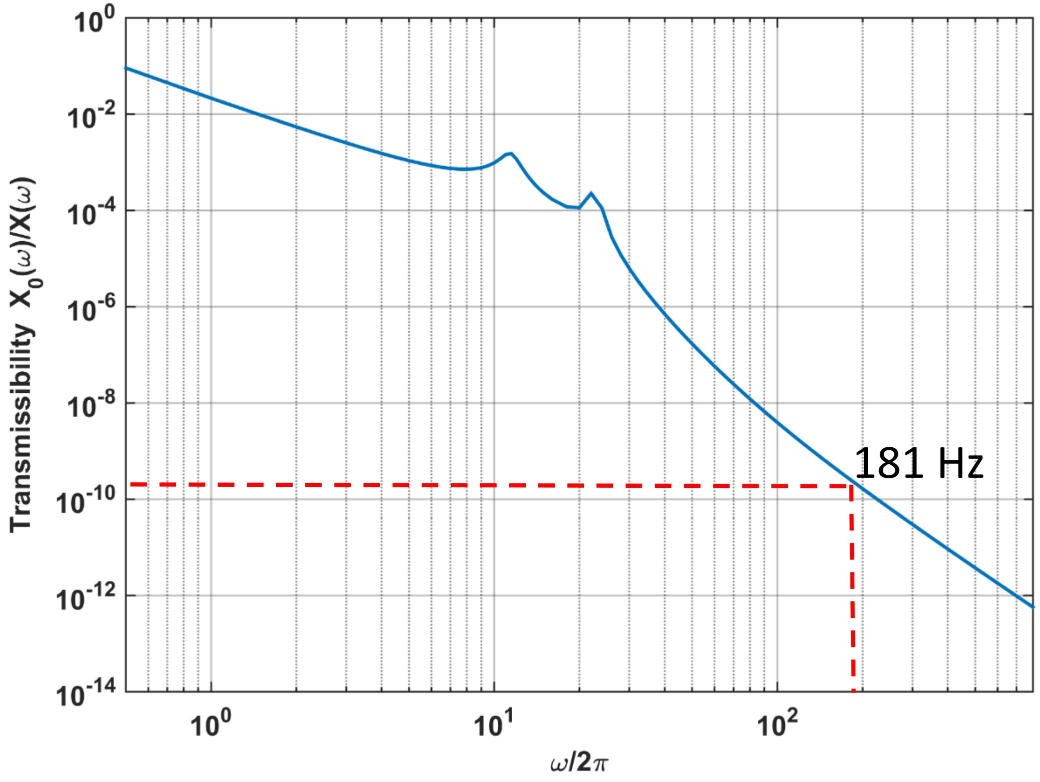


Fig. 5 Transfer function from source mass to experimental plate, with realistic mass and spring values.

Conclusion

- Material → ok
- Driving amplitude → ok
- Resonance frequency → ok
- Coupling noise → achievable with smart design
  - Shielding（demagnetization）
  - Vibration Isolation
- Q factor － ??

Summary

- Goal: to test quantum nature of the Newtonina potential
- Motivation: to understand gravity more deeply
- Method: table top experiments based on GW detector’s technology
- Current status: gravity sensor for mg-scale gravity
- Future plan: demonstration of mg-scale gravity measurements

- $C_q = \frac{C}{n_{th}} = \frac{S_{rad}}{S_{th}} \sim 0.1 \left(\frac{\mathcal{F}}{1800}\right)^2 \left(\frac{P_{in}}{30\ \mathrm{mW}}\right)\left(\frac{Q}{10^8}\right)\left(\frac{7\ \mathrm{mg}}{m}\right)$
- $C = \frac{2G^2}{\kappa_{half}\gamma_{full}}$
- $G = g_0\sqrt{n_c}$
- $g_o = \frac{\partial\omega_{cav}}{\partial x}\ x_{zpf} = \frac{2\omega_0}{L}\ cos\beta\ x_{zpf}$
- $\kappa_{half} = \frac{\pi}{\mathcal{F}\tau}$
- $n_c = \frac{\tau P_{cav}}{\hbar\omega_0}$
- $P_c \simeq \frac{2\kappa_{in}}{\tau\kappa^2}\ P_{in}$