Towards observation of quantum radiation pressure fluctuation acting on a massive torsion pendulum

Middle presentation in Ando laboratory

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Contents

- Motivation
- Super-detailed noise estimation and design
- Future plan

Motivation

Observation of quantum radiation pressure fluctuation

R&D for GW detectors

- radiation pressure noise
- observation and reduction on the table ahead

Tests of quantum mechanics

- opto-mechanics experiment
- toward superposition of macroscopic objects

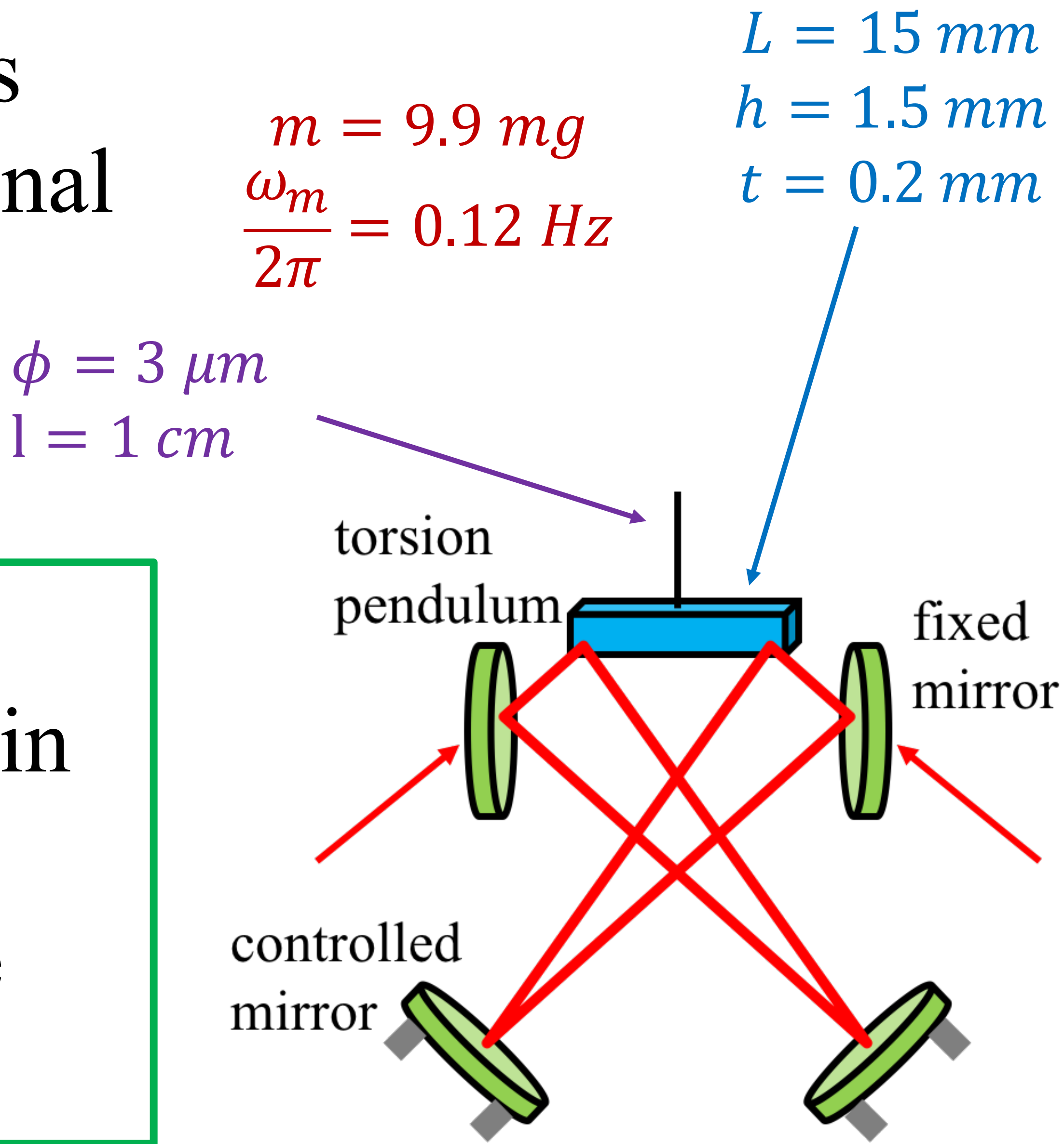
✓ No precedent ever with a massive pendulum over wide frequency range ⇨ Torsion pendulum

Torsion pendulum as test mass

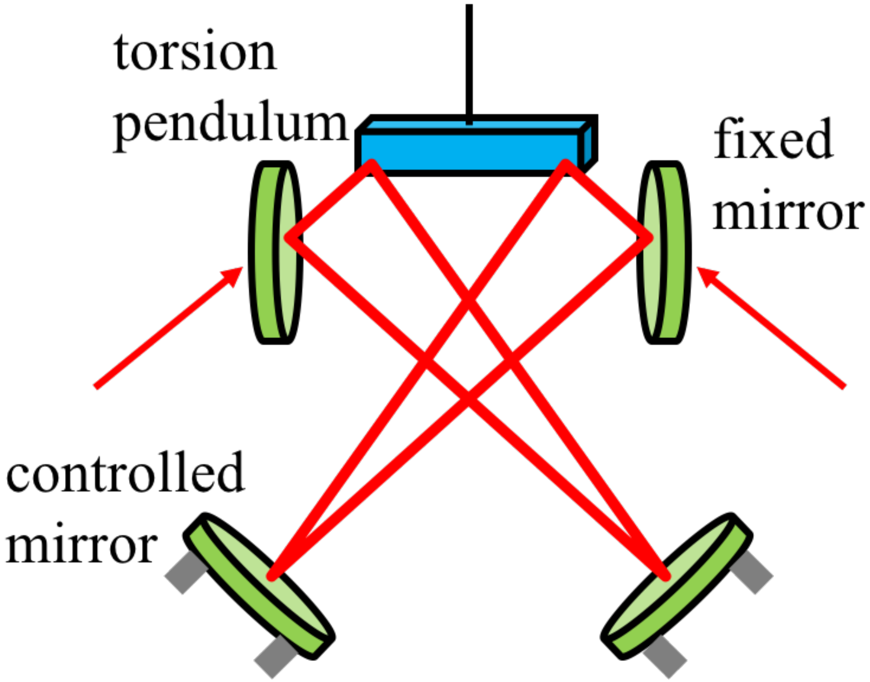
- two triangle cavities at both edges
- read out differential signal (torsional mode)

Advantages

- small effective mass
- low resonant frequency resulting in suspension thermal noise
- common mode rejection with one test mass



Parameter



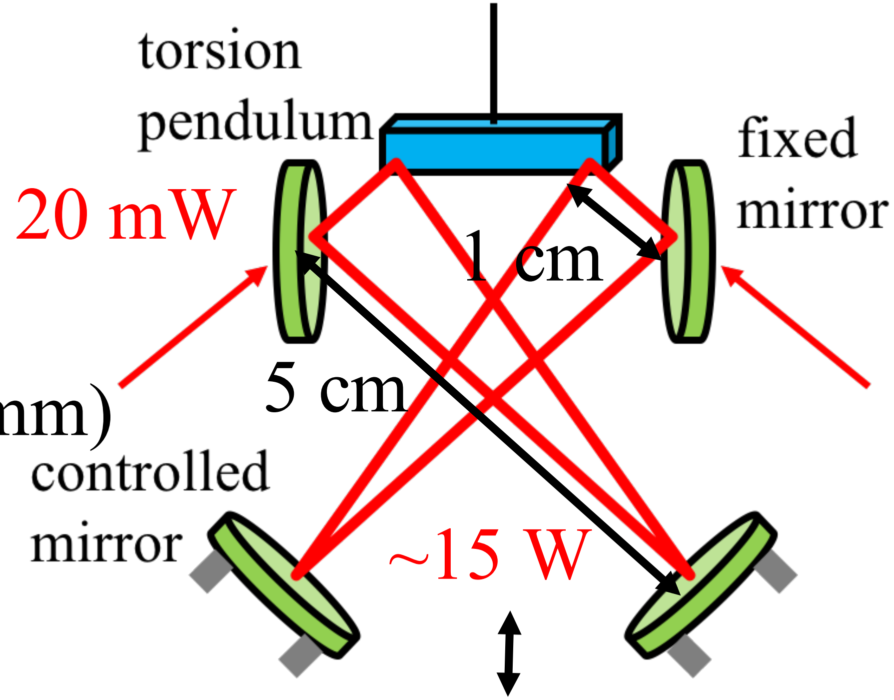
- finesse : 2000
- each input power : 20 mW
- resonant frequency : 0.12 Hz
- Q of rotational mode : 2000
- Q of pendulum mode : 1×10^{5}
- air pressure : 1×10^{-4} Pa
- frequency stabilization : 100/f Hz/$\sqrt{\text{Hz}}$ (below SQL)
- intensity stabilization : 1×10^{-8} /$\sqrt{\text{Hz}}$ (2 times shot noise)
- cavity round trip length : 11 cm
- common mode rejection rate : 10
- on a platform suspended from intermediate mass

Mirrors

- ➢ torsion pendulum (prepared)
  - dimension : 1.5 mm * 15 mm * 0.2 or 0.3 mm
  - reflectivity : R>99.99% (1064 nm, p-pol, 42º)
  - curvature : flat
- ➢ controlled mirror (prepared)
  - dimension : 0.5 inch covered with holders (ϕ=35mm)
  - reflectivity : R>99.98% (1064 nm, 0º)
  - curvature : 500 mm
- ➢ fixed mirror (ordered)
  - dimension : 0.5 inch, t=3 mm
  - reflectivity : R>99.8% (1064 nm, p-pol, 43º)
  - curvature : flat

Designed
$\mathcal{F}\sim 2800$, $\kappa_{in}/\kappa \sim 0.9$

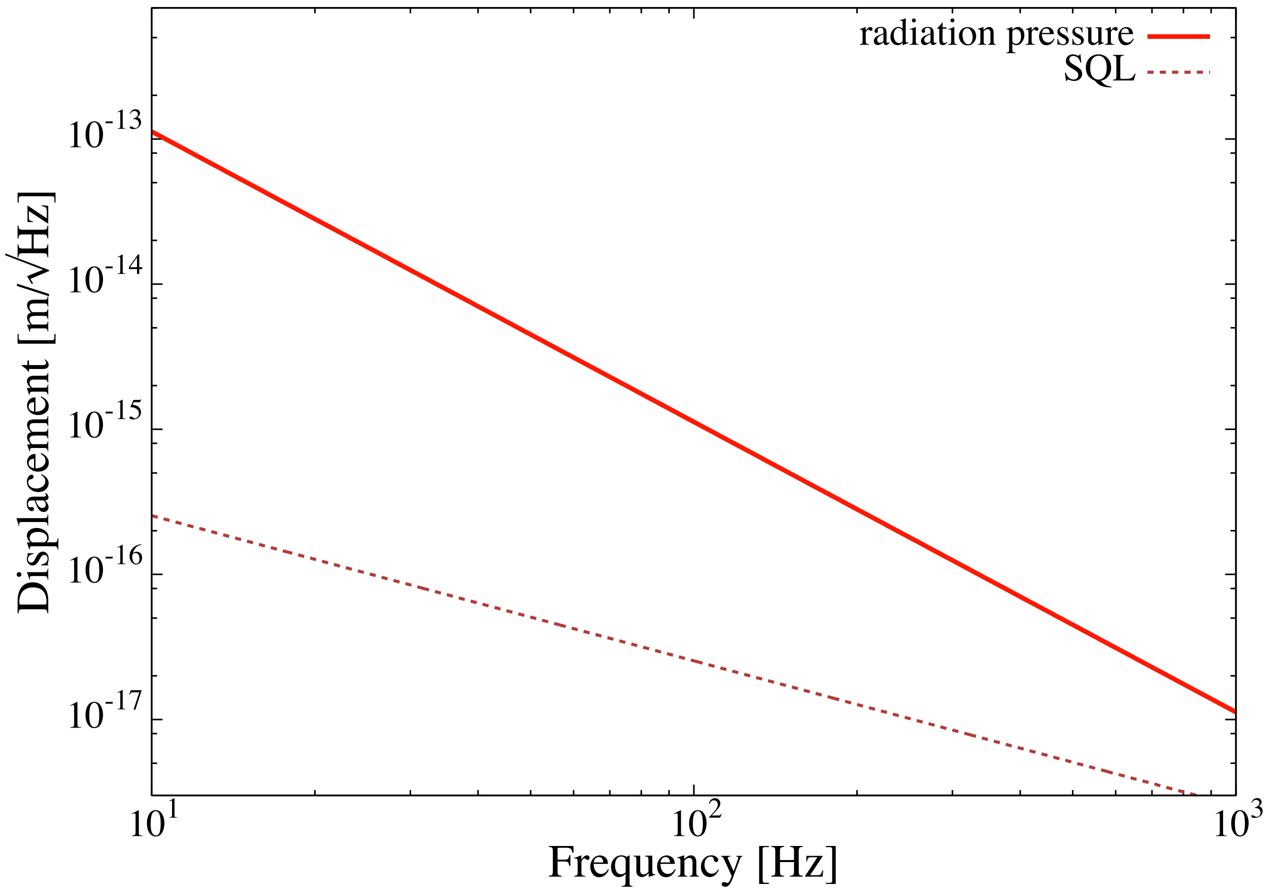
all mirrors are made of fused silica



$\mathcal{F}\sim 2000$, $P_{circ}\sim 10$ W in the previous 5-mg experiment

Radiation pressure

$$\sqrt{S_{qrp}(\omega)} = \frac{\mathcal{F}\cos\beta\sqrt{16\hbar\omega_c P_{in}}}{\pi c(1+\delta^2)}\frac{12}{m\omega^2}$$



$\mathcal{F} = 2000$

$\beta = 42.6°$

$P_{in} = 20$ mW

$\delta = 0$

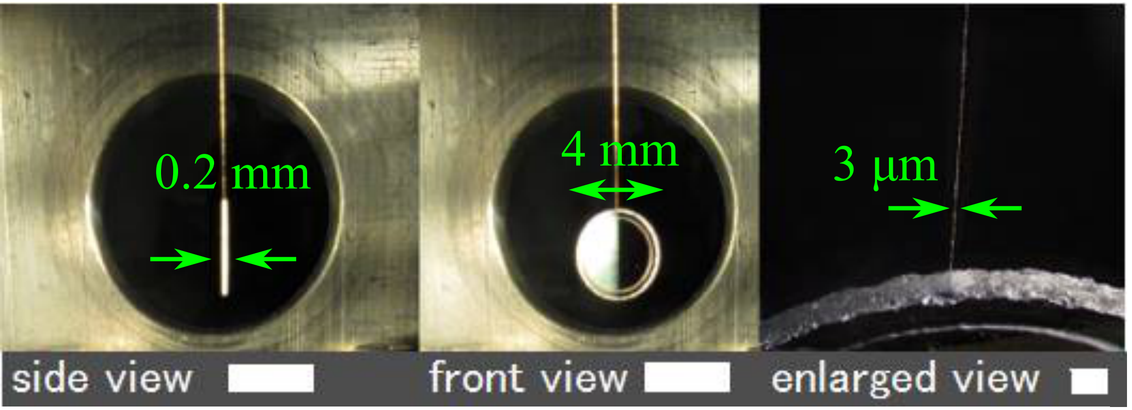
$m = 9.9$ mg

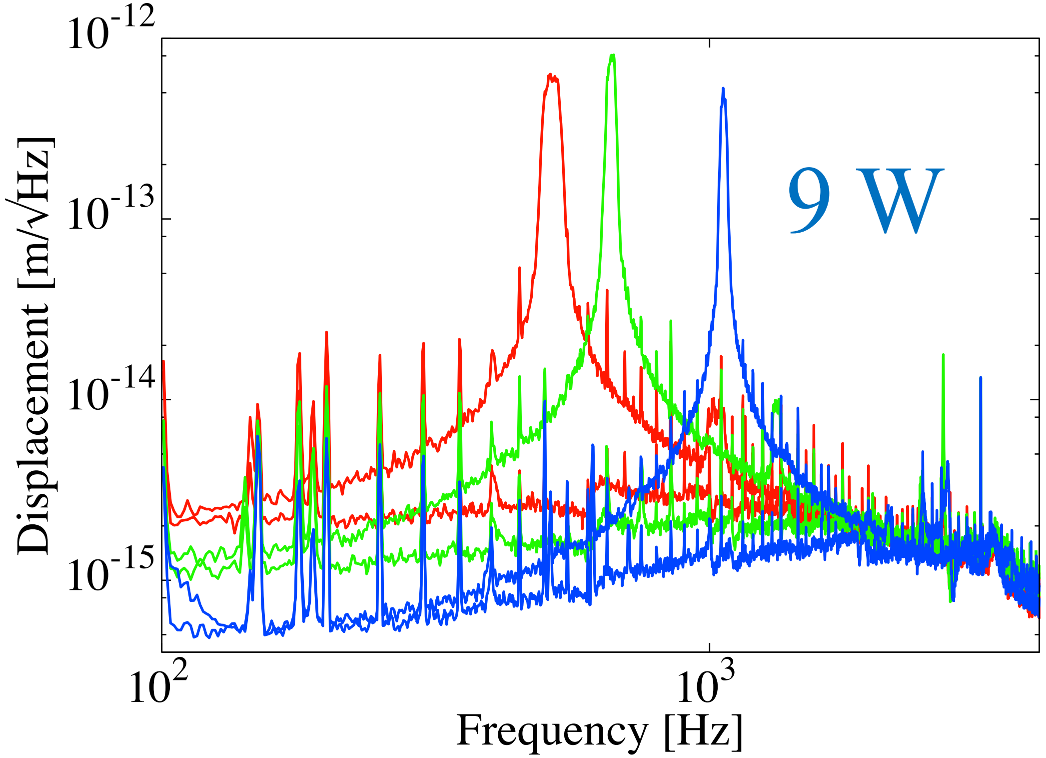
$P_{circ} \sim 15$ W

1×10^{-15} m/√Hz
@100 Hz

➢ SQL frequency ~ 4 kHz

Radiation pressure





achieved → $\mathcal{F} = 2000$

$\beta = 42.6°$

stabilized → $P_{in} = 20$ mW

$\delta = 0$

suspended → $m = 9.9$ mg

achieved → $P_{circ} \sim 10$ W

1×10^{-15} m/√Hz @100 Hz ← achieved

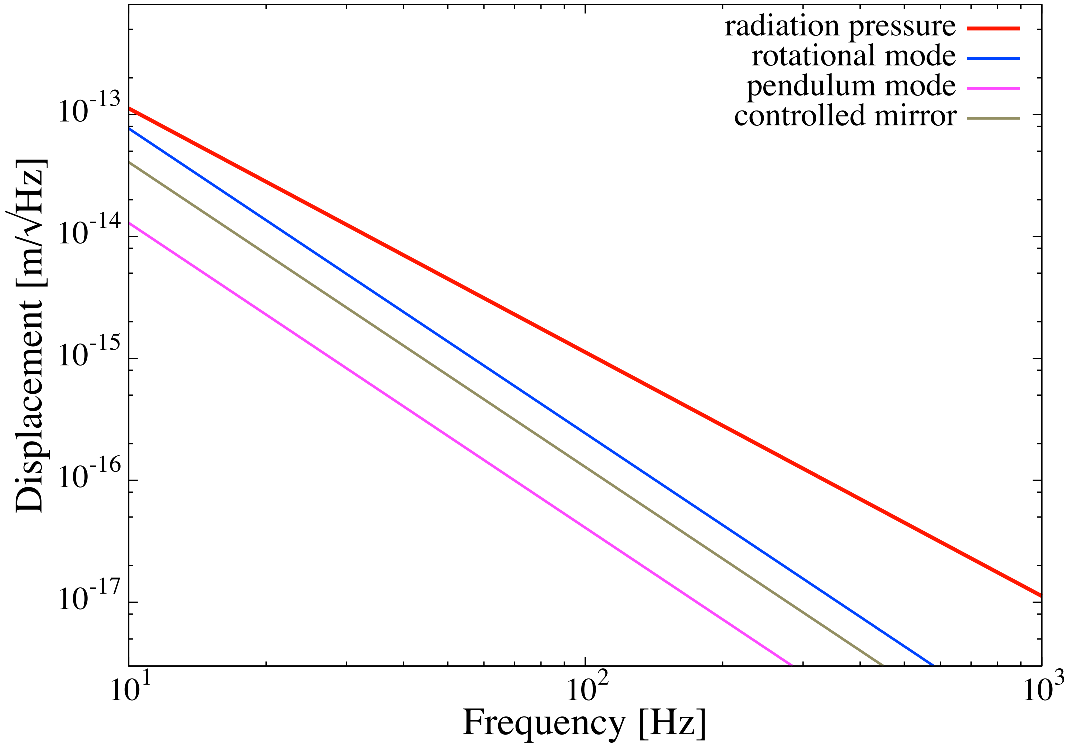
Suspension thermal

$$\sqrt{S_{rs}(\omega)} = \sqrt{\frac{4k_B T_{th} m\omega_{rot}^2}{Q_{rot}\omega}} \frac{\sqrt{12}}{m\omega^2}$$

$$\sqrt{S_{ps}(\omega)} = \sqrt{\frac{4k_B T_{th} m\omega_{pend}^2}{Q_{pend}\omega}} \frac{r_{CMRR}}{m\omega^2}$$

$$\sqrt{S_{ms}(\omega)} = \sqrt{\frac{4k_B T_{th} M\omega_{M}^2}{Q_{M}\omega}} \frac{1}{M\omega^2}$$

$f_{rot} = 0.12$ Hz, $f_{pend} = f_M = 5$ Hz



$Q_{rot} = 2000$

$Q_{pend} = 10^5$

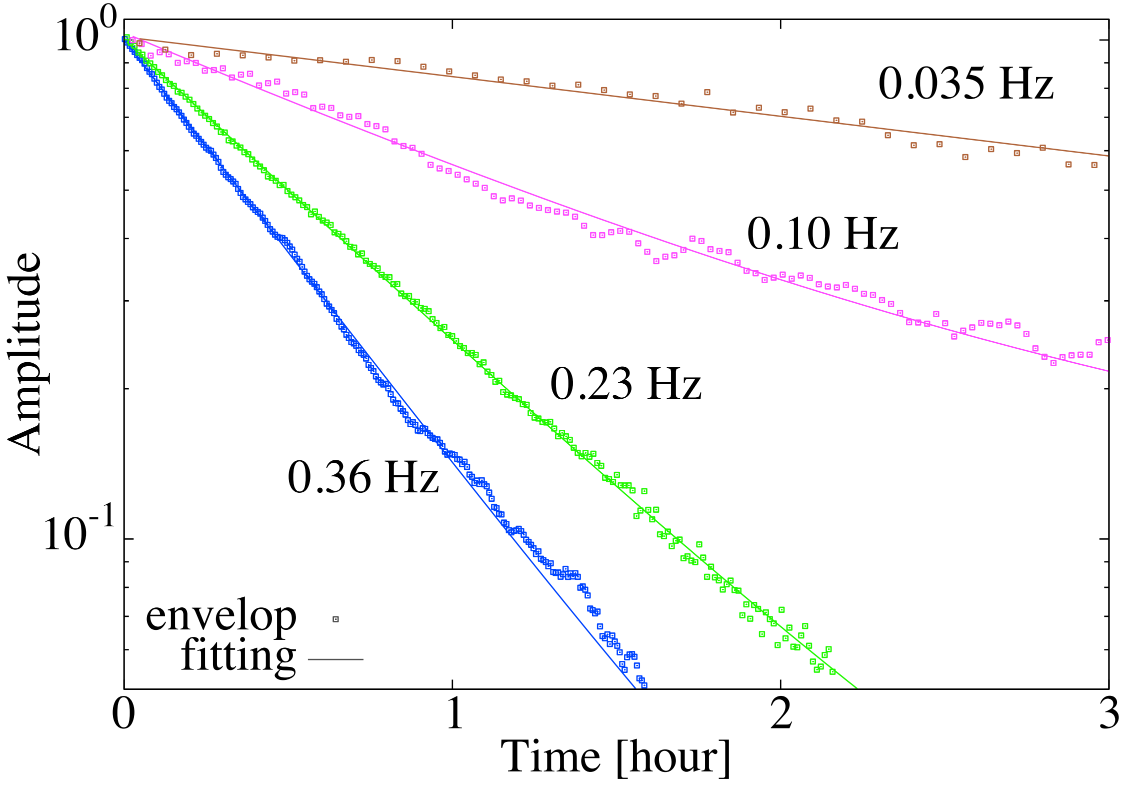
$Q_M = 10^2$

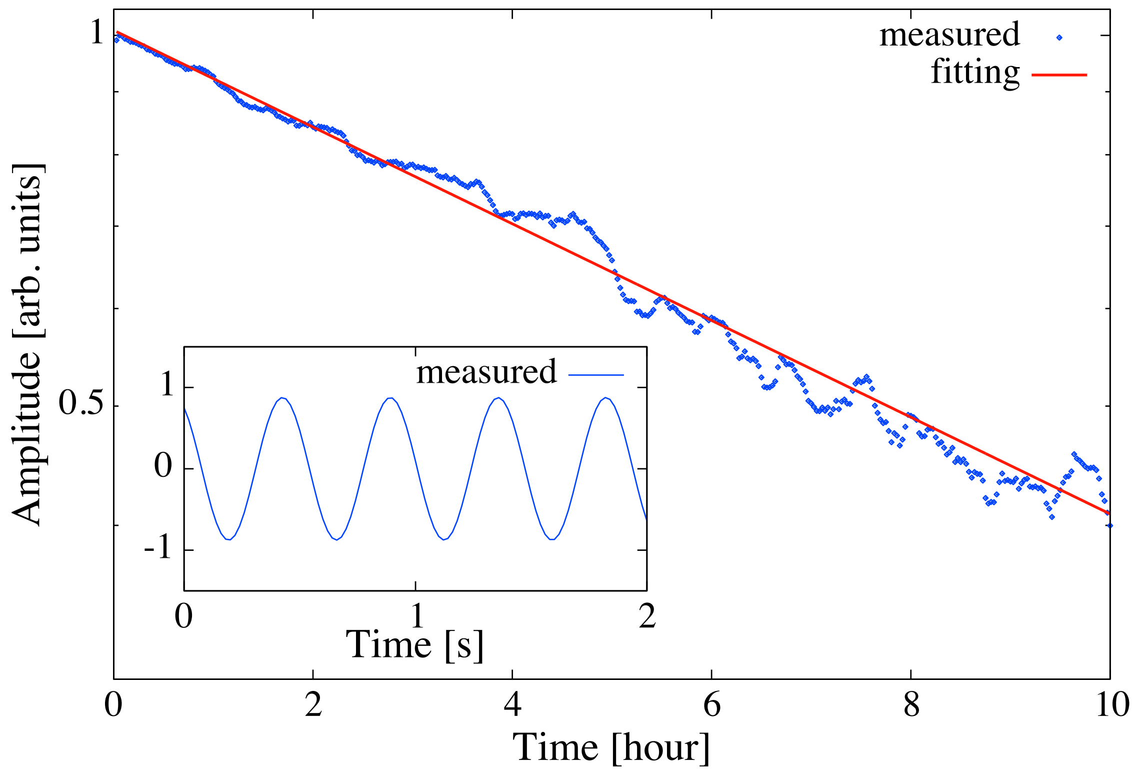
Suspension thermal

$Q_{rot} = 2000$ ← achieved with 3um wire and various bars

$Q_{pend} = 10^5$ ← achieved with 3um wire

$Q_M = 10^2$ ← easy

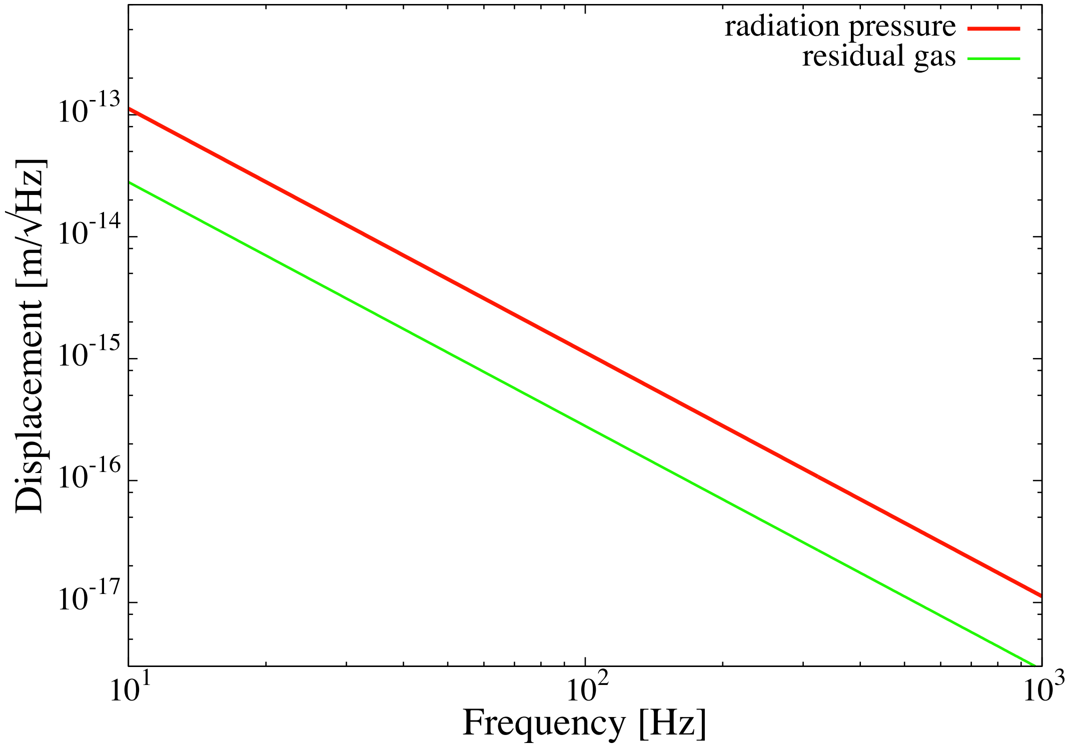




Residual gas

$$\sqrt{S_{f,gas}(\omega)} = \sqrt{4P_{air}S\sqrt{m_{mol}k_BT_{th}}}$$

$P_{air} = 1\times10^{-4}$ Pa
$S = 15$ mm $\times$ 1.5 mm
molecule : H_2O



$$\sqrt{S_{gas}(\omega)} = \sqrt{\int_{-L/2}^{L/2} 4P_{air}\sqrt{m_{mol}k_BT_{th}}\, lx^2dx}\ \frac{L}{I\omega^2}$$

$$= \sqrt{4P_{air}S\sqrt{m_{mol}k_BT_{th}}}\ \frac{\sqrt{12}}{m\omega^2}$$

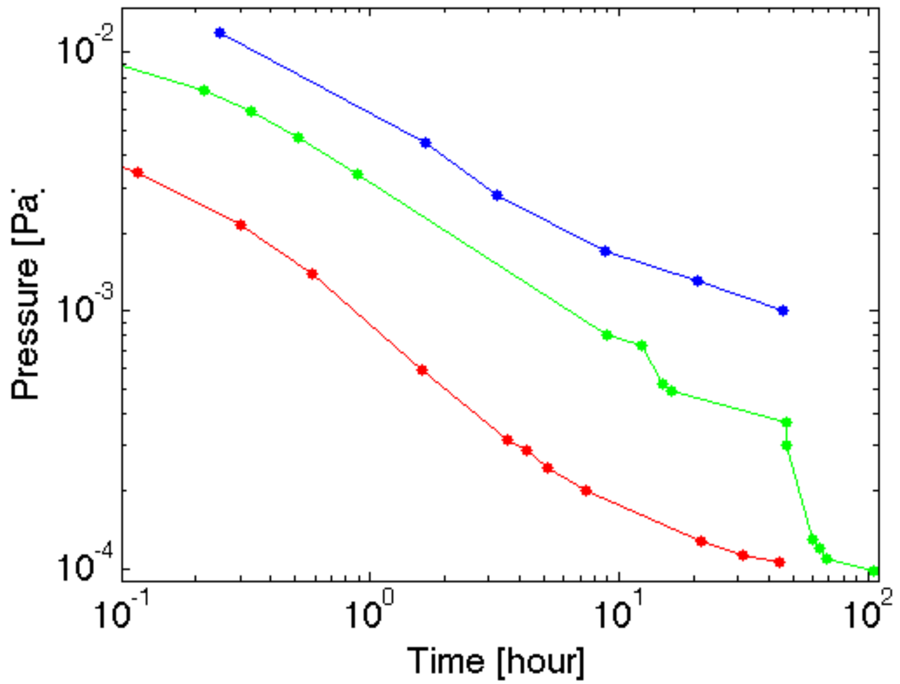
Residual gas

$$\sqrt{S_{f,gas}(\omega)} = \sqrt{4P_{air}S\sqrt{m_{mol}k_BT_{th}}}$$

$P_{air} = 1\times10^{-4}$ Pa ← achieved ($< 2\times10^{-4}$ Pa with some parts)
$S = 15$ mm × 1.5 mm
molecule : H_2O

$$\sqrt{S_{gas}(\omega)} = \sqrt{\int_{-L/2}^{L/2} 4P_{air}\sqrt{m_{mol}k_BT_{th}}\, l x^2 dx}\ \frac{L}{I\omega^2}$$

$$= \sqrt{4P_{air}S\sqrt{m_{mol}k_BT_{th}}}\ \frac{\sqrt{12}}{m\omega^2}$$



Mirror and bar thermal

$$\sqrt{S_{mir}(\omega)} = \sqrt{\frac{4k_B T_{th}}{\sqrt{\pi} w_0} \frac{1-\nu_s^2}{Y_s} \frac{\phi_{eff}}{\omega}}$$

$$\sqrt{S_{bar}(\omega)} = \sqrt{\frac{4k_B T_{th}}{m\omega_{bar}^2} \frac{\phi_{eff}}{\omega}}$$

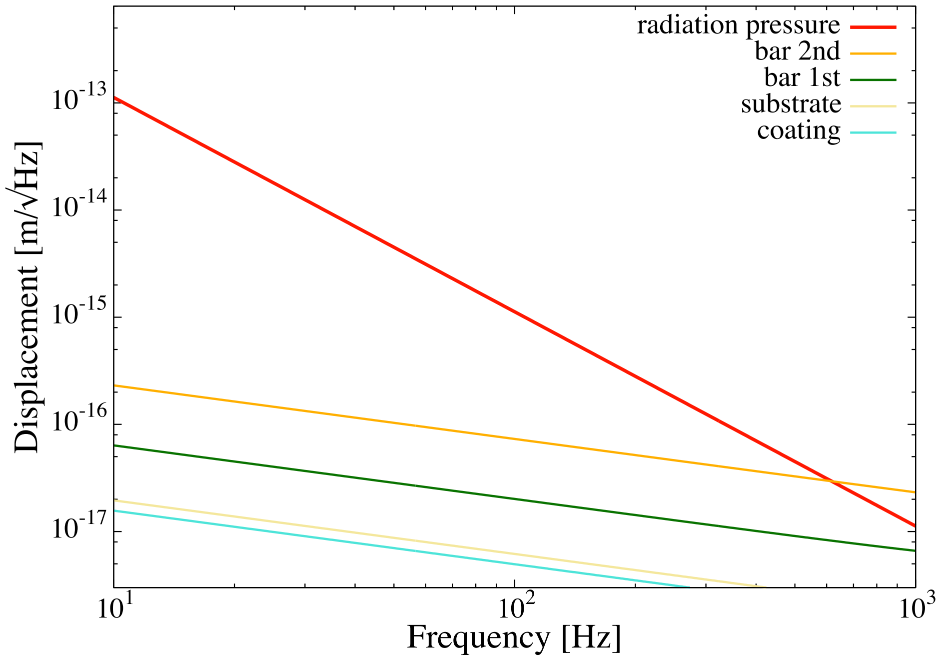
$$\phi_{eff} = \phi_s + \frac{1}{\sqrt{\pi} w_0} \begin{bmatrix} d_1\phi_1 \left(\frac{Y_1}{Y_s} + \frac{Y_s}{Y_1}\right) \\ +d_2\phi_2 \left(\frac{Y_2}{Y_s} + \frac{Y_s}{Y_2}\right) \end{bmatrix}$$

$\phi_s = 1\times10^{-5}$: SiO_2

$\phi_1 = 1\times10^{-4}$: SiO_2

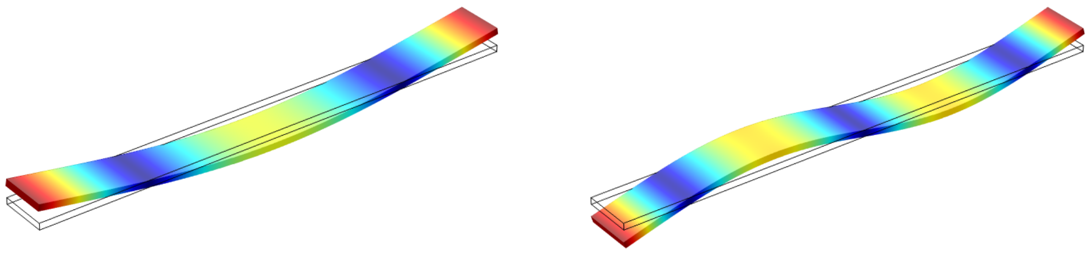
$\phi_2 = 4\times10^{-4}$: Ta_2O_5

$w_0 = 0.21$ mm



Mirror and bar thermal

$$\sqrt{S_{bar}(\omega)} = \sqrt{\frac{4k_B T_{th}}{m\omega_{bar}^2}\frac{\phi_{eff}}{\omega}}$$



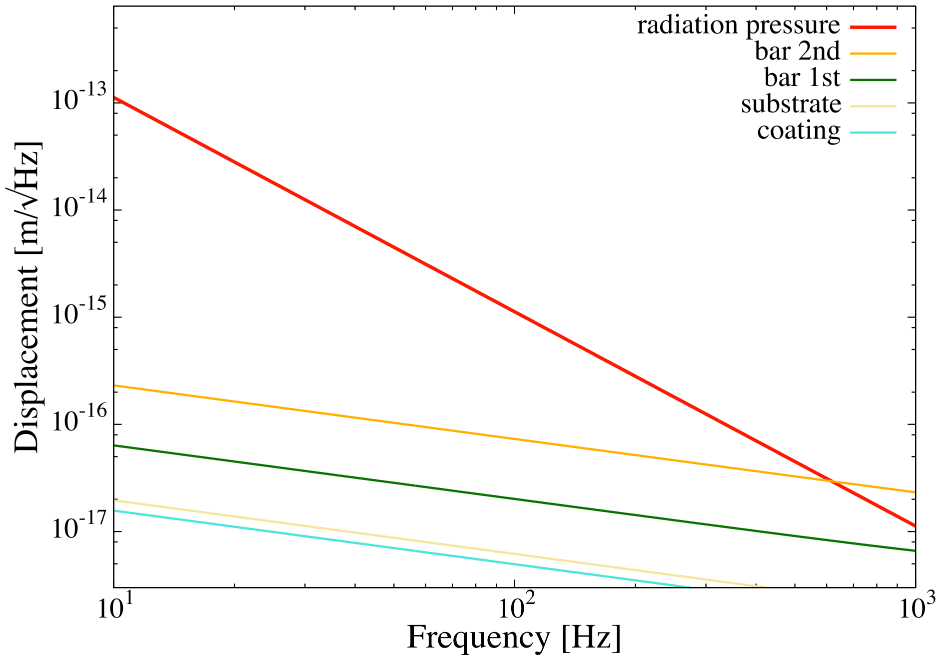
5.3 kHz

14 kHz

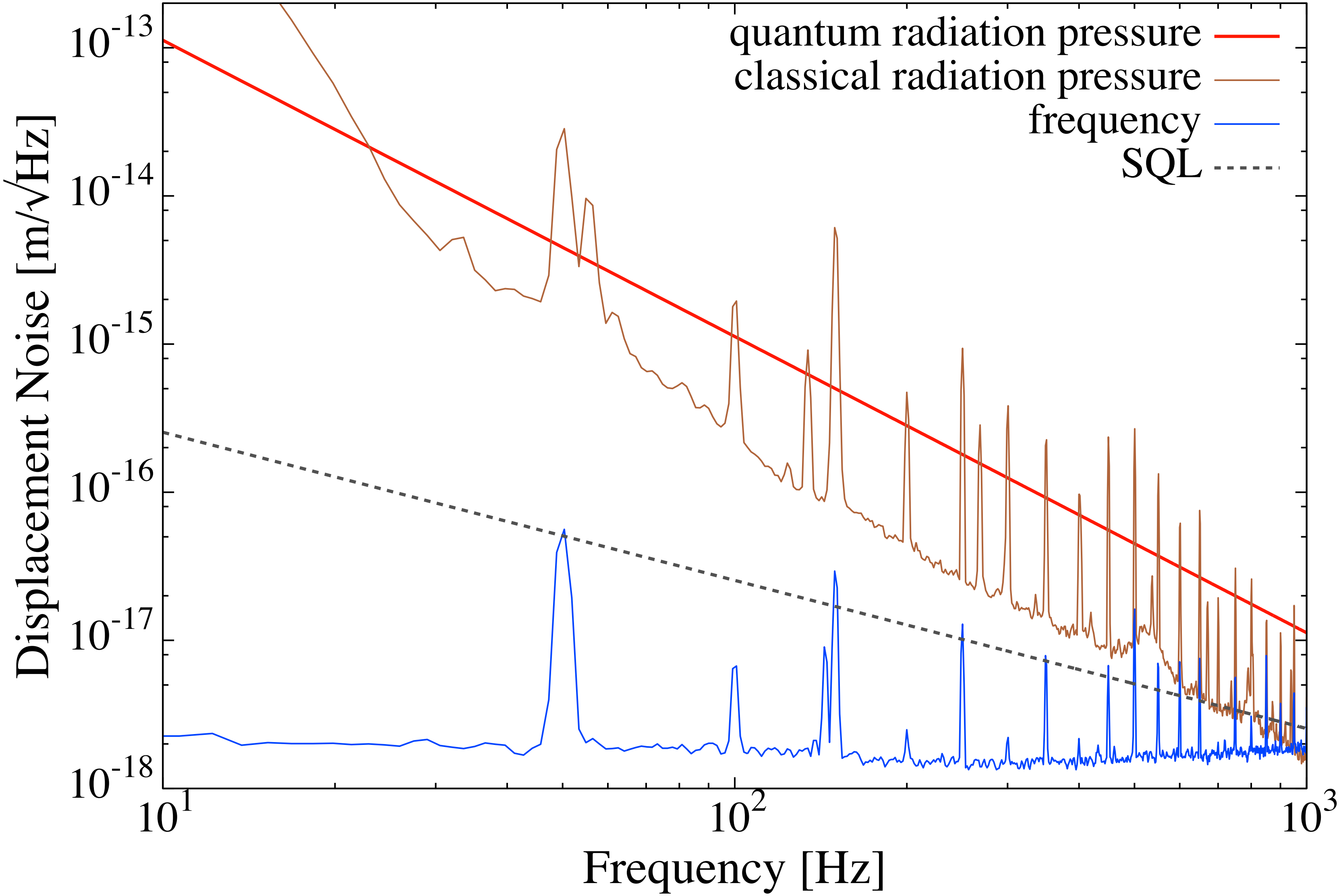
1×10^{-5}

6×10^{-6}

$$\phi_{eff} = \phi_s + \frac{1}{\sqrt{\pi}w_0}\left[\begin{array}{c} d_1\phi_1\left(\frac{Y_1}{Y_s}+\frac{Y_s}{Y_1}\right) \\ +d_2\phi_2\left(\frac{Y_2}{Y_s}+\frac{Y_s}{Y_2}\right)\end{array}\right]$$



Frequency and Intensity

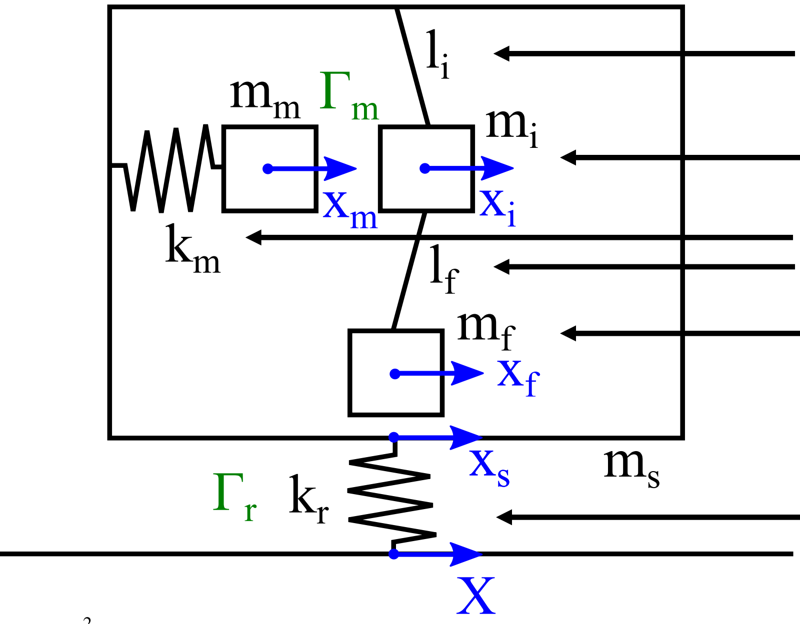


achieved

but not yet with the turbo pomp on

VIS

horizontal



20 cm

intermediate : Cu 2.2 kg

20 cm

platform : Al 1.5 kg

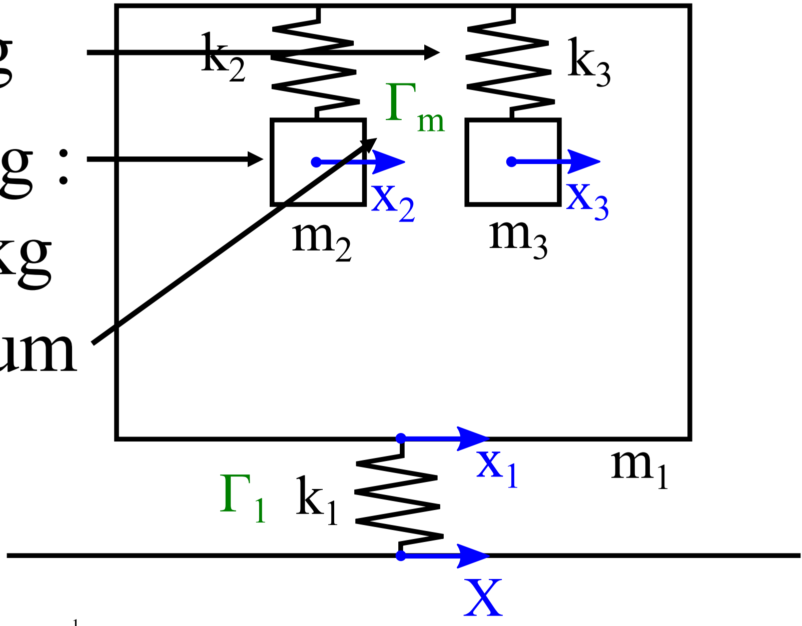
rubber viton

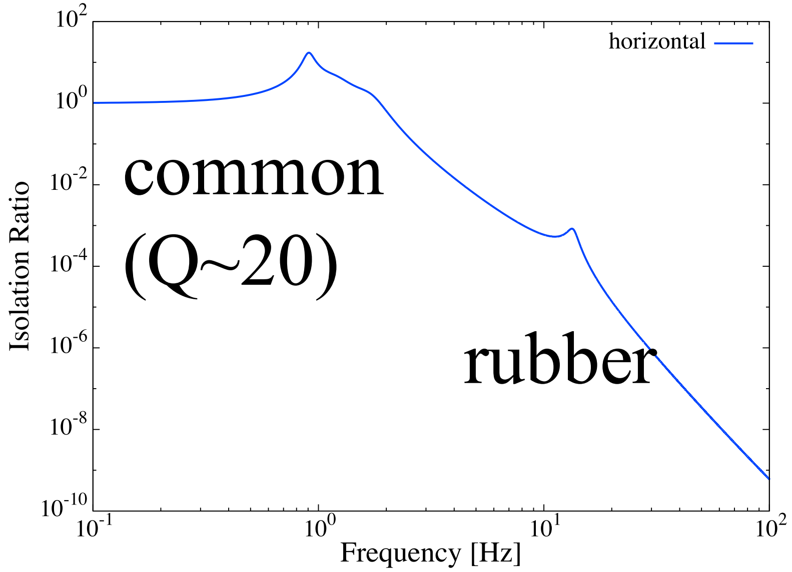
vertical

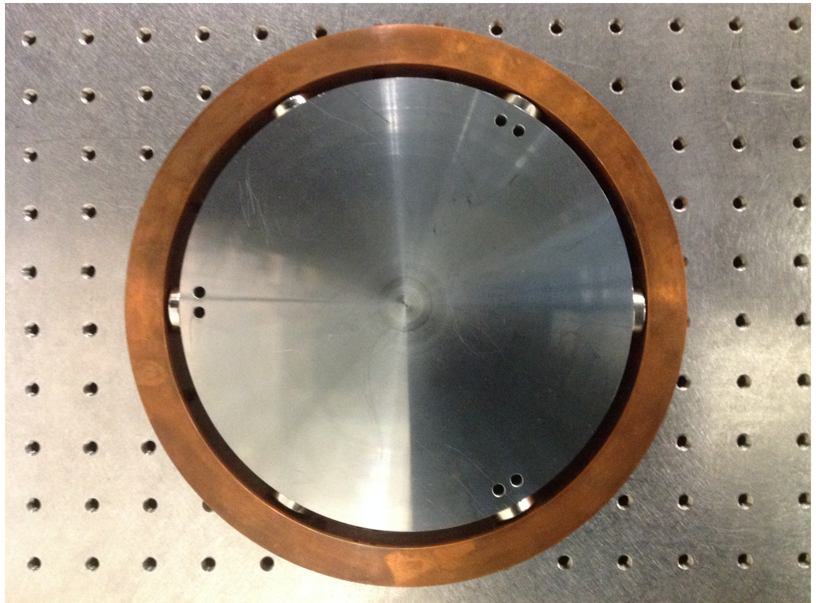
spring

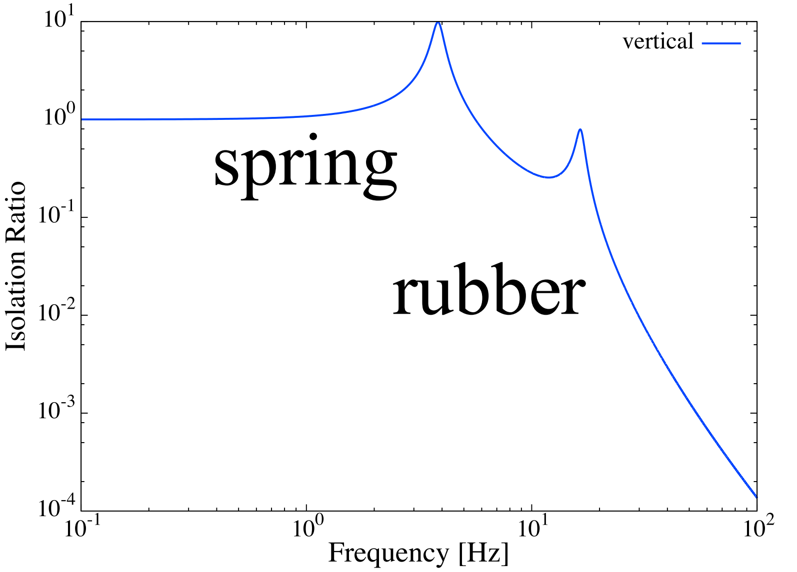
damping : Fe 4.9 kg

neodymium

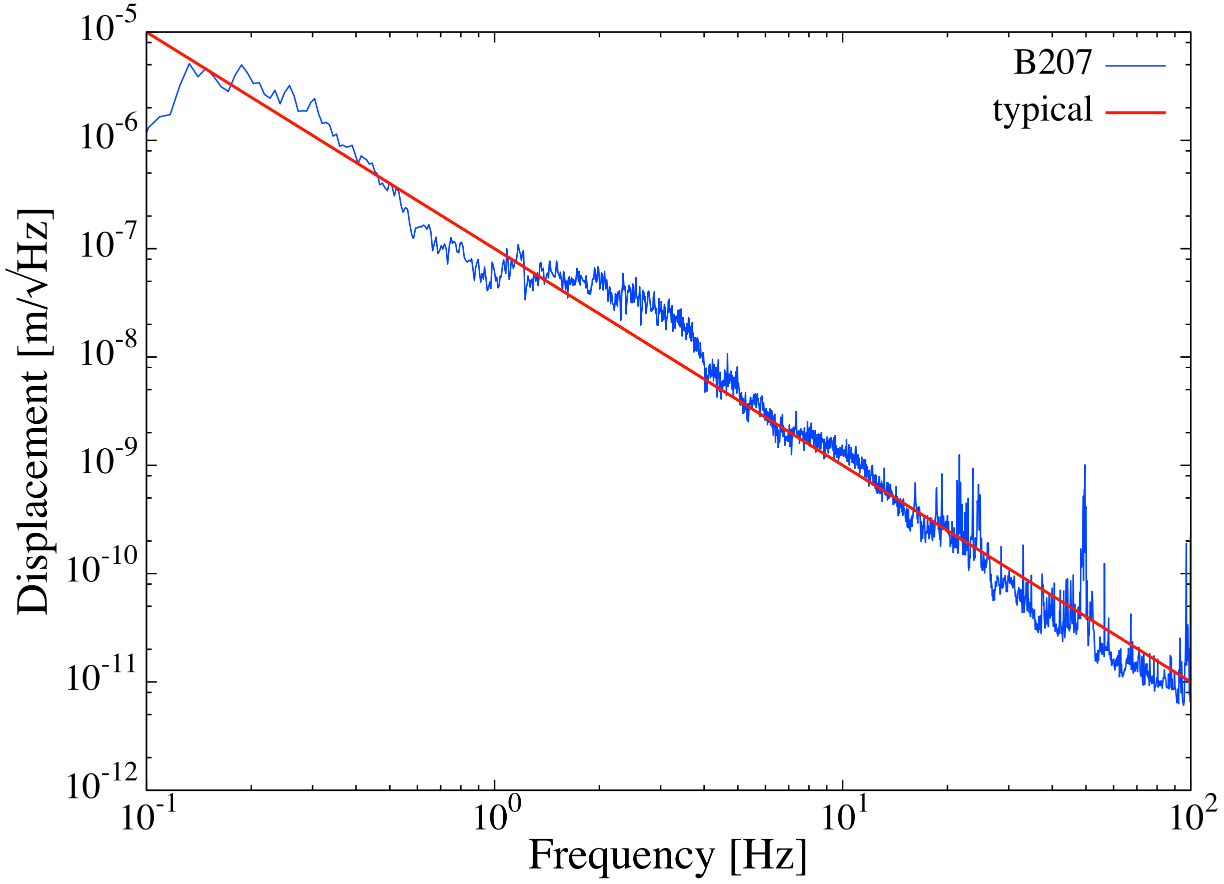




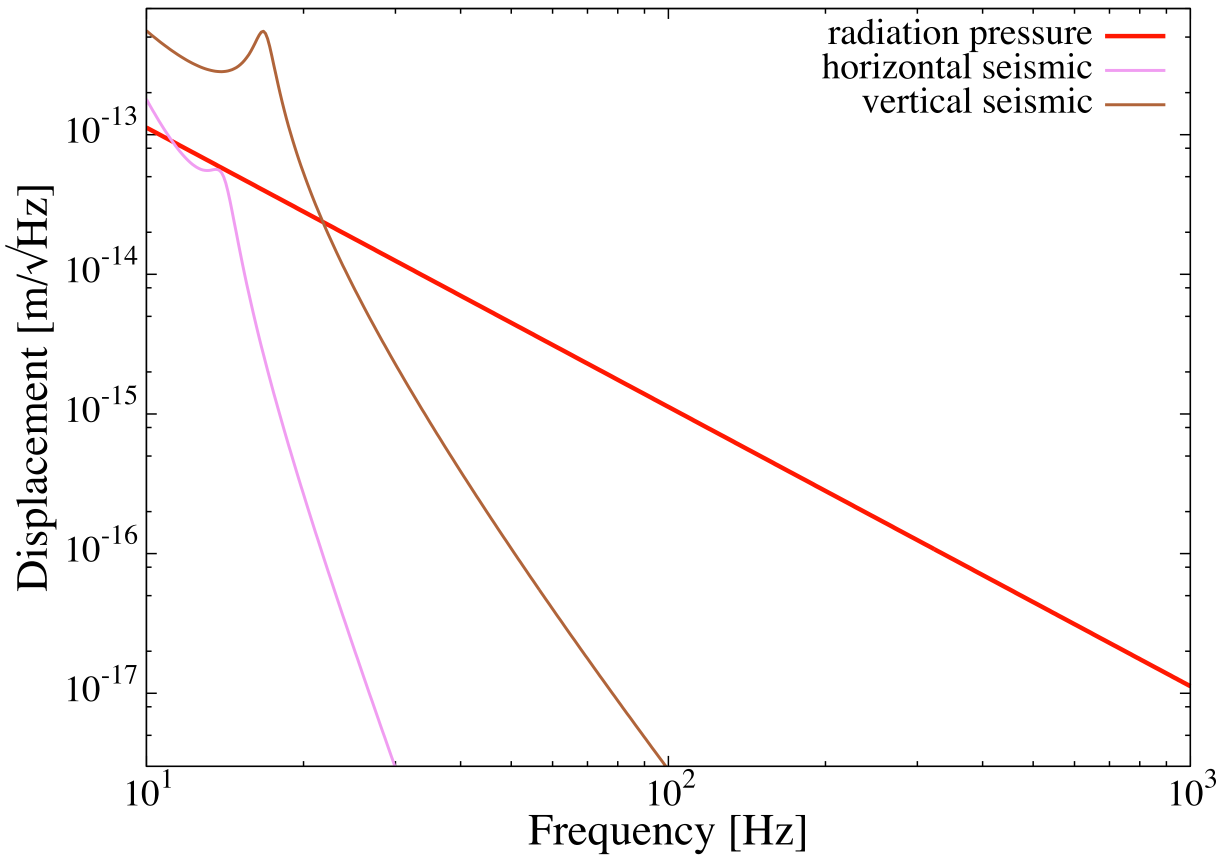




Seismic



measured by Shimoda-kun



vertical and horizontal coupling : 1/50

Lock acquisition

$$v_{rms} < \sqrt{\frac{F_{act}\lambda}{M\mathcal{F}}} = 2\times10^{-6}\ \mathrm{m/s}$$

$$F_{act} = 1\times10^{-3}\ \mathrm{N}$$

$$H_{act} = 1\times10^{-4}\ \mathrm{N/V}$$

⇨

$$x_{rms} < 7\times10^{-8}\ \mathrm{m}$$

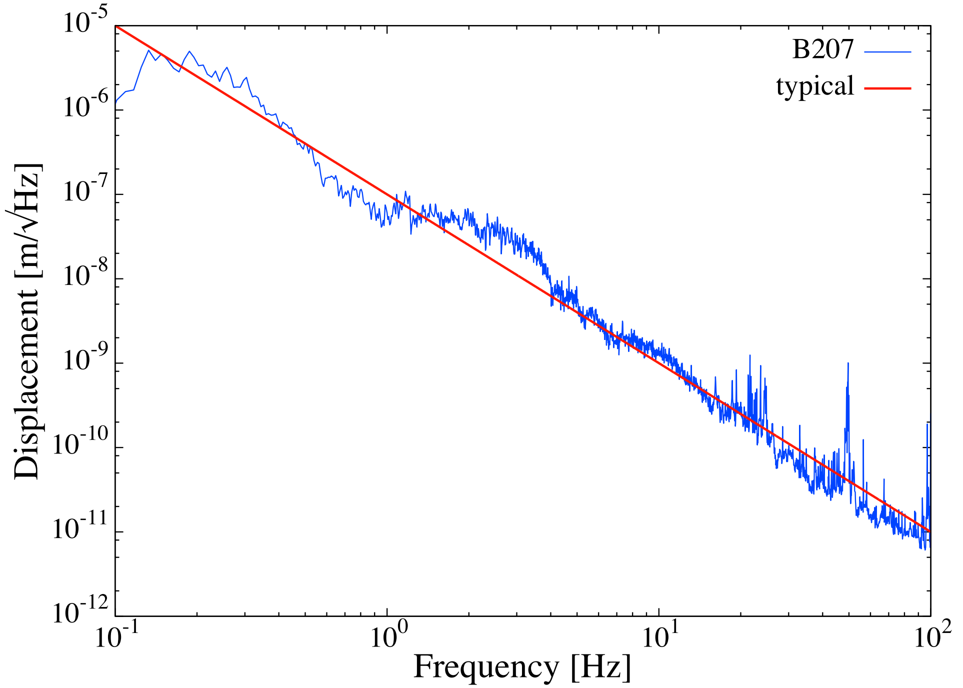
$$f_{pend} = 5\ \mathrm{Hz}$$

⇙

$$x_{plat}(\omega_{pend}) < 8\times10^{-11}\ \mathrm{m/\sqrt{Hz}}$$

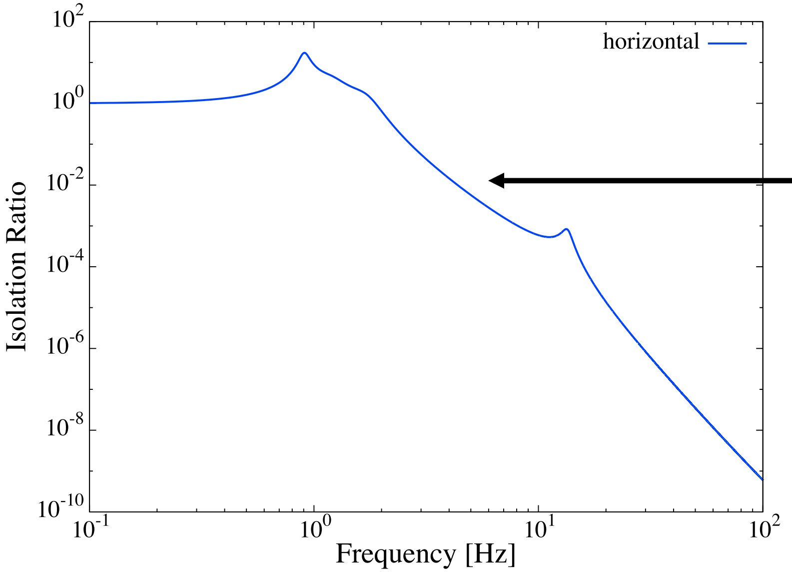
$$x_{rms} = \frac{\sqrt{\omega_{pend}Q_{pend}}}{2}x_{plat}(\omega_{pend})$$

⇨ $$x_{plat}/x_{seis}(\omega_{pend}) < 1/50$$



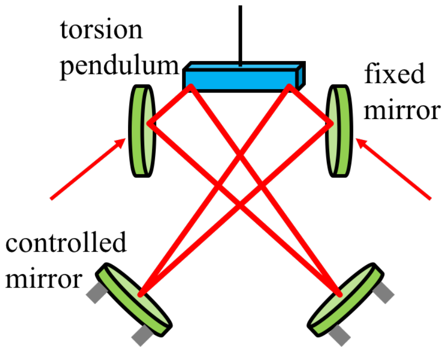
Lock acquisition

$x_{plat}/x_{seis}(\omega_{pend}) < 1/50$



0.006
(cleared)

- One arm can be locked easily.



$$F_{rad} = \frac{2\cos\beta}{c(1+\delta^2)}\frac{\mathcal{F}P_{in}}{\pi}$$

$\delta = 2, P_{in} = 1\,\mathrm{mW}$

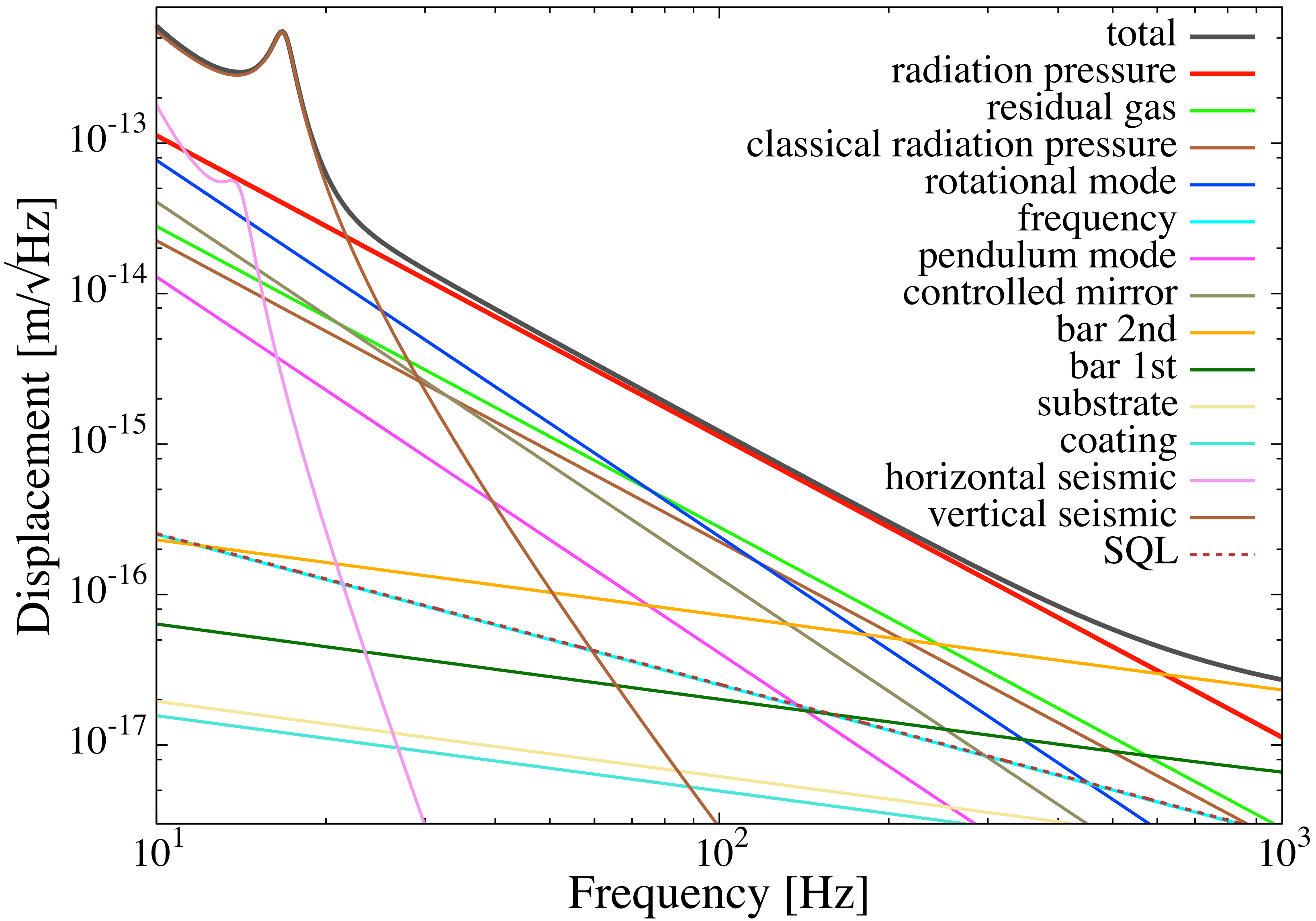
$$v_{arm} = \sqrt{6F_{rad}x_d/m}$$
$$= 2\times10^{-6}\sqrt{x_d/10^{-8}}\ \mathrm{m/s}$$

$v_{rms} < 2\times10^{-6}$ m/s

$x_{rms} < 1\times10^{-8}$ m

$x_{pend} = 2\times10^{-8}$ m   not bad

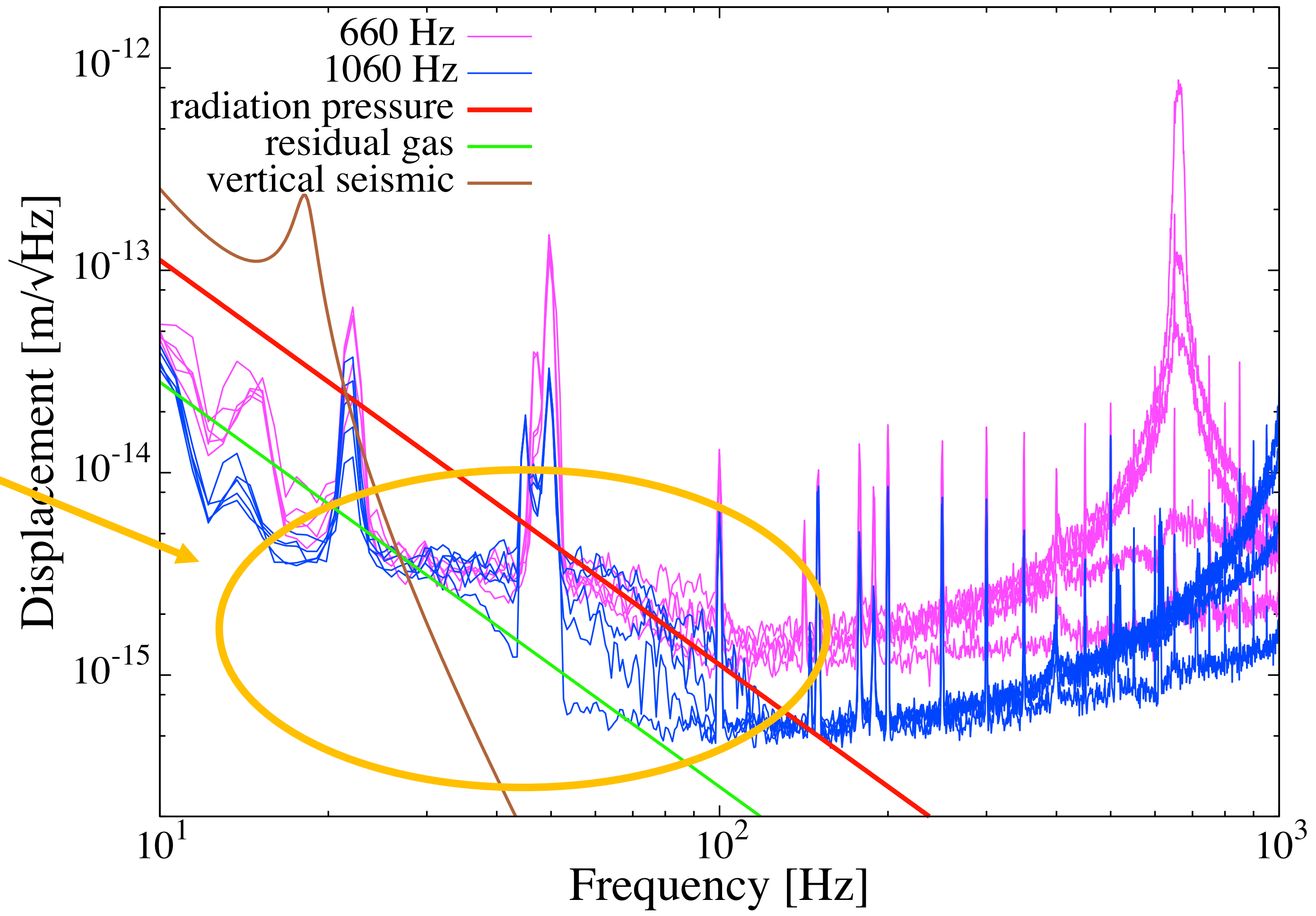
Total noise



total
radiation pressure
residual gas
classical radiation pressure
rotational mode
frequency
pendulum mode
controlled mirror
bar 2nd
bar 1st
substrate
coating
horizontal seismic
vertical seismic
SQL
Displacement [m/√Hz]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{1}
10^{2}
10^{3}
Frequency [Hz]

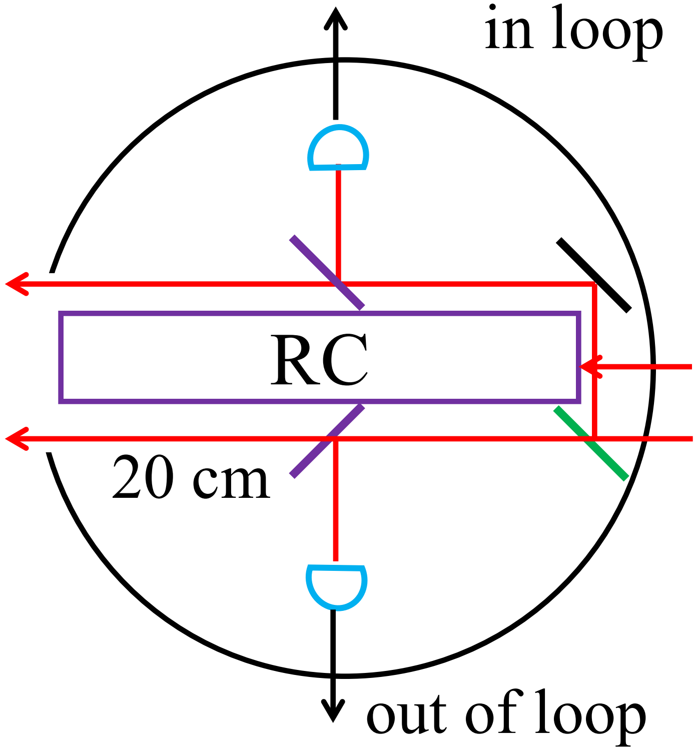
Matters of concern

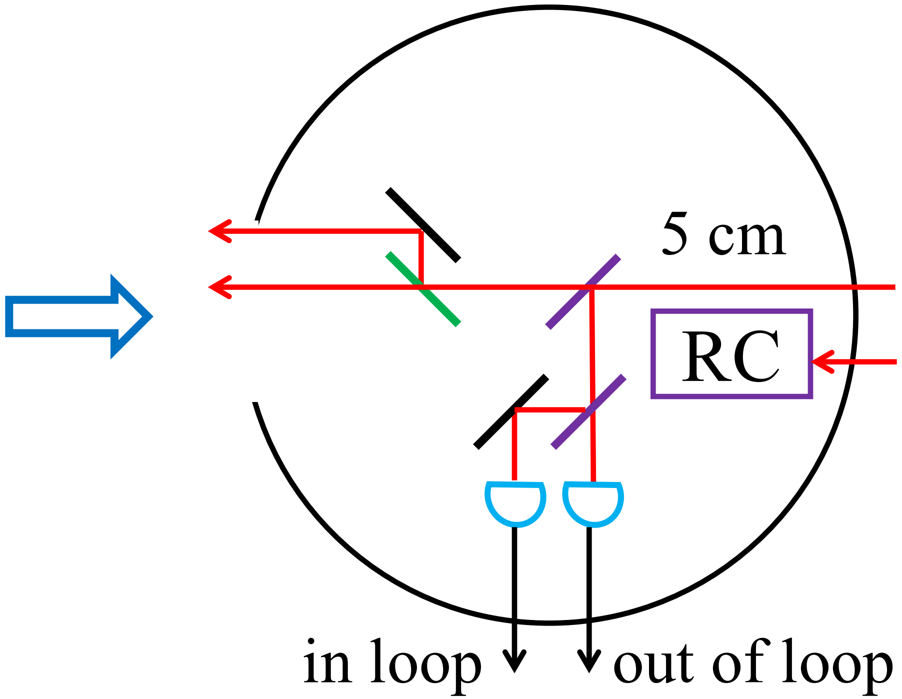
- Almost nothing
- Scattering ?
- Other fluctuation of the cavity length at initial lock

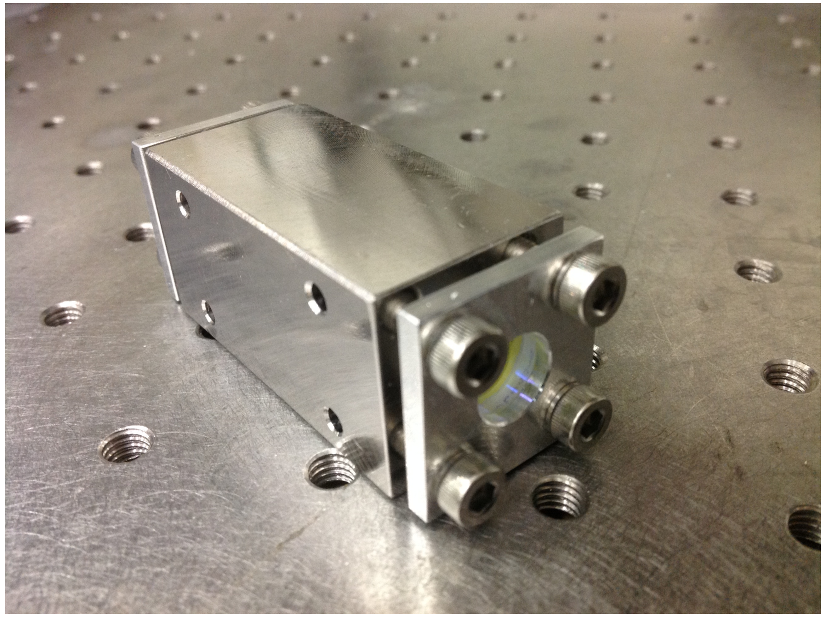


Current status

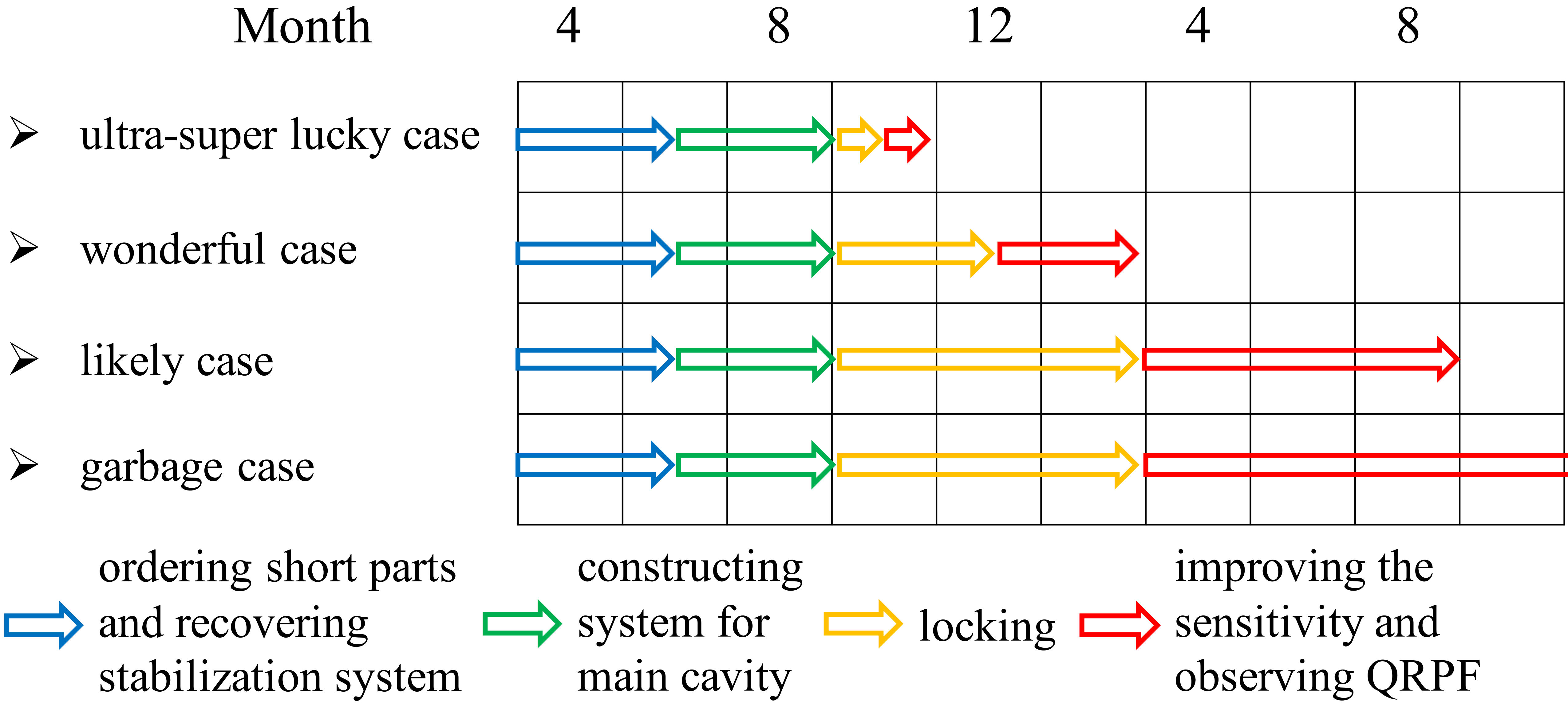
- finish to design the set up for the main cavity and to order short parts (maybe)
- change the set up of the platform for stabilization system







Future plan


Month
4
8
12
4
8
ultra-super lucky case
wonderful case
likely case
garbage case
ordering short parts and recovering stabilization system
constructing system for main cavity
locking
improving the sensitivity and observing QRPF