Classical Pendulum Feels Quantum Back-Action

University of Tokyo
Nobuyuki Matsumoto

GWADW2014

Outline

- Introduction of our recent research

arXiv:1312.5031v1 [quant-ph] 18 Dec 2013

Classical Pendulum Feels Quantum Back-Action

Nobuyuki Matsumoto[1,*], Yuta Michimura[1], Gen Hayase[2], Yoichi Aso[1], and Kimio Tsubono[1]

[1]*Department of Physics, Graduate School of Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*

[2]*Department of Chemistry, Graduate School of Science, Kyoto University, Sakyo, Kyoto 606-8502, Japan*

- Advantages of the triangular optical cavity

(suppl. info. A.1) ⇒ [Opt. Express 22, 12915 (2014)]

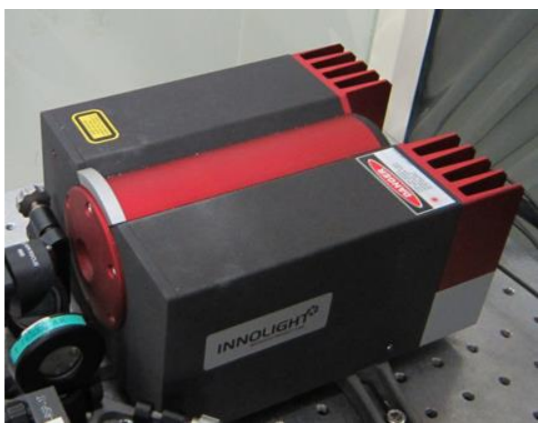
- Observation of Quantum Back-Action

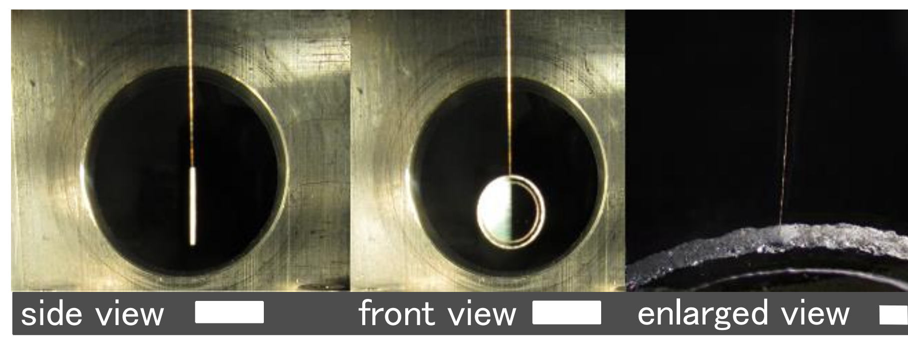
(RPN: Radiation Pressure Noise)

What is Quantum Back-Action?

Image
(classical case)

Our case





Vacuum fluctuation of the coherent light sways the mirror

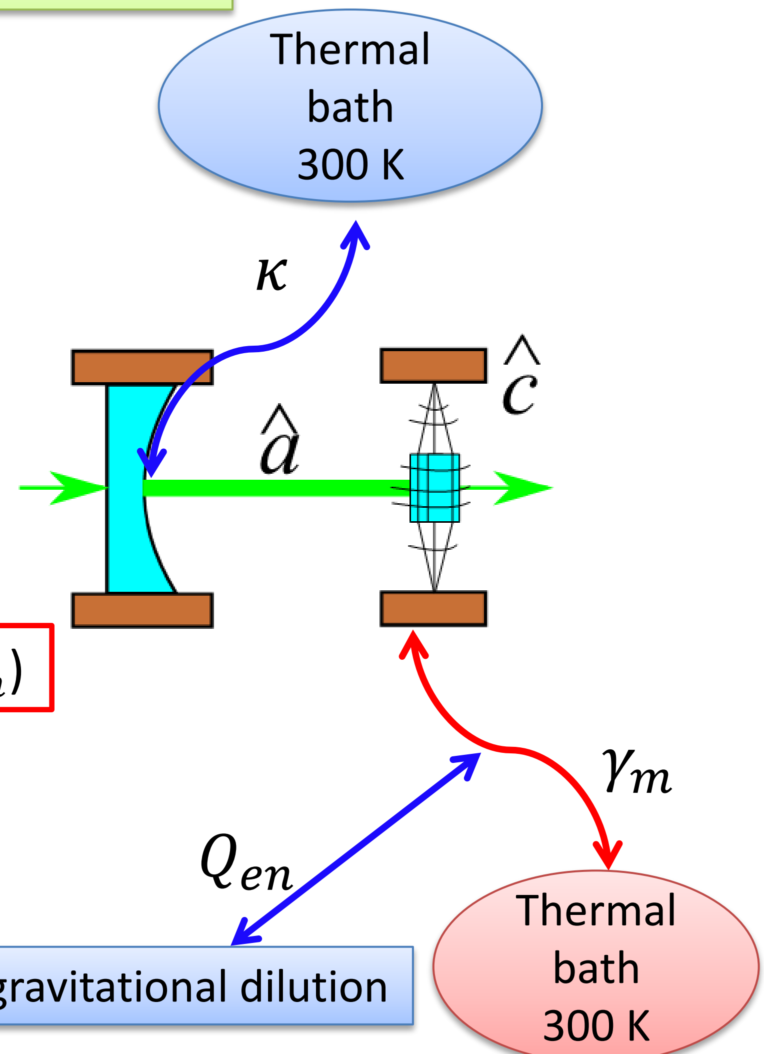
Requirement for reaching the SQL

Quantum back-action/thermal fluctuating force > 1

$$R_s = \frac{S^{(2)}_{FF,q}}{S^{(2)}_{FF,th}} = |G_{opt}|^2/(n_{th}\kappa\gamma_m) > 1,$$

Increase of intra-cavity power

Decrease of mechanical decay (Q_{en})



$\hat{a}$: photon annihilation operator
$\hat{c}$: phonon annihilation operator
κ: decay rate of the optical cavity
γ_m: decay rate of the pendulum
Q_{en}: Q enhancement factor due to the dilution

Requirement for reaching the SQL

Quantum back-action/thermal fluctuating force > 1

$$R_s = \frac{S^{(2)}_{FF,q}}{S^{(2)}_{FF,th}} = |G_{opt}|^2/(n_{th}\kappa\gamma_m) > 1,$$

Increase of intra-cavity power

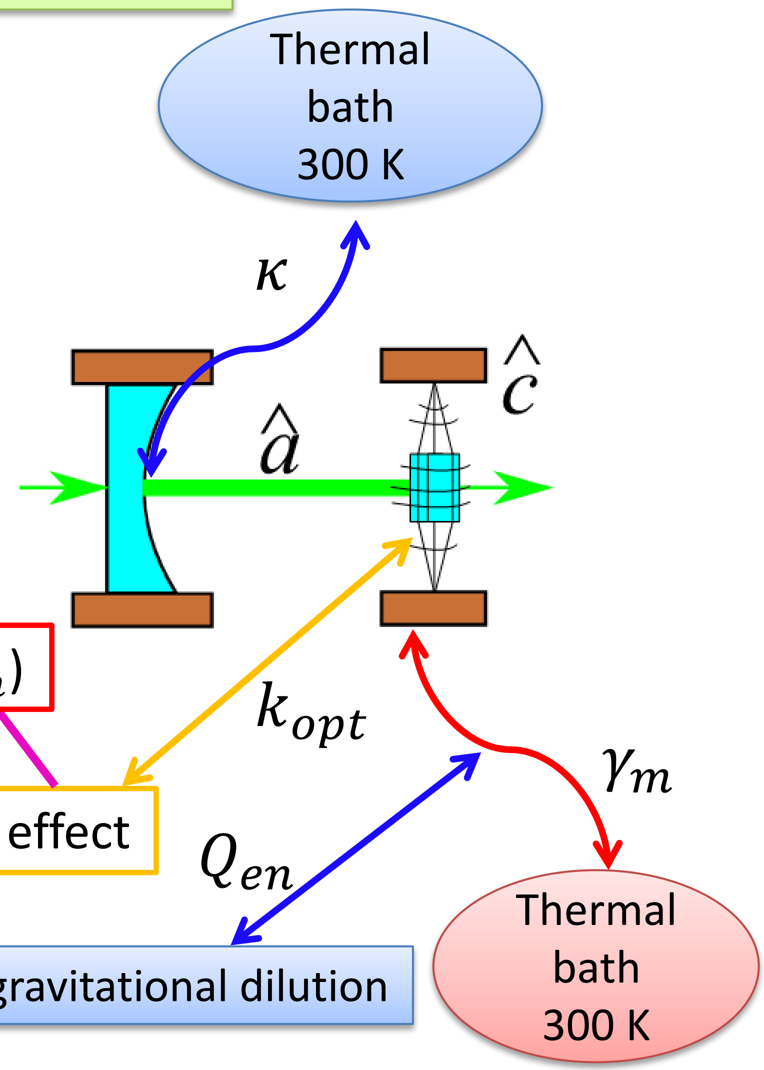
$$Q_{en} < \sqrt{\frac{G}{Y} 8lmg \frac{1}{\tau P_{circ}}} = \sqrt{\frac{2lmg}{(1+\sigma)} \frac{\kappa}{P_{in}}}.$$

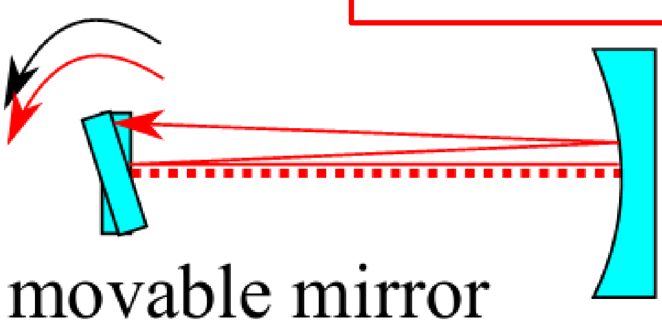
Trade-off

Decrease of mechanical decay (Q_{en})

Anti torsional spring effect

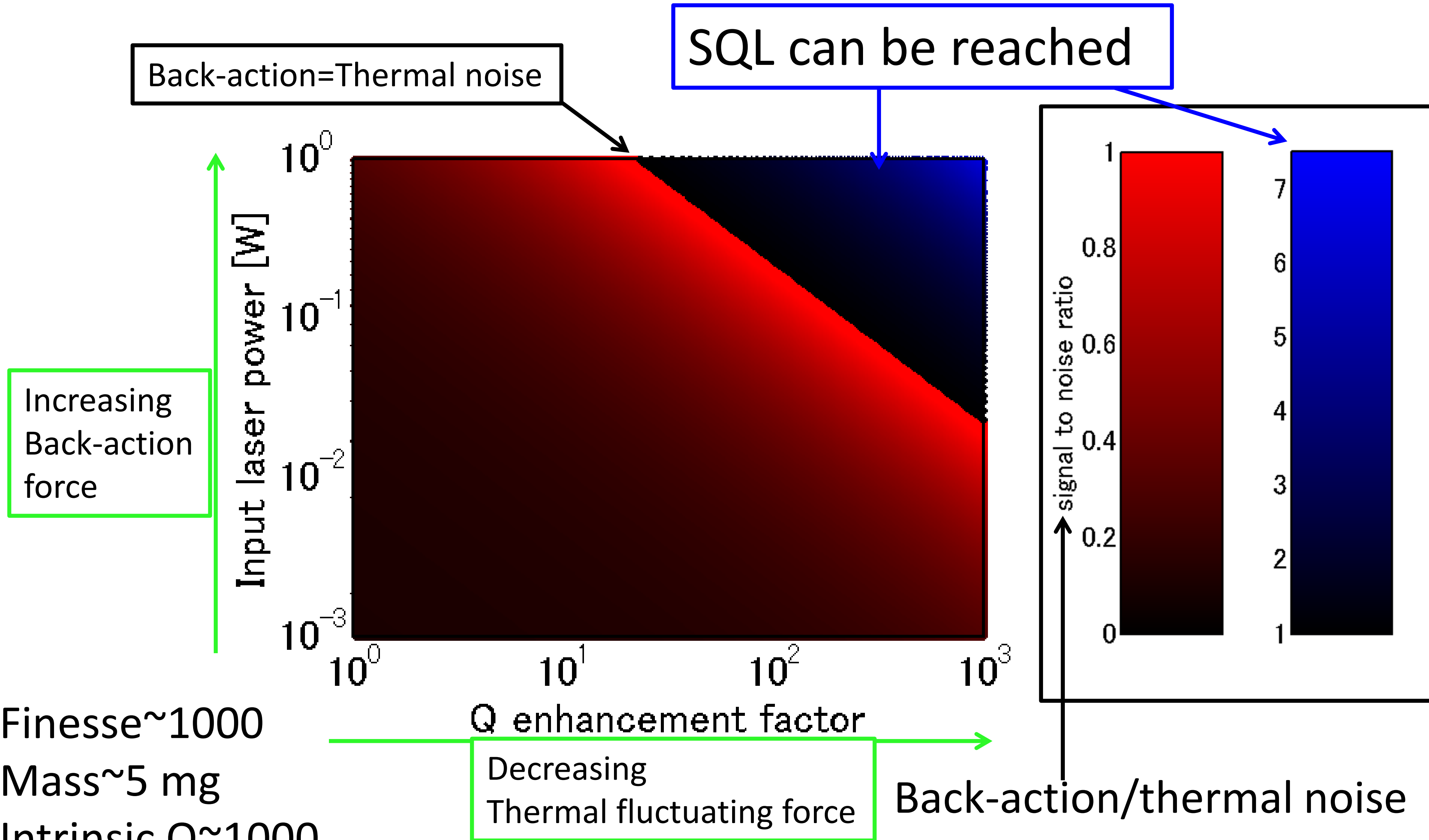
gravitational dilution





trade-off is not considered

signal to noise ratio of RPN to TN



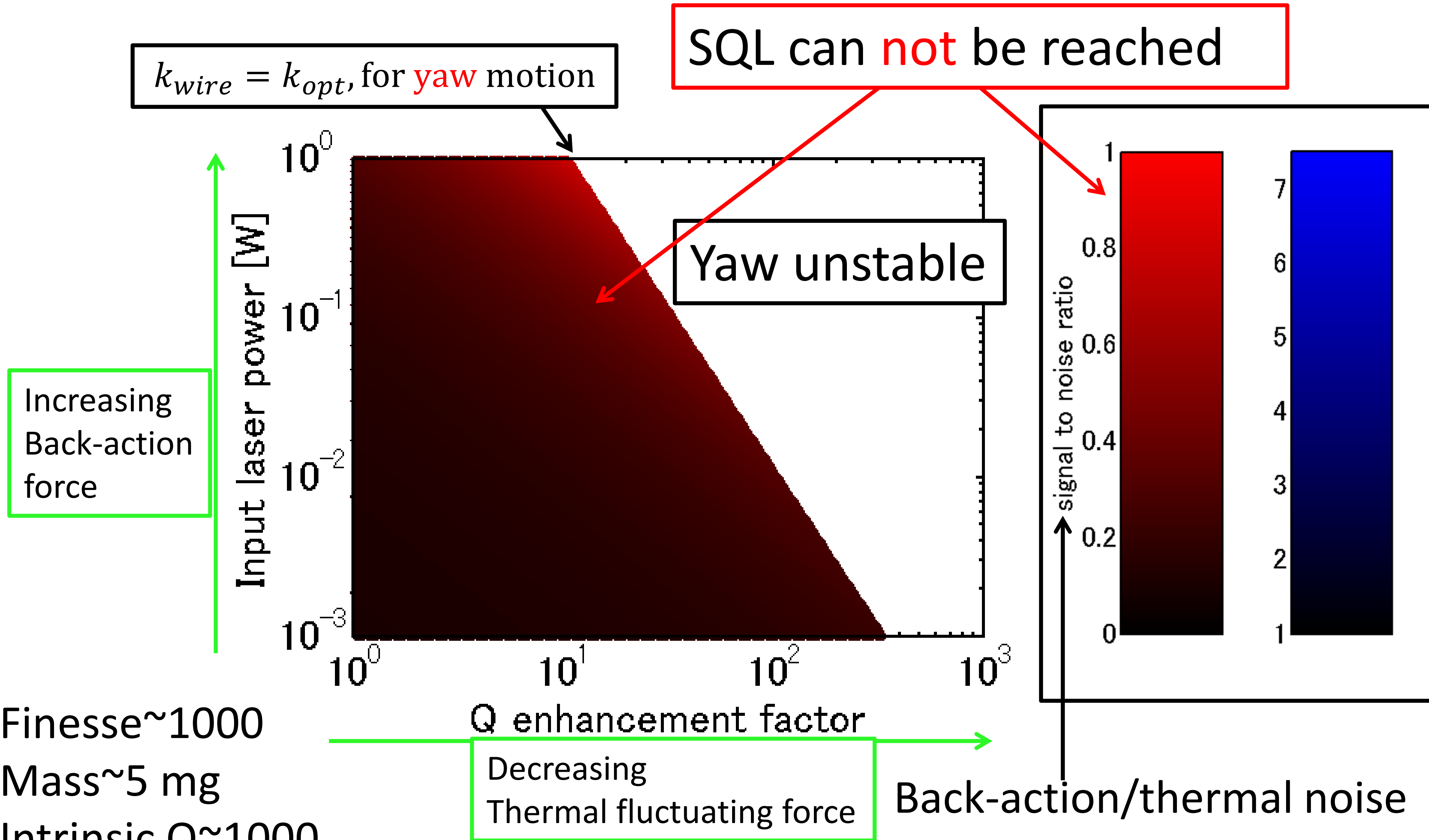
Finesse~1000

Mass~5 mg

Intrinsic Q~1000

trade-off is considered

$$Q_{\rm en} < \sqrt{\frac{G}{Y} 8lmg \frac{1}{\tau P_{\rm circ}}} = \sqrt{\frac{2lmg}{(1+\sigma)} \frac{\kappa}{P_{\rm in}}}.$$



Finesse~1000

Mass~5 mg

Intrinsic Q~1000

Optically trapped mirror for reaching the standard quantum limit

Nobuyuki Matsumoto,* Yuta Michimura, Yoichi Aso, and Kimio Tsubono

Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

*matsumoto@granite.phys.s.u-tokyo.ac.jp

Opt. Express 22, 12915 (2014)

- Our strategy for reaching the SQL

Key feature:

Optical positive torsional spring effect

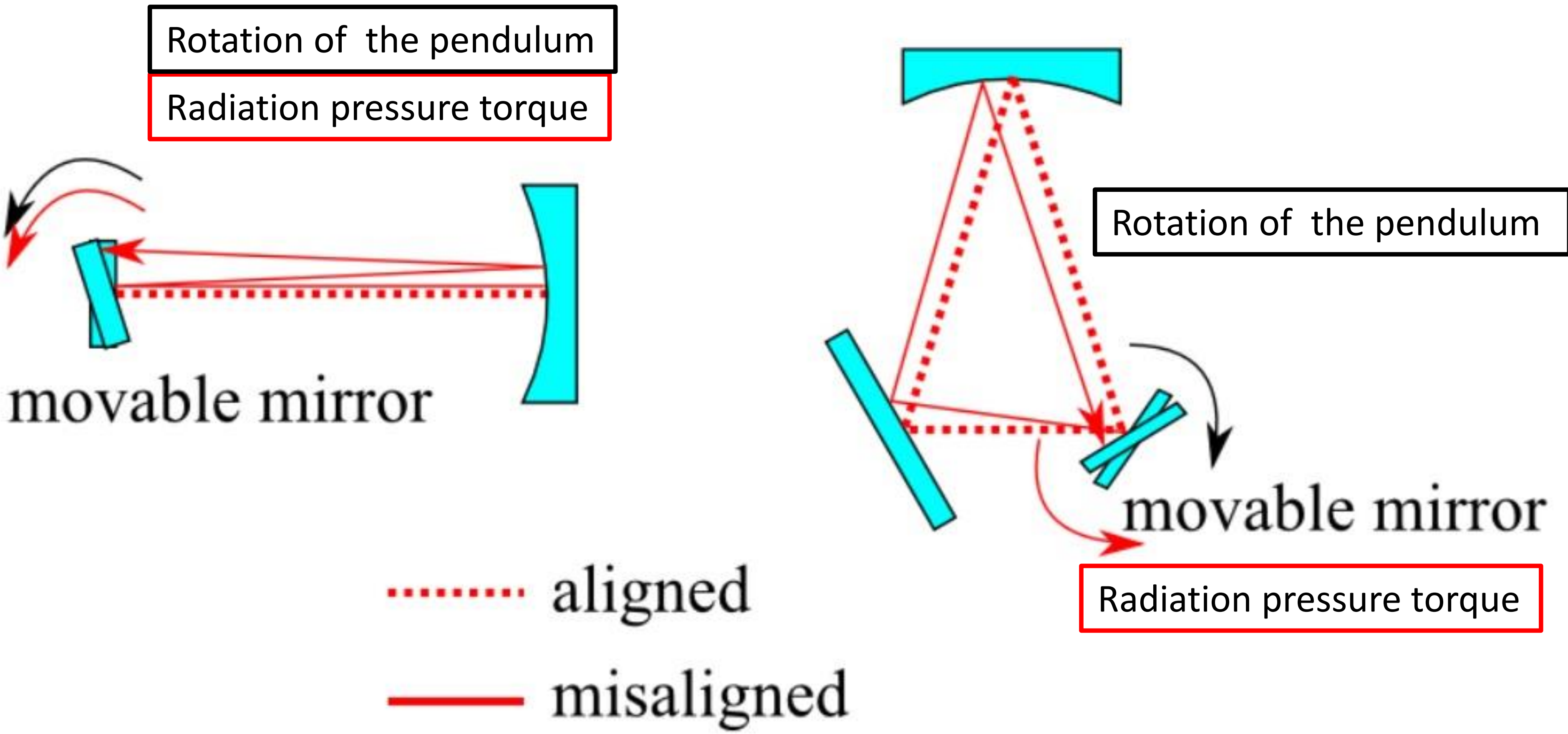
(triangular optical cavity)

⇒Large gravitational dilution under high circulating power

The difference between linear and triangular cavities

Anti-restoring force

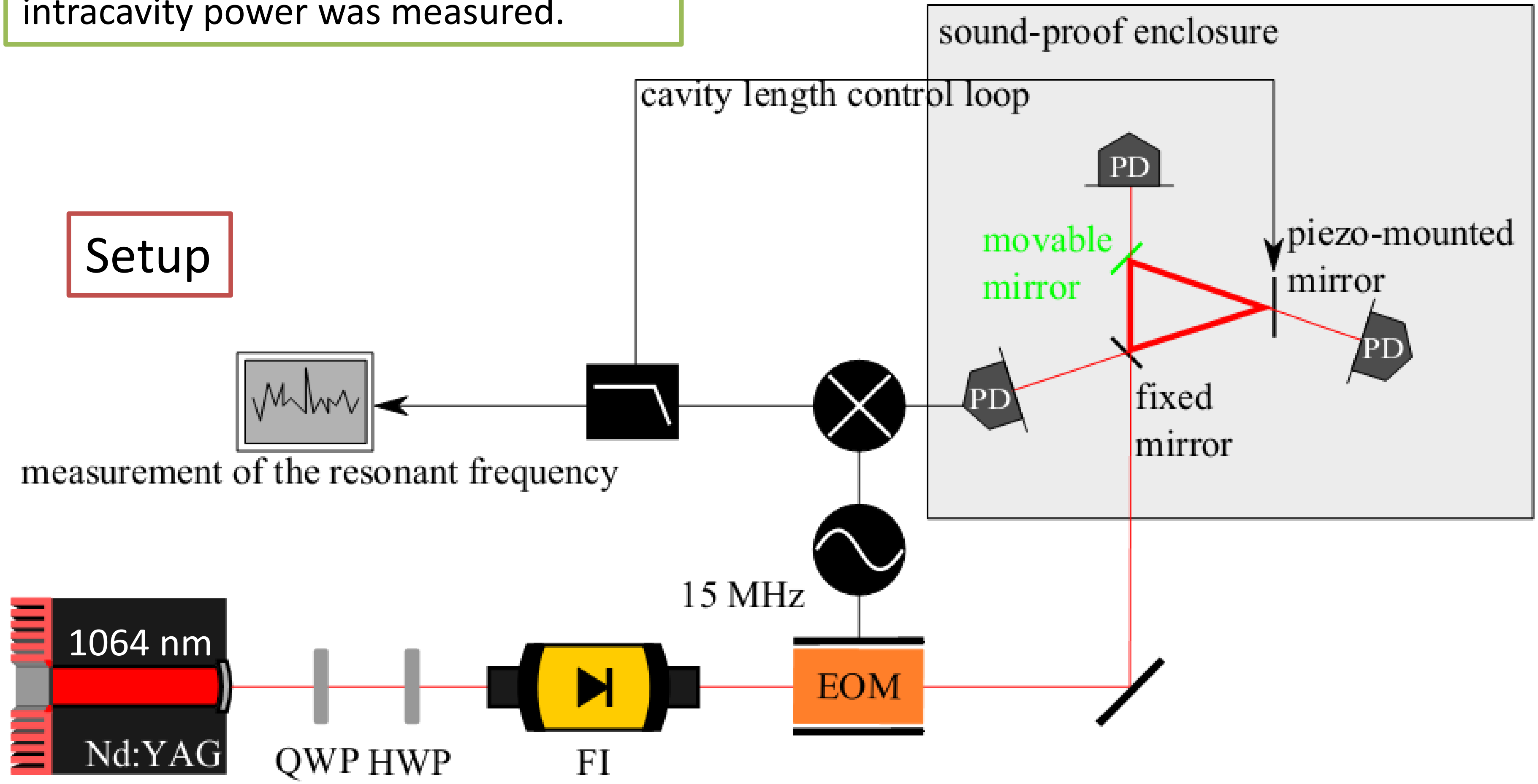
Restoring force?



Measurement of an optical torsional spring in a triangular cavity

The change of the resonant frequency of the yaw motion with increasing the intracavity power was measured.

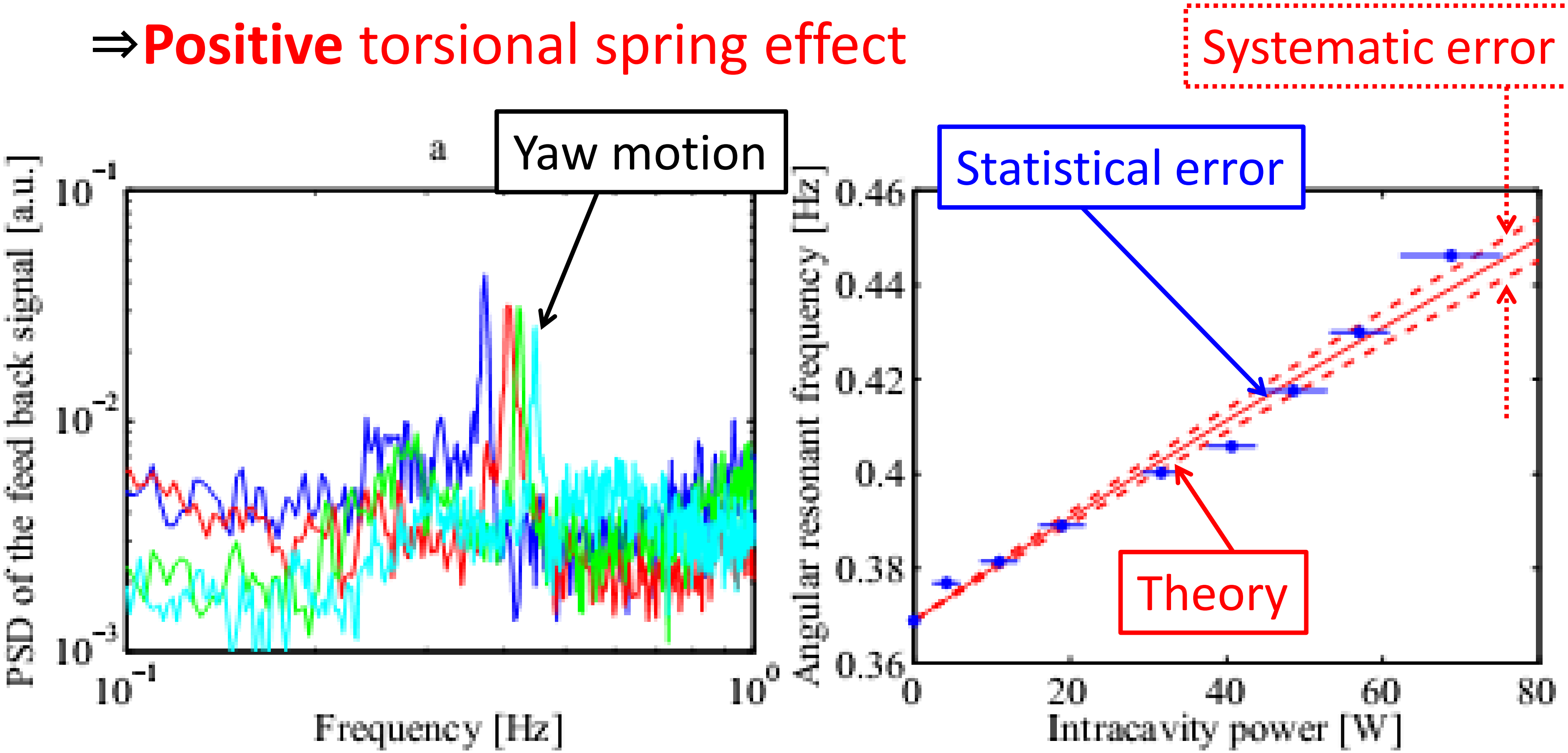
Setup



Measurement of an optical torsional spring in a triangular cavity

- The change of the resonant frequency (yaw motion) with increasing the intracavity power

⇒**Positive** torsional spring effect



The second half

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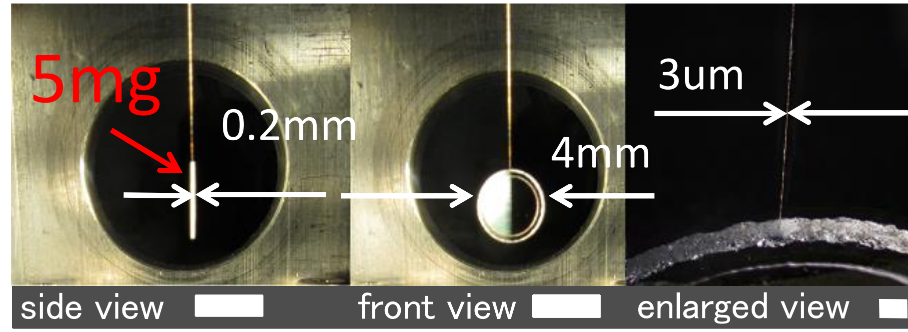
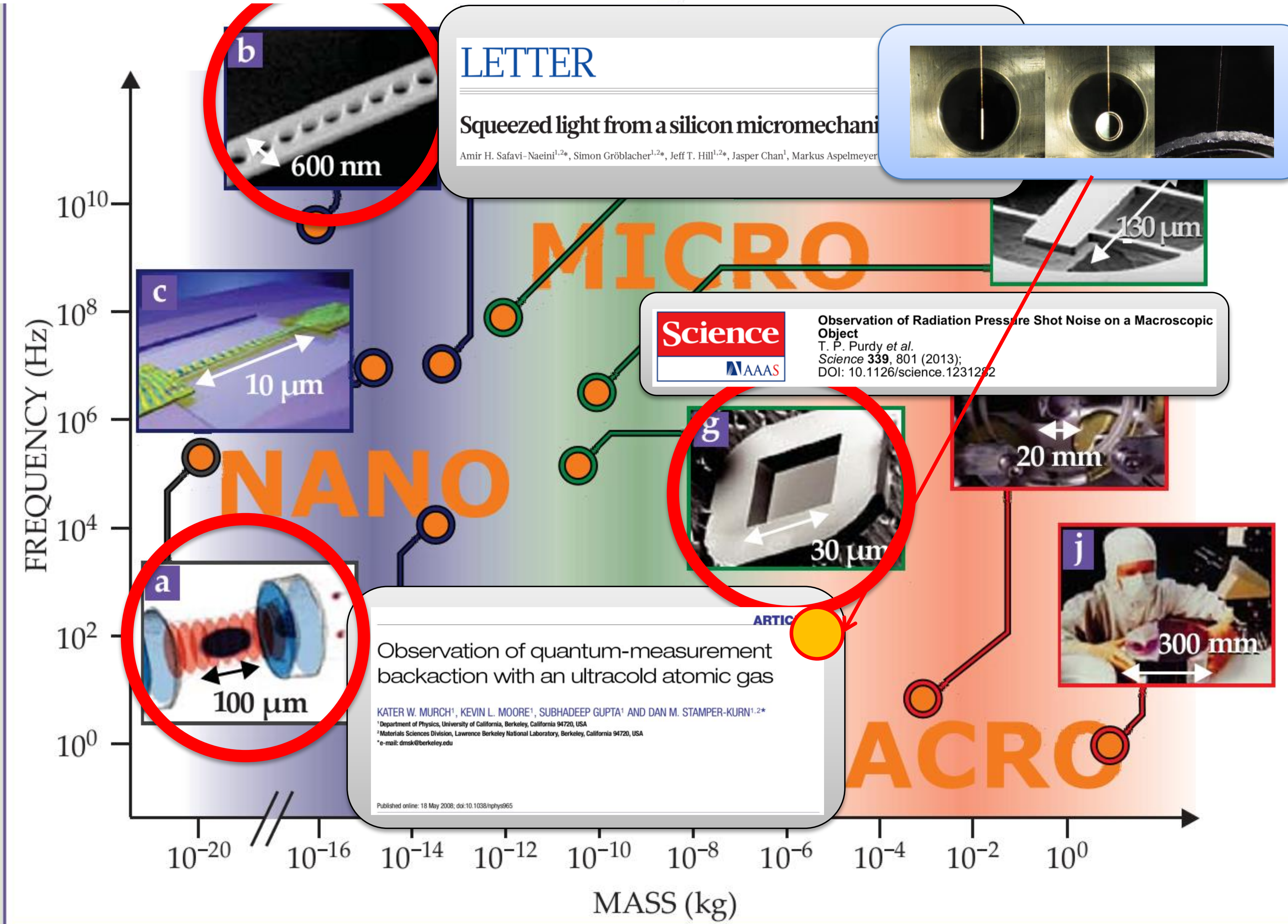


- Parts of the measurement is underway to show validity of our result. (error evaluation of the mechanical Q-factor, frequency noise)
- Our strategy for reaching the RPN

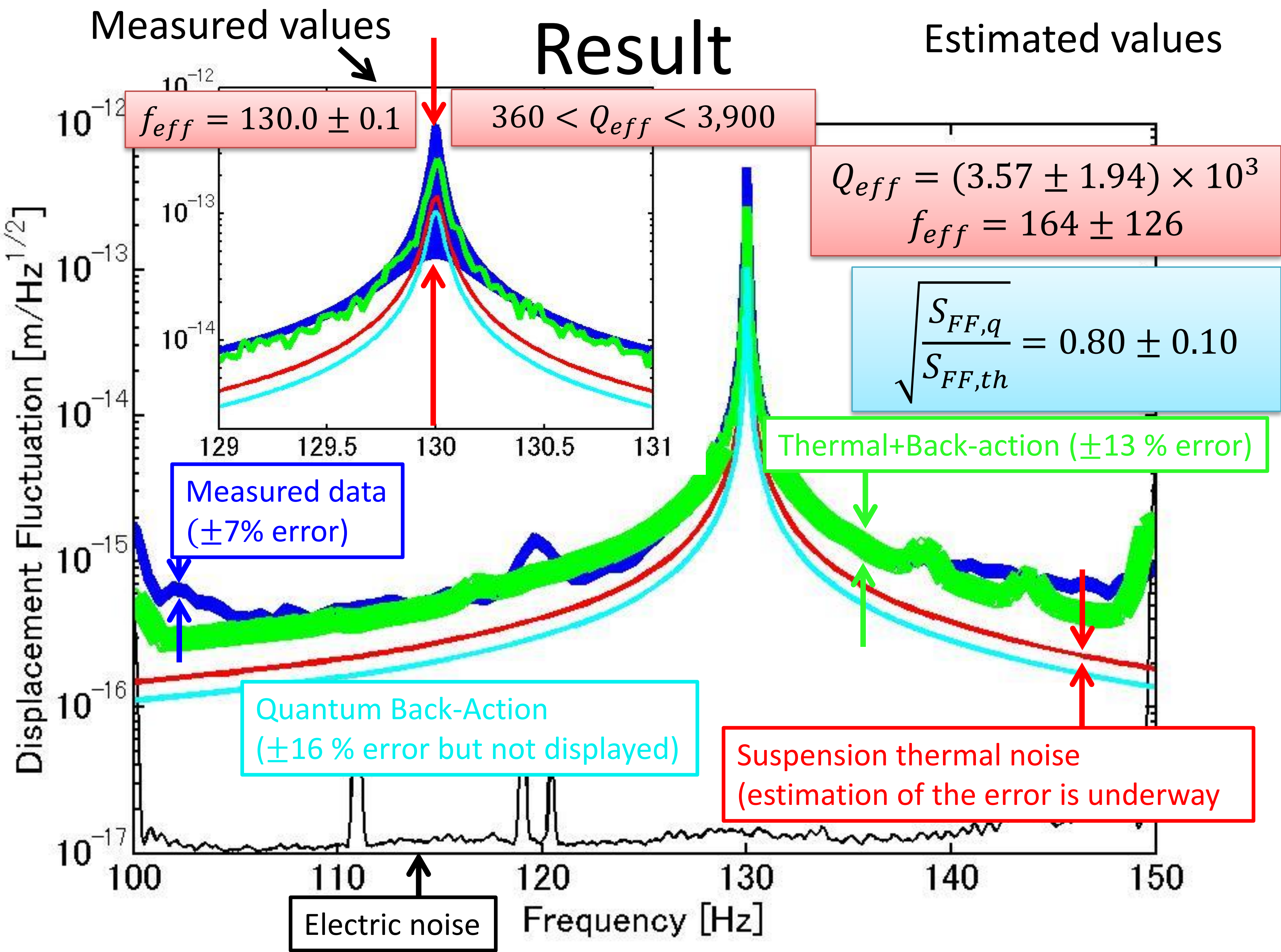
Key features:

- Optical positive torsional spring effect
- Gravitational dilution
- Double optical spring (Optical dilution)

Phys. Today **65**(7), 29 (2012); doi: 10.1063/PT.3.1640



Result



Measured values
Estimated values
$f_{eff} = 130.0 \pm 0.1$
$360 < Q_{eff} < 3,900$
$Q_{eff} = (3.57 \pm 1.94) \times 10^3$
$f_{eff} = 164 \pm 126$
$\sqrt{\frac{S_{FF,q}}{S_{FF,th}}} = 0.80 \pm 0.10$
Thermal+Back-action (±13 % error)
Measured data
(±7% error)
Quantum Back-Action
(±16 % error but not displayed)
Suspension thermal noise
(estimation of the error is underway
Electric noise
Displacement Fluctuation [m/Hz$^{1/2}$]
Frequency [Hz]

Double optical spring

①Triangular cavity

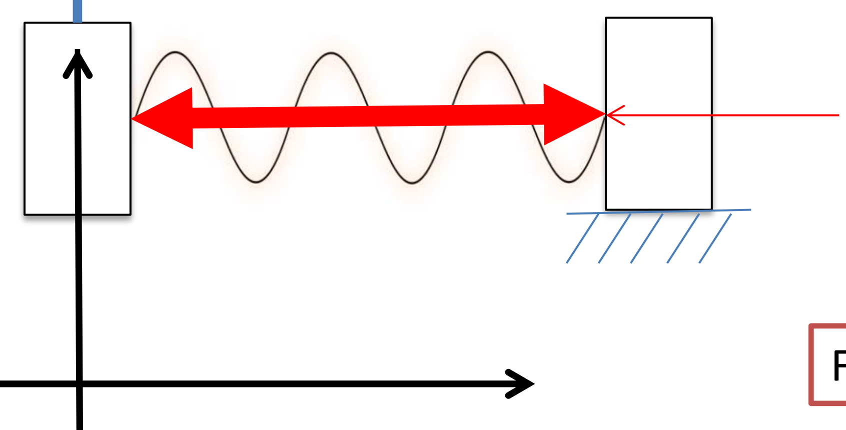
→stability & low dissipation

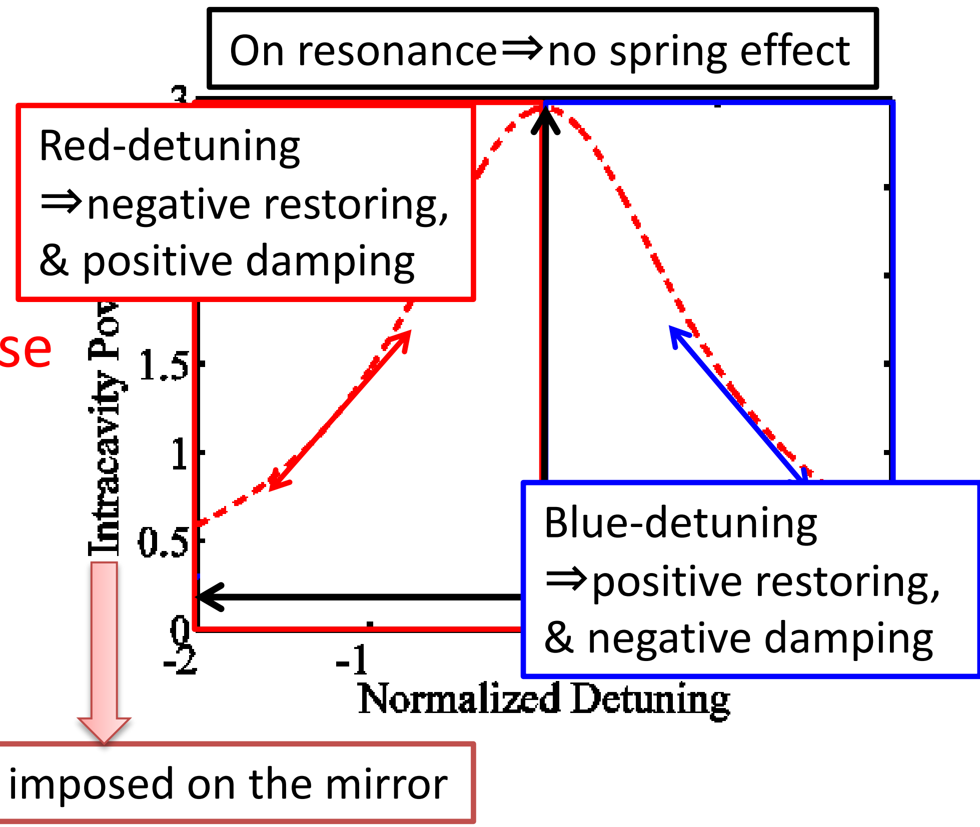
②Stability

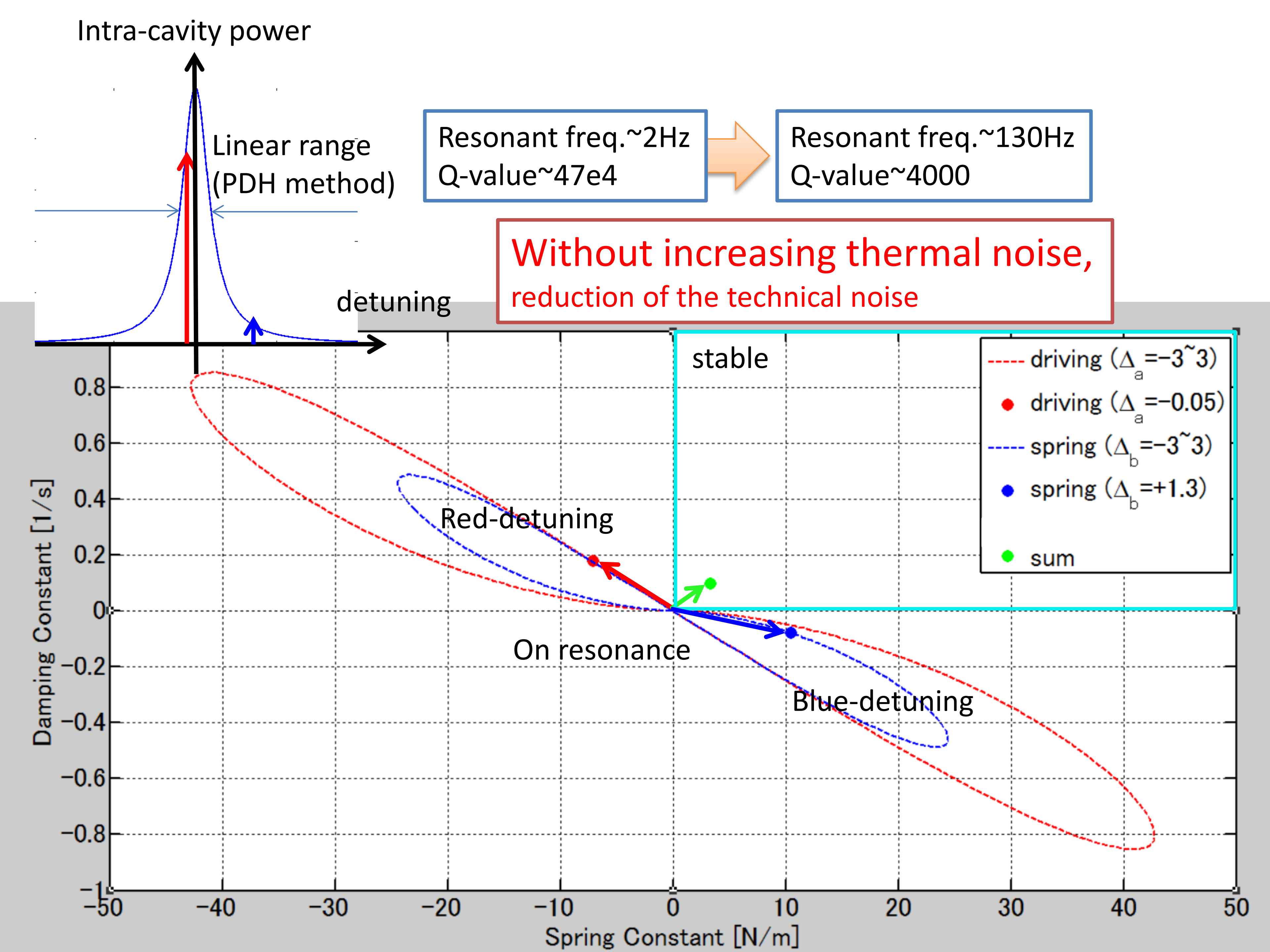
→high intracavity power

→use of（translational） optical spring

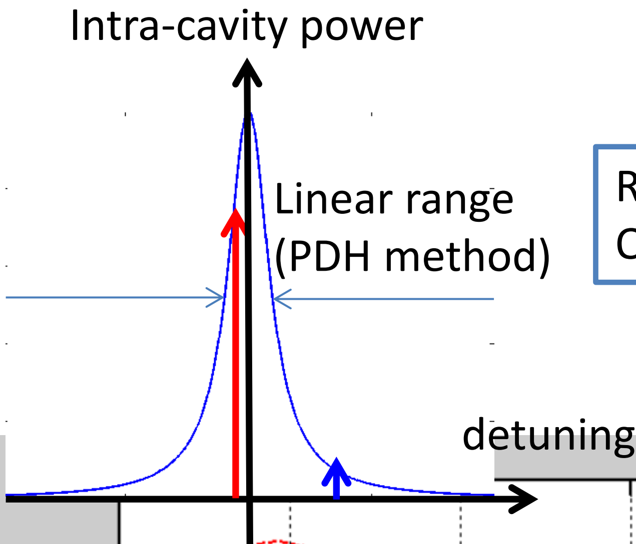
→reduction of the technical noise







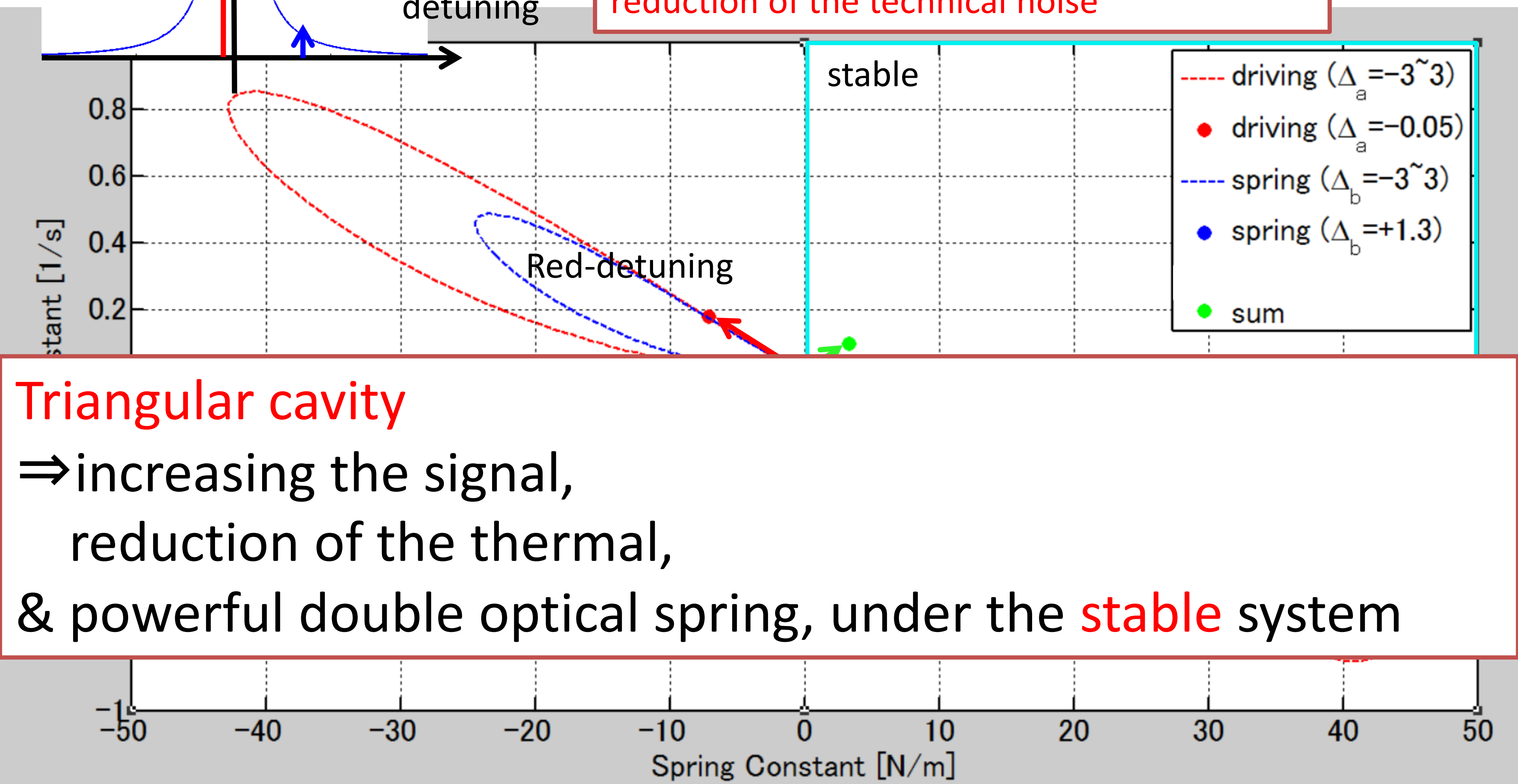
Intra-cavity power
Linear range
(PDH method)
detuning
Resonant freq.~2Hz
Q-value~47e4
Resonant freq.~130Hz
Q-value~4000
Without increasing thermal noise,
reduction of the technical noise
stable
driving (Δa=−3~3)
driving (Δa=−0.05)
spring (Δb=−3~3)
spring (Δb=+1.3)
sum
Red-detuning
On resonance
Blue-detuning
Damping Constant [1/s]
Spring Constant [N/m]



Resonant freq.~2Hz
Q-value~47e4

Resonant freq.~130Hz
Q-value~4000

Without increasing thermal noise,
reduction of the technical noise



Triangular cavity

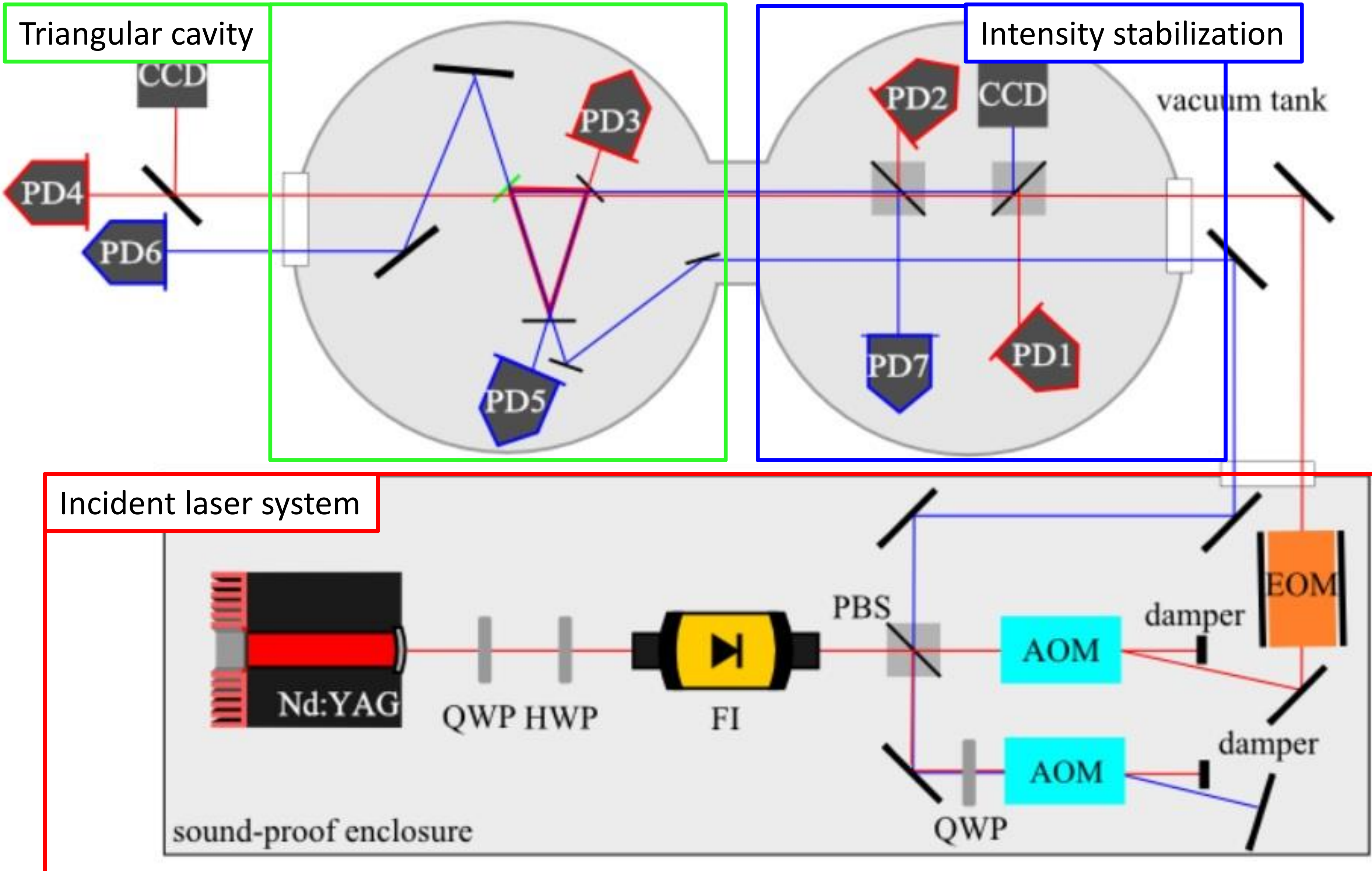
⇒increasing the signal,
reduction of the thermal,
& powerful double optical spring, under the stable system

Details of the experiment

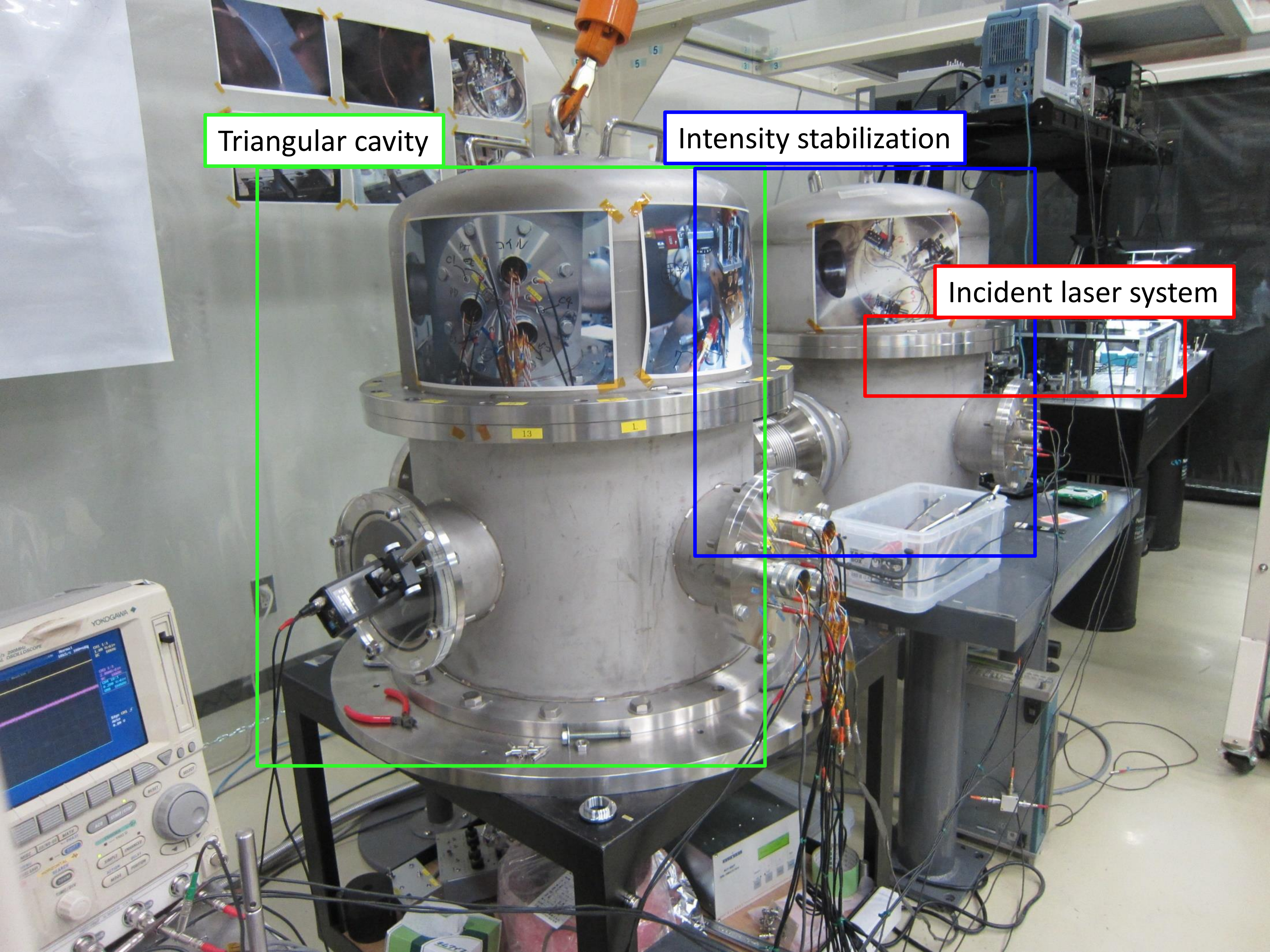
Main experiment

i. Setup
ii. Measurement of the cavity linewidth
iii. Measurement of an optical spring
iv. Quality factor of the pendulum
v. Intensity stabilization of the laser
vi. Calibration

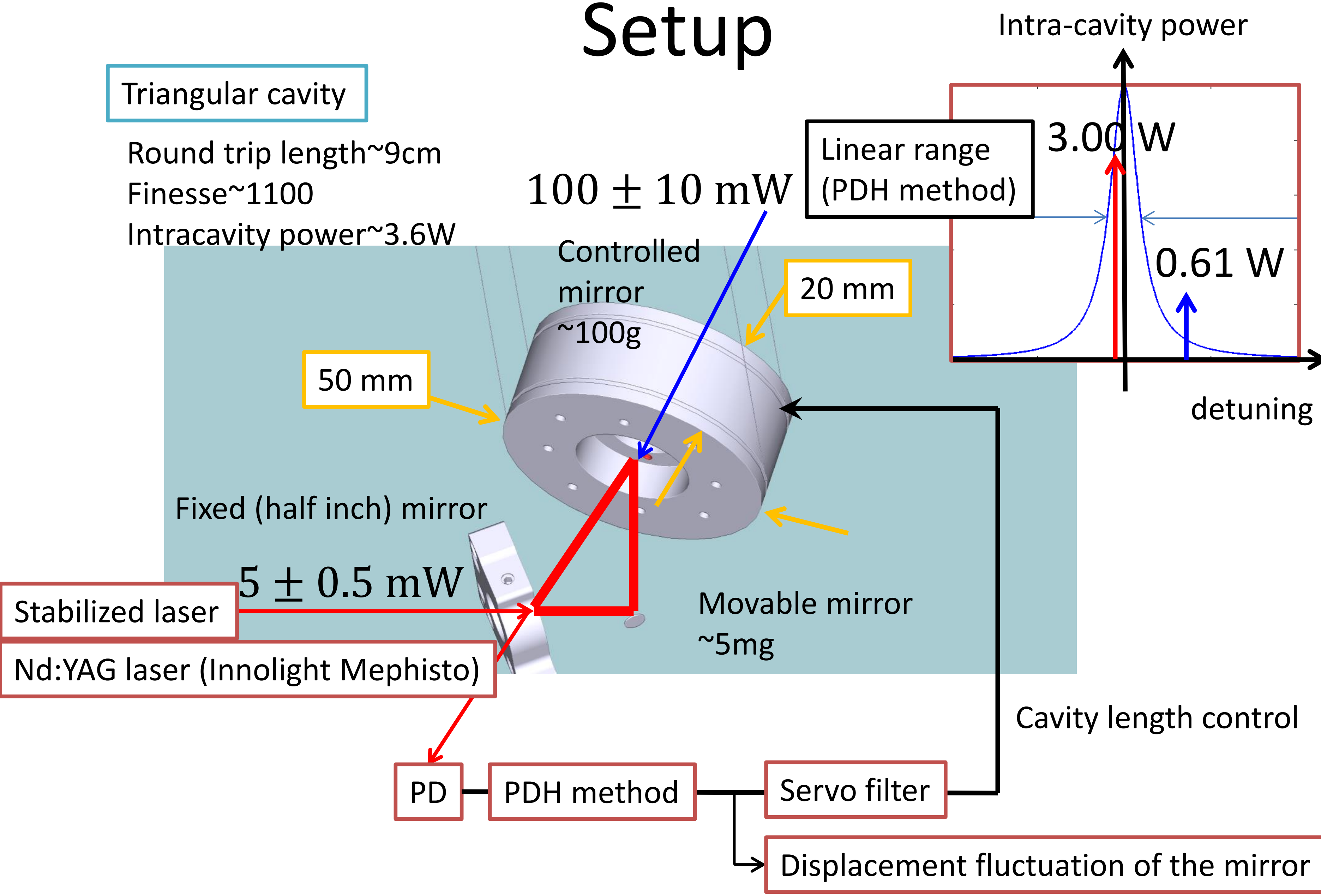
Setup



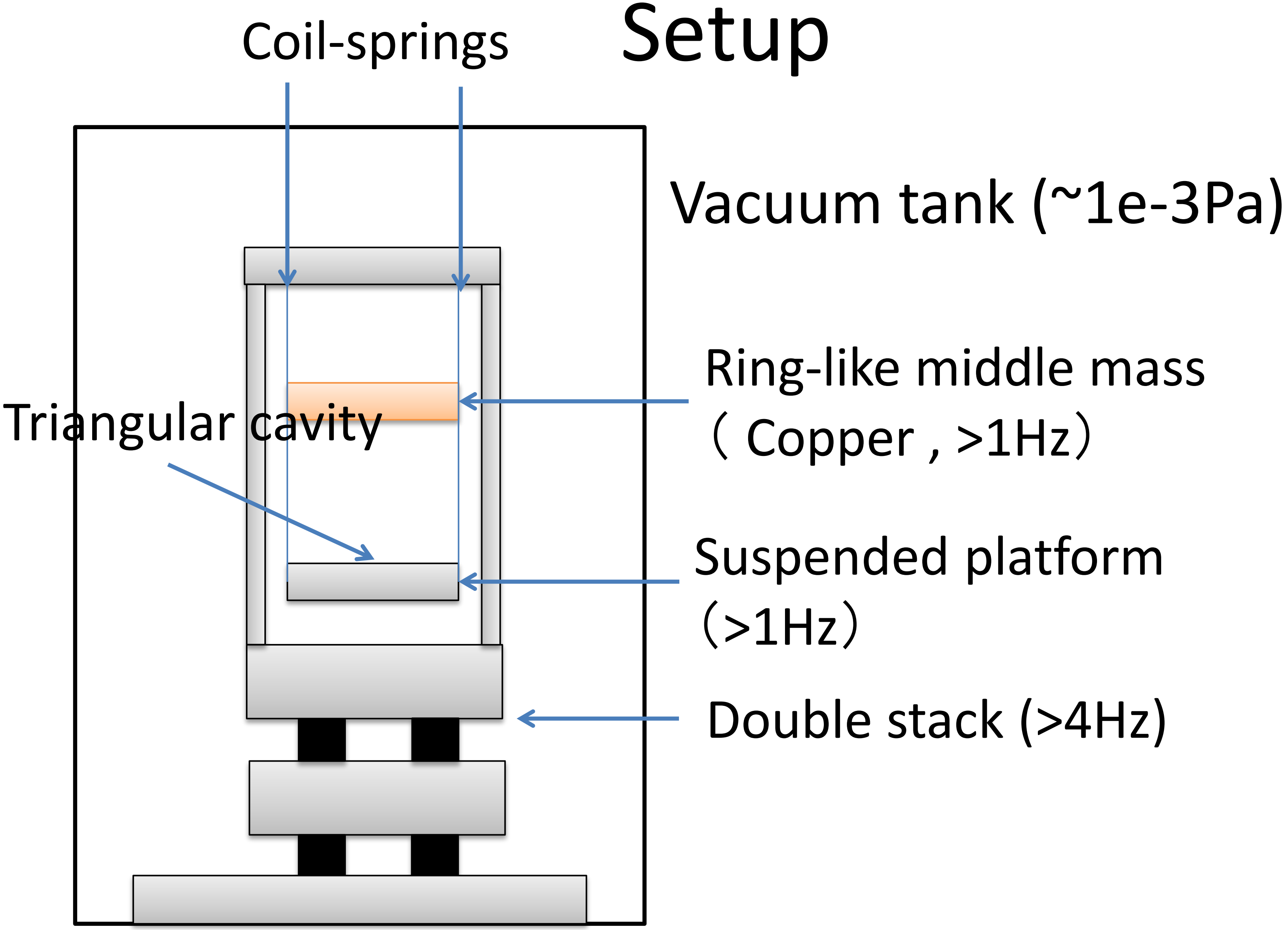
Triangular cavity
Intensity stabilization
CCD
PD2
CCD
vacuum tank
PD3
PD4
PD6
PD7
PD1
PD5
Incident laser system
EOM
PBS
damper
Nd:YAG
AOM
QWP HWP
FI
damper
AOM
QWP
sound-proof enclosure

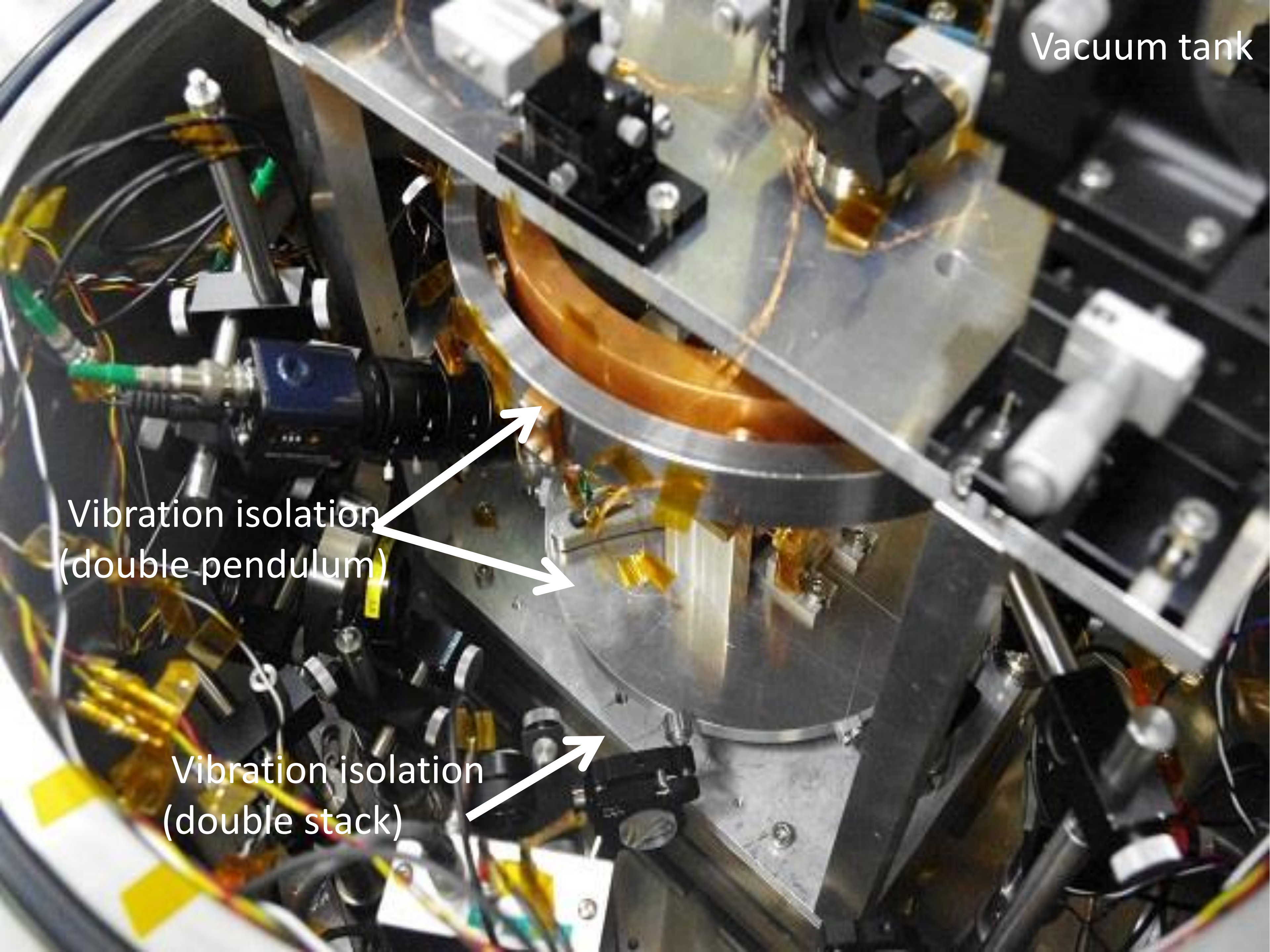

Triangular cavity
Intensity stabilization
Incident laser system

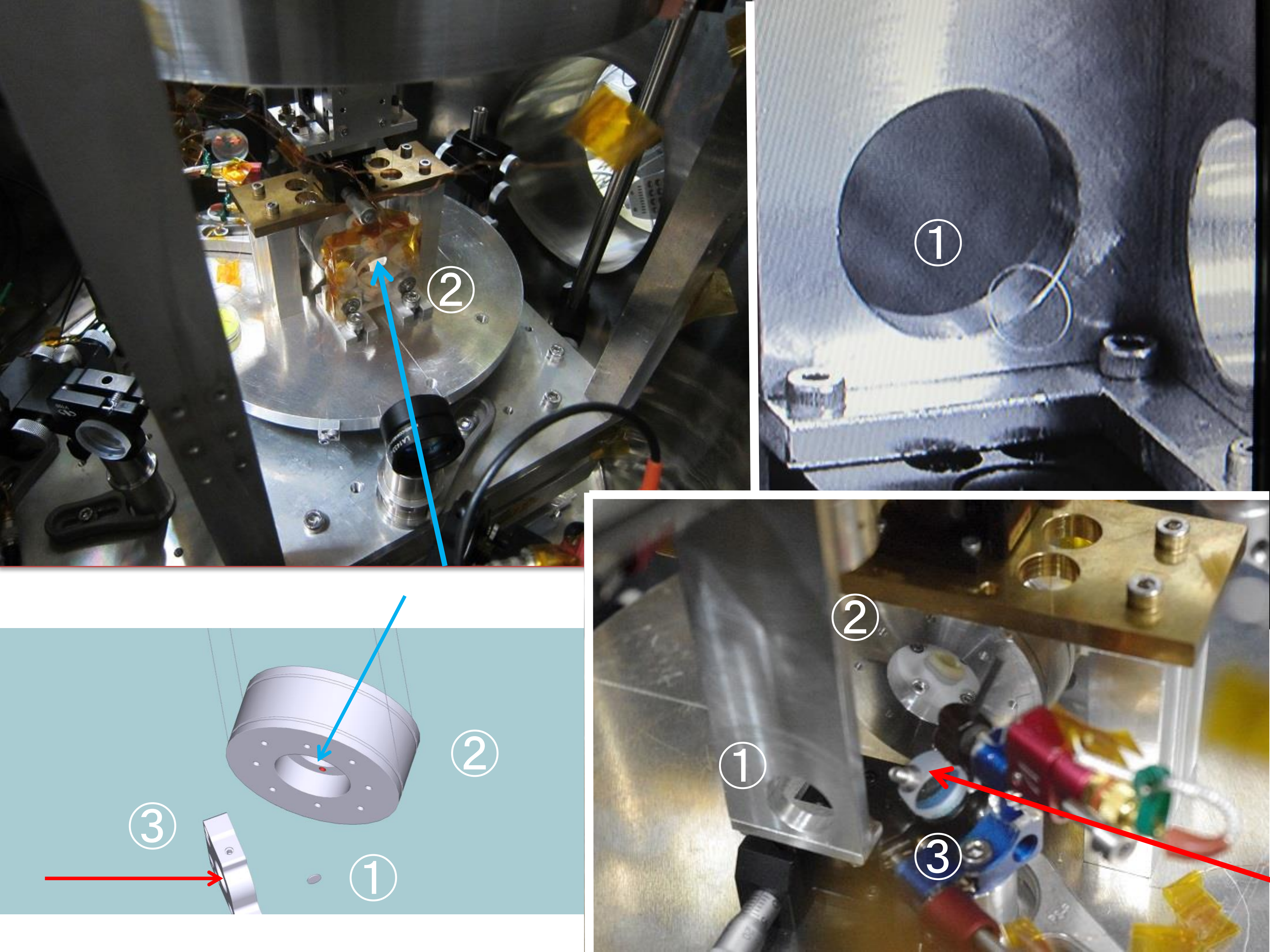
Setup


Triangular cavity
Round trip length~9cm
Finesse~1100
Intracavity power~3.6W
Intra-cavity power
3.00 W
0.61 W
detuning
Linear range
(PDH method)
100 ± 10 mW
Controlled
mirror
~100g
20 mm
50 mm
Fixed (half inch) mirror
5 ± 0.5 mW
Stabilized laser
Nd:YAG laser (Innolight Mephisto)
Movable mirror
~5mg
Cavity length control
PD
PDH method
Servo filter
Displacement fluctuation of the mirror

Setup


Coil-springs
Vacuum tank (~1e-3Pa)
Ring-like middle mass
(Copper , >1Hz)
Triangular cavity
Suspended platform
(>1Hz)
Double stack (>4Hz)


Vacuum tank
Vibration isolation
(double pendulum)
Vibration isolation
(double stack)



②
①
②
①
③
②
③
①

Details of the experiment

Main experiment

i. Setup

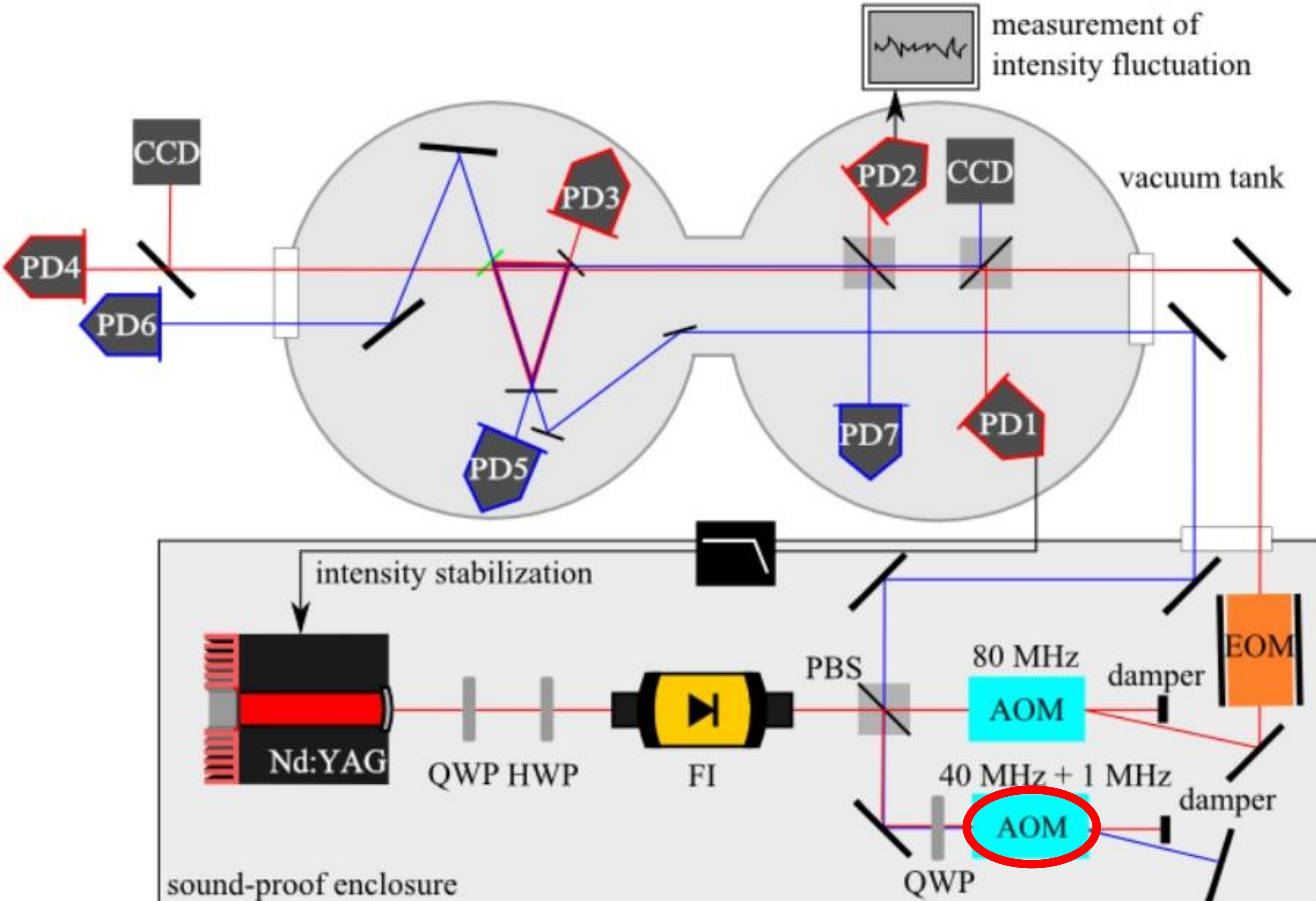
ii. Measurement of the cavity linewidth
⇒Estimation of the signal level

iii. Property measurement of the optical spring
⇒Estimation of the signal level

iv. Quality factor of the pendulum
⇒Estimation of the thermal noise level

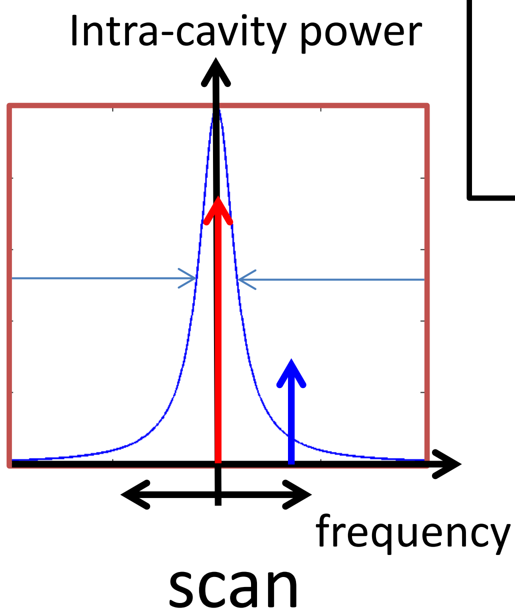
v. Intensity stabilization of the laser
⇒Elimination of the classical noise of the light

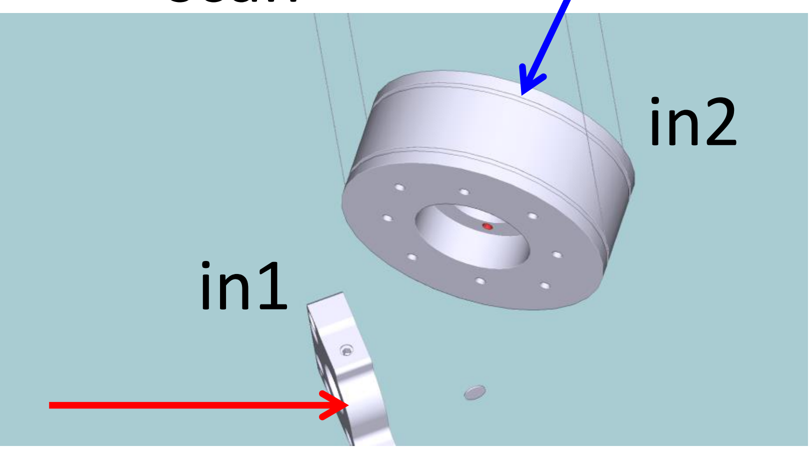
vi. calibration

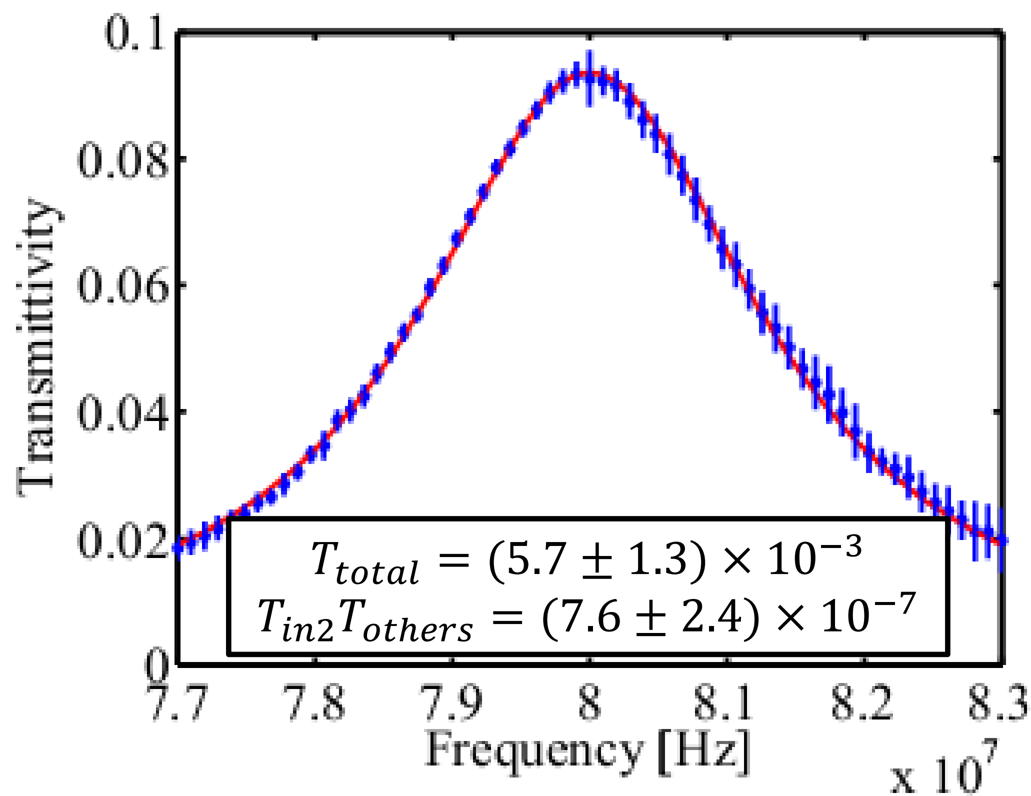

measurement of
intensity fluctuation
CCD
PD2
CCD
PD3
vacuum tank
PD4
PD6
PD5
PD7
PD1
intensity stabilization
Nd:YAG
QWP HWP
FI
PBS
80 MHz
AOM
damper
EOM
40 MHz + 1 MHz
AOM
damper
QWP
sound-proof enclosure

cavity decay rate	$\kappa/2\pi$	Hz	$(1.52 \pm 0.03) \times 10^6$
cavity decay rate (in1)	$\kappa_{\mathrm{in1}}/2\pi$	Hz	$(1.30 \pm 0.03) \times 10^6$
cavity decay rate (in2)	$\kappa_{\mathrm{in2}}/2\pi$	Hz	$(3.64 \pm 2.46) \times 10^4$

$$
\begin{aligned}
S^{(2)}_{\mathrm{FF,q}} &= \langle \delta \hat{F}_{\mathrm{BA}}(-\omega)\delta \hat{F}_{\mathrm{BA}}(\omega)\rangle \\
&= 2\hbar^2\kappa|G_{\mathrm{a}}|^2|\chi_{\mathrm{a}}(-\omega)|^2 + 2\hbar^2\kappa|G_{\mathrm{b}}|^2|\chi_{\mathrm{b}}(-\omega)|^2 \\
&= 2N_{\mathrm{in1,circ}}\frac{\hbar^2 g^2}{\kappa}\left(1+\left(\frac{\omega+\Delta_{\mathrm{a}}}{\kappa}\right)^2\right)^{-1} + 2N_{\mathrm{in2,circ}}\frac{\hbar^2 g^2}{\kappa}\left(1+\left(\frac{\omega+\Delta_{\mathrm{b}}}{\kappa}\right)^2\right)^{-1}.
\end{aligned}
$$

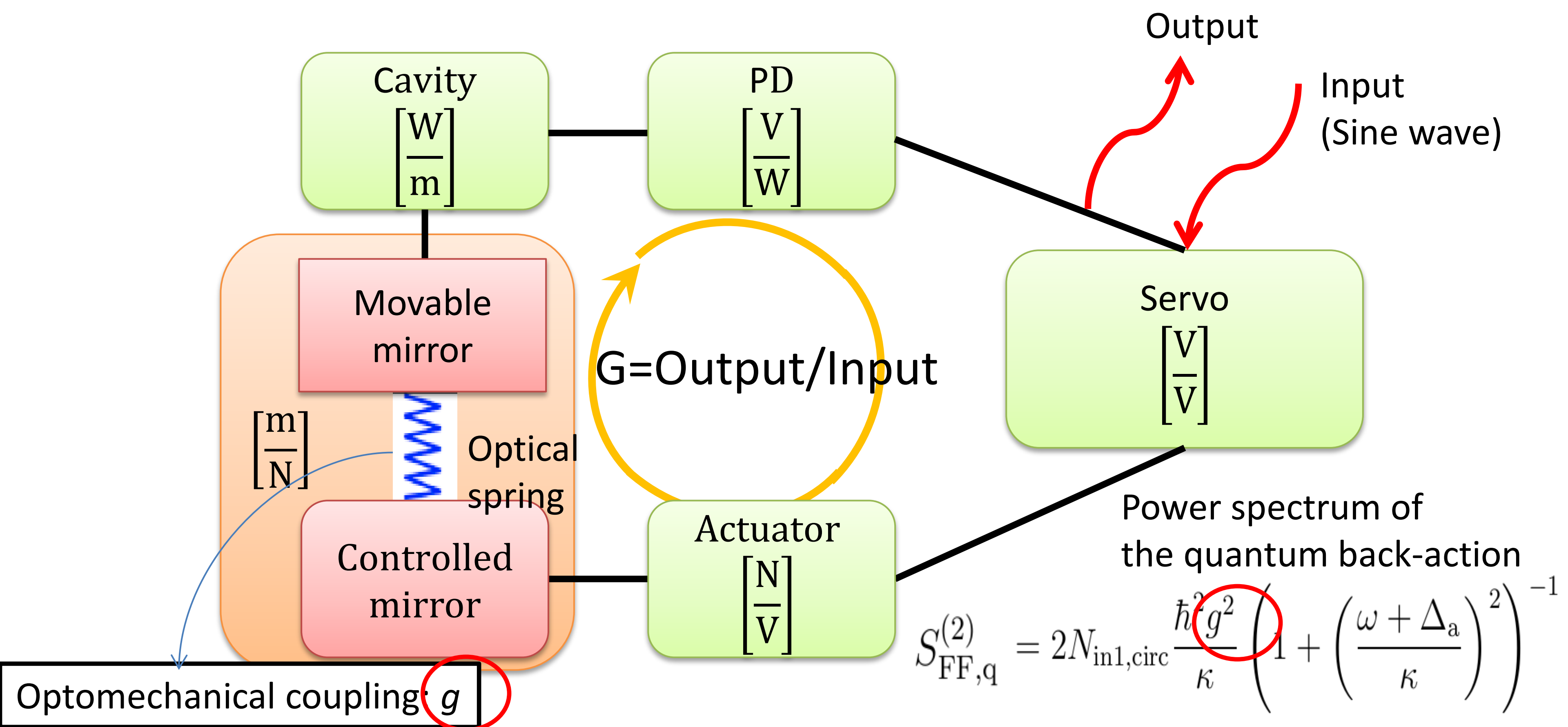




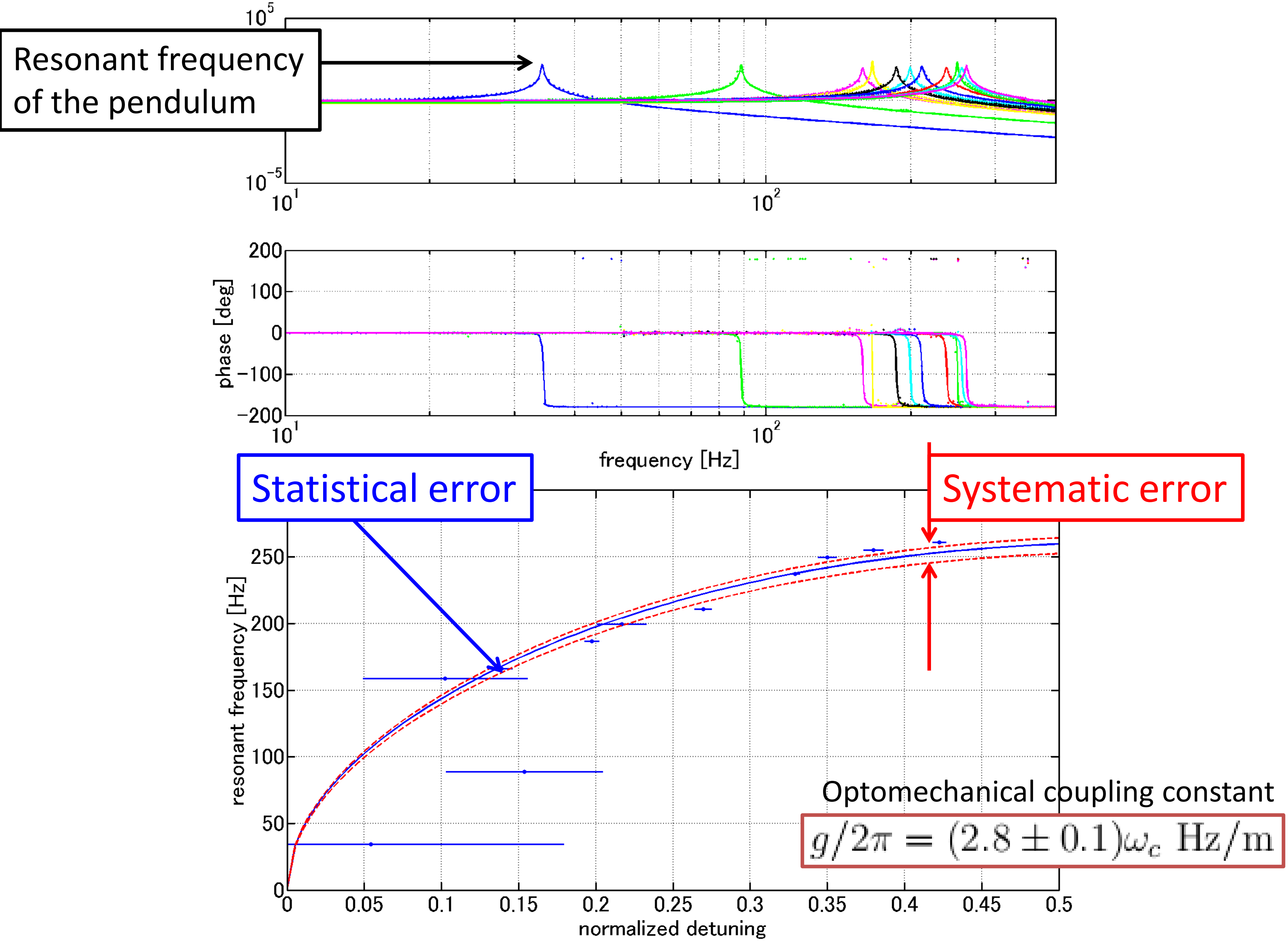


Measurement of the optical spring

Measurement of the optical spring by the open-loop transfer function
1. Disturbance input→ Measurement of a response
2. Offset adjustment of a control signal (detuning adjustment) ⇒returning to 1



$$S^{(2)}_{\mathrm{FF,q}} = 2N_{\mathrm{in1,circ}}\frac{\hbar^2 g^2}{\kappa}\left(1+\left(\frac{\omega+\Delta_{\mathrm{a}}}{\kappa}\right)^2\right)^{-1}$$

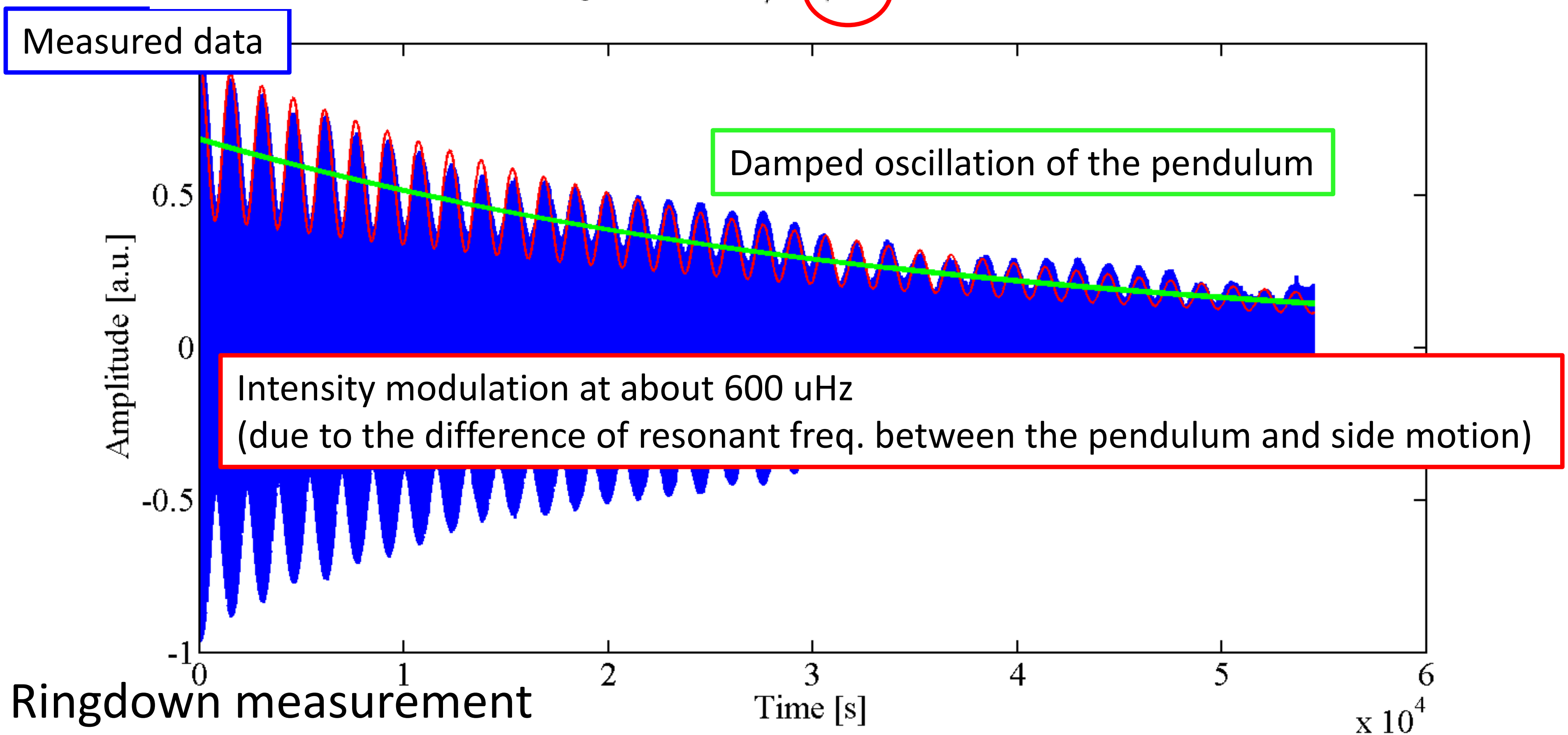


Resonant frequency of the pendulum
10^5
10^-5
10^1
10^2
200
100
0
−100
−200
phase [deg]
frequency [Hz]
Statistical error
Systematic error
resonant frequency [Hz]
250
200
150
100
50
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
normalized detuning
Optomechanical coupling constant
$g/2\pi = (2.8 \pm 0.1)\omega_c$ Hz/m

Quality factor of the pendulum

- Thermal fluctuating force $S^{(2)}_{\mathrm{FF,th}} = 4k_{\mathrm{B}}T\gamma_{\mathrm{m}}m.$
- Damped oscillation→life time⇔mechanical Q-value

⇒ $Q_{\mathrm{m}} = 4.7 \times 10^{5} \quad (Q_{\mathrm{m}} = \omega_{\mathrm{m}}/2\gamma_{\mathrm{m}})$



Ringdown measurement

Error of the quality factor

Q-factor is currently measured to obtain its error by Kentaro Komori.

Improvement for reducing the side motion:

i. the direction of the incident laser on the suspended mirror

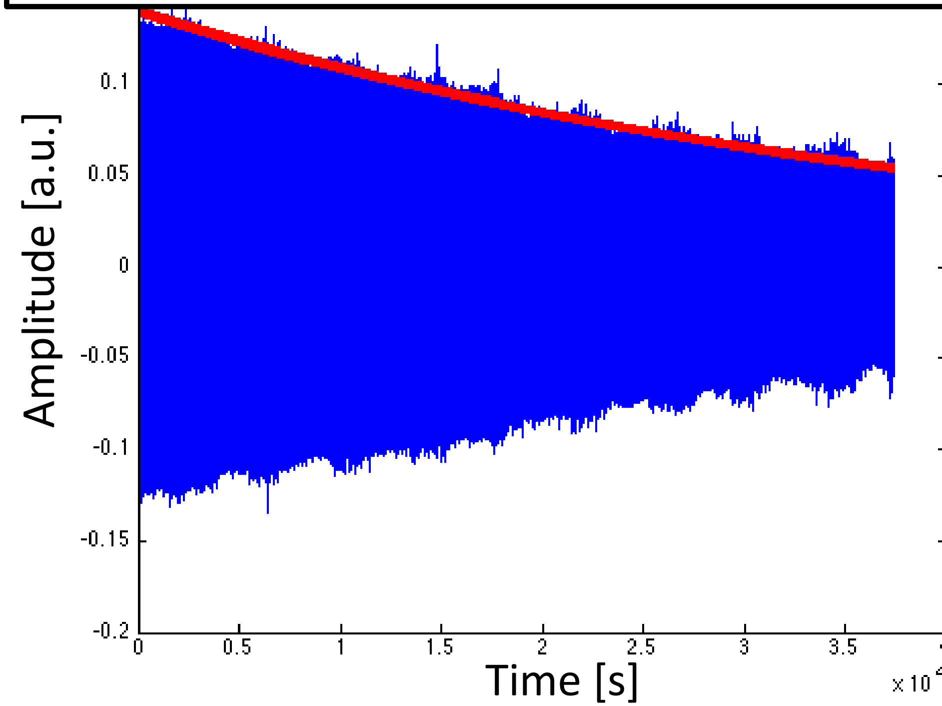
ii. excitation of the pendulum

Komori-kun

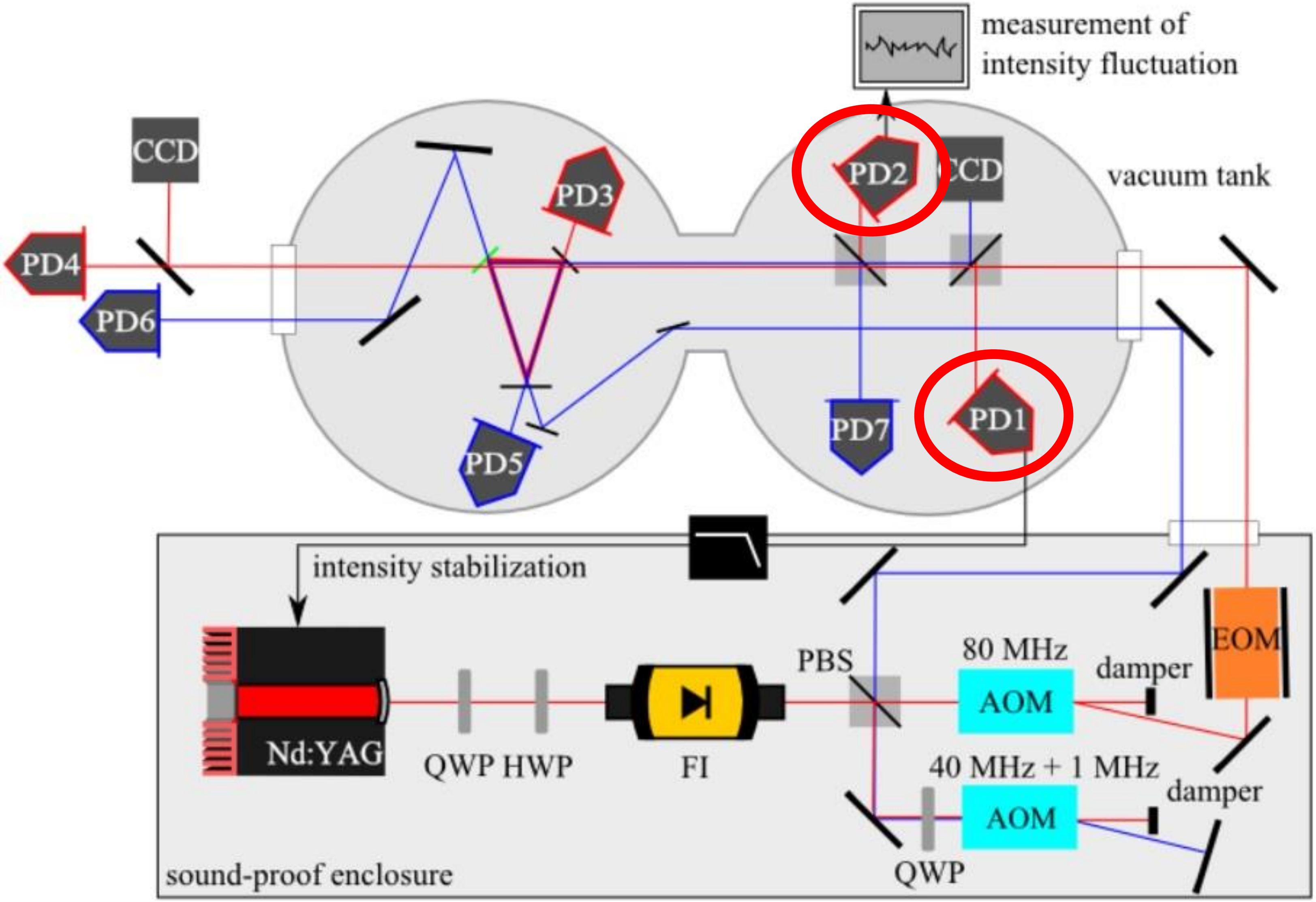
[redacted]

Preliminary result: Q~270,000

(Similar but low-quality pendulum was used)

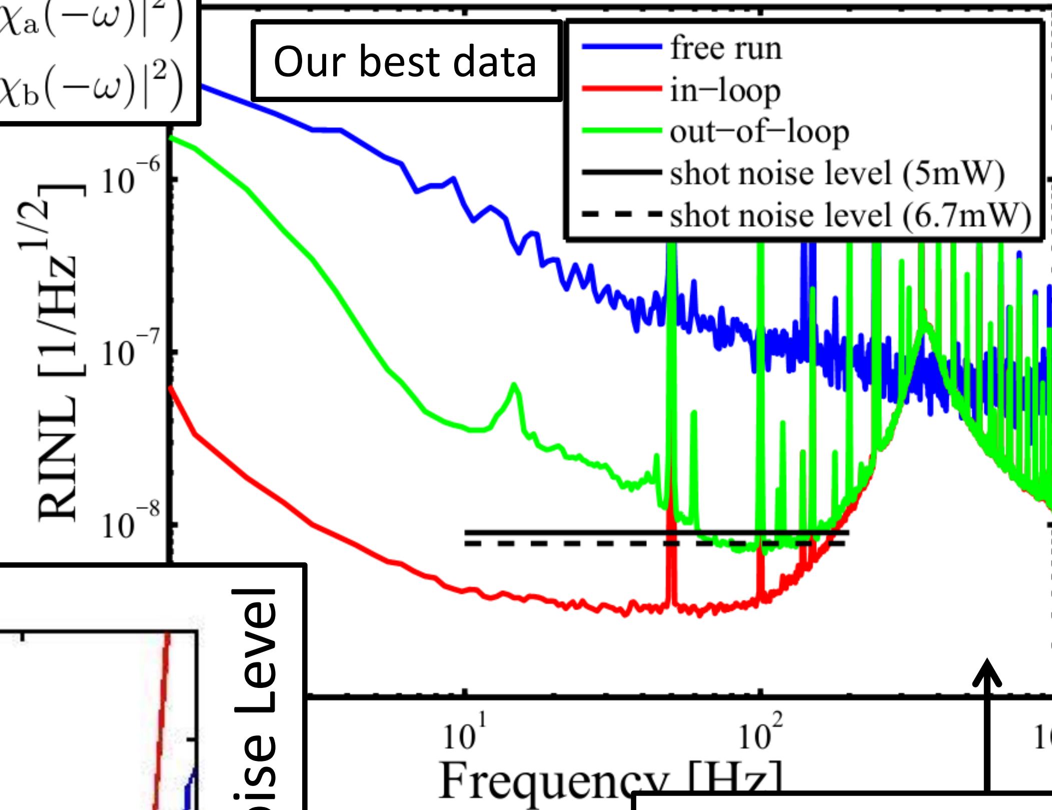


Intensity stabilization of the laser



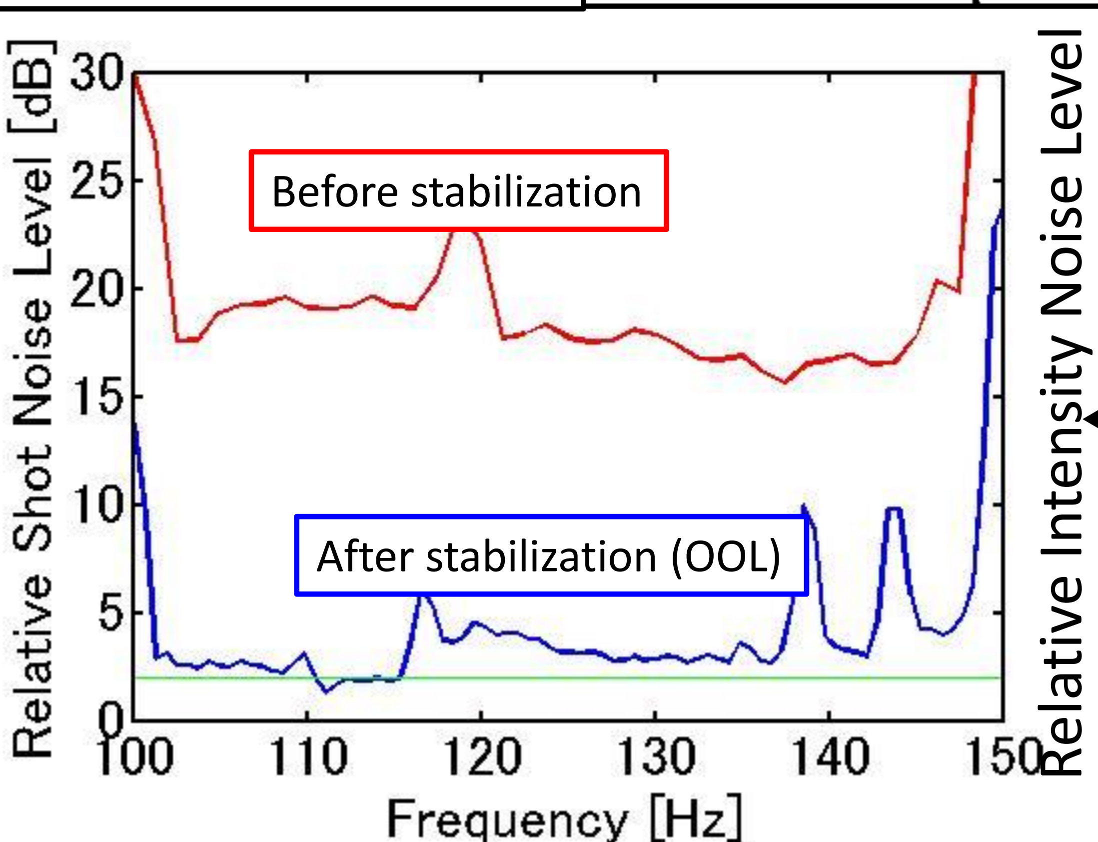
$$S^{(2)}_{\mathrm{FF,c}} = 2(B_{\mathrm{in1}} - 1)\hbar^2\kappa_{\mathrm{in1}}|G_{\mathrm{a}}|^2\left(|\chi_{\mathrm{a}}(\omega)|^2 + |\chi_{\mathrm{a}}(-\omega)|^2\right) + 2(B_{\mathrm{in2}} - 1)\hbar^2\kappa_{\mathrm{in2}}|G_{\mathrm{b}}|^2\left(|\chi_{\mathrm{b}}(\omega)|^2 + |\chi_{\mathrm{b}}(-\omega)|^2\right)$$

Back-action force is enhanced by the classical noise



turbomolecular pumps is switched off

simultaneous measurement



turbomolecular pumps is switched on

Requirement

$1.4 \times 10^{-8}\ [1/\sqrt{\mathrm{Hz}}]$

Details of the experiment

Main experiment

i. Setup
ii. Measurement of the cavity linewidth
⇒Estimation of the signal level
iii. Property measurement of the optical spring
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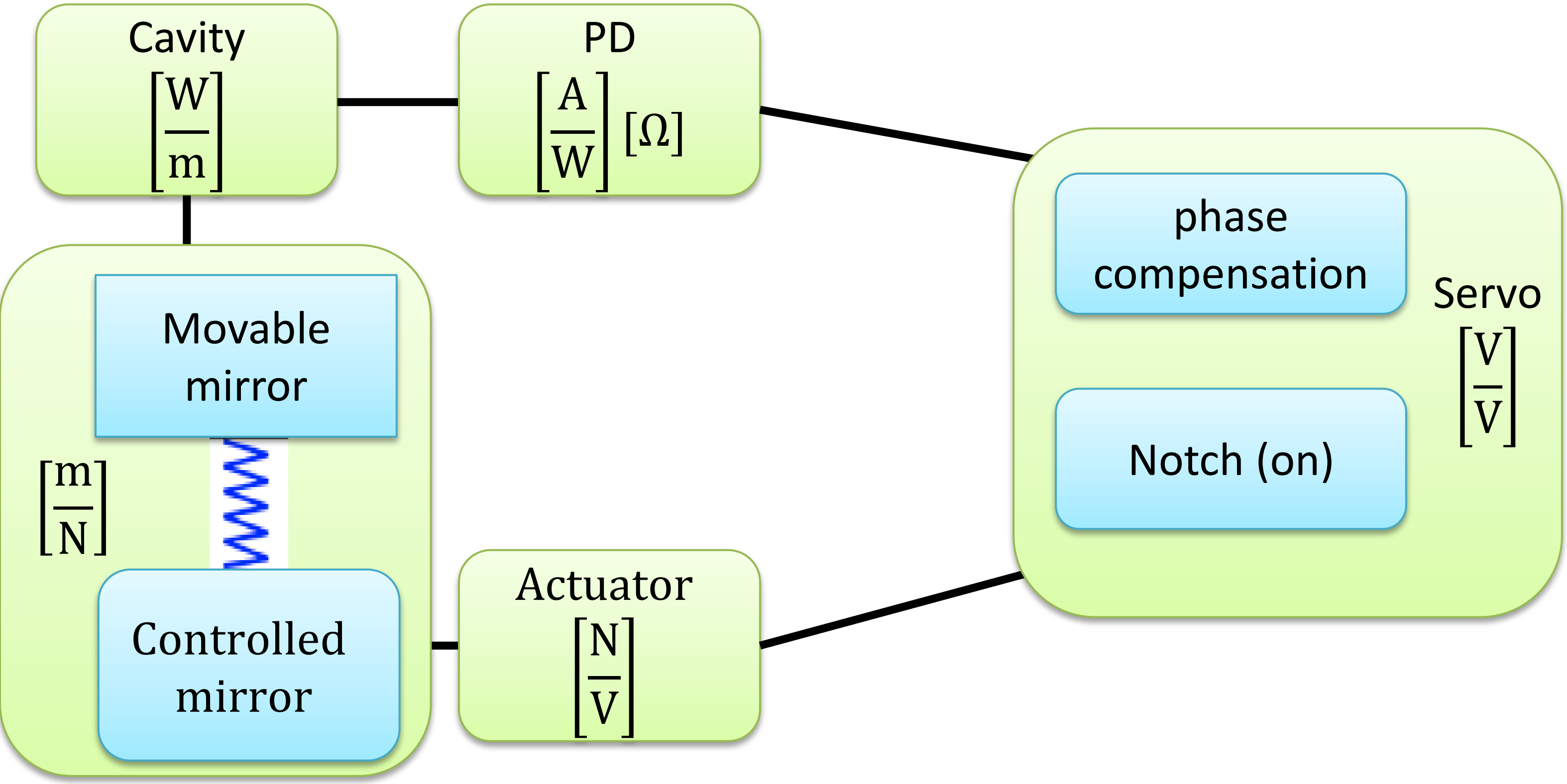
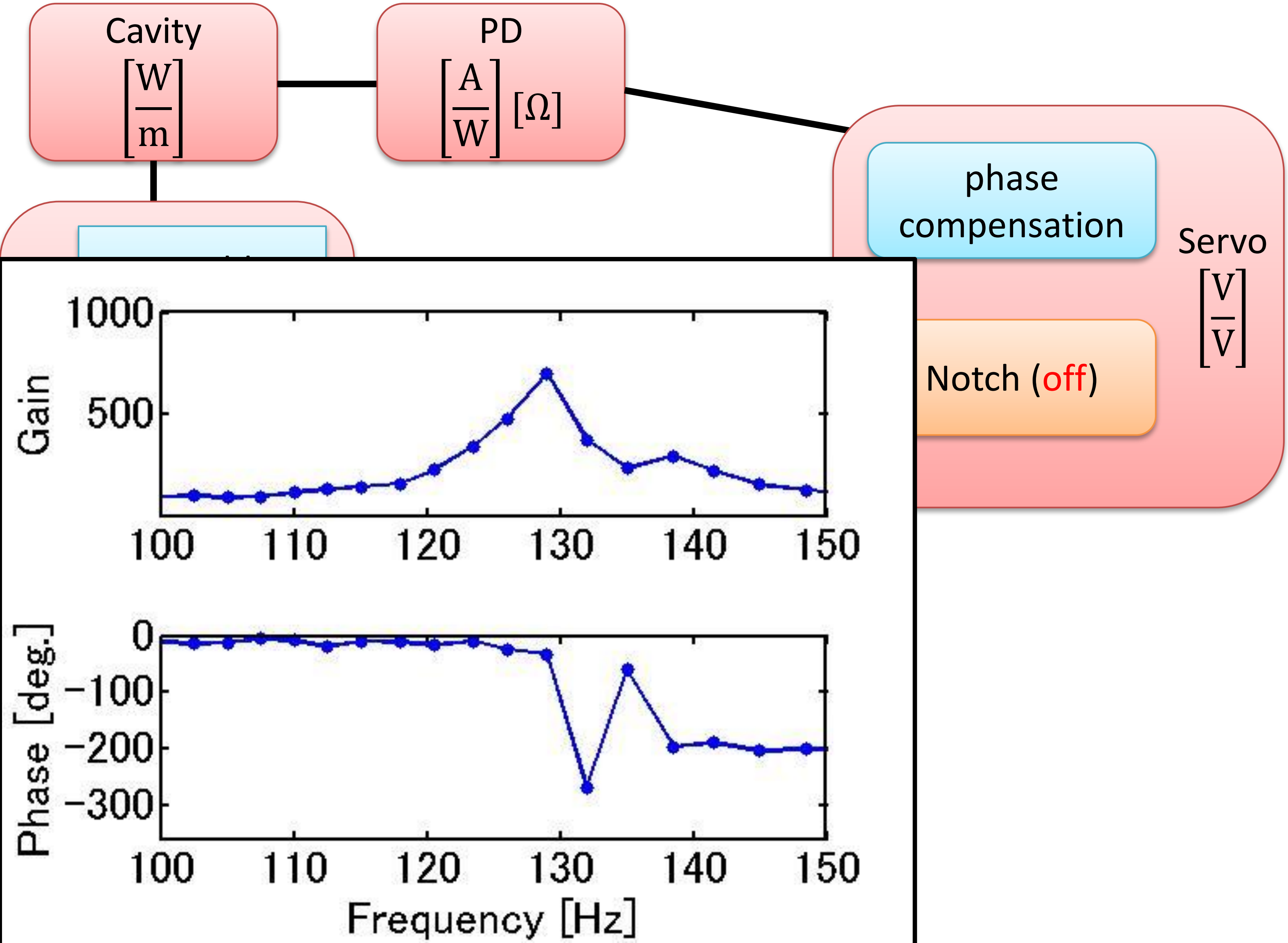
iv. Quality factor of the pendulum
⇒Estimation of the thermal noise level
v. Intensity stabilization of the laser
⇒Elimination of the classical noise of the light
vi. Calibration

Calibration



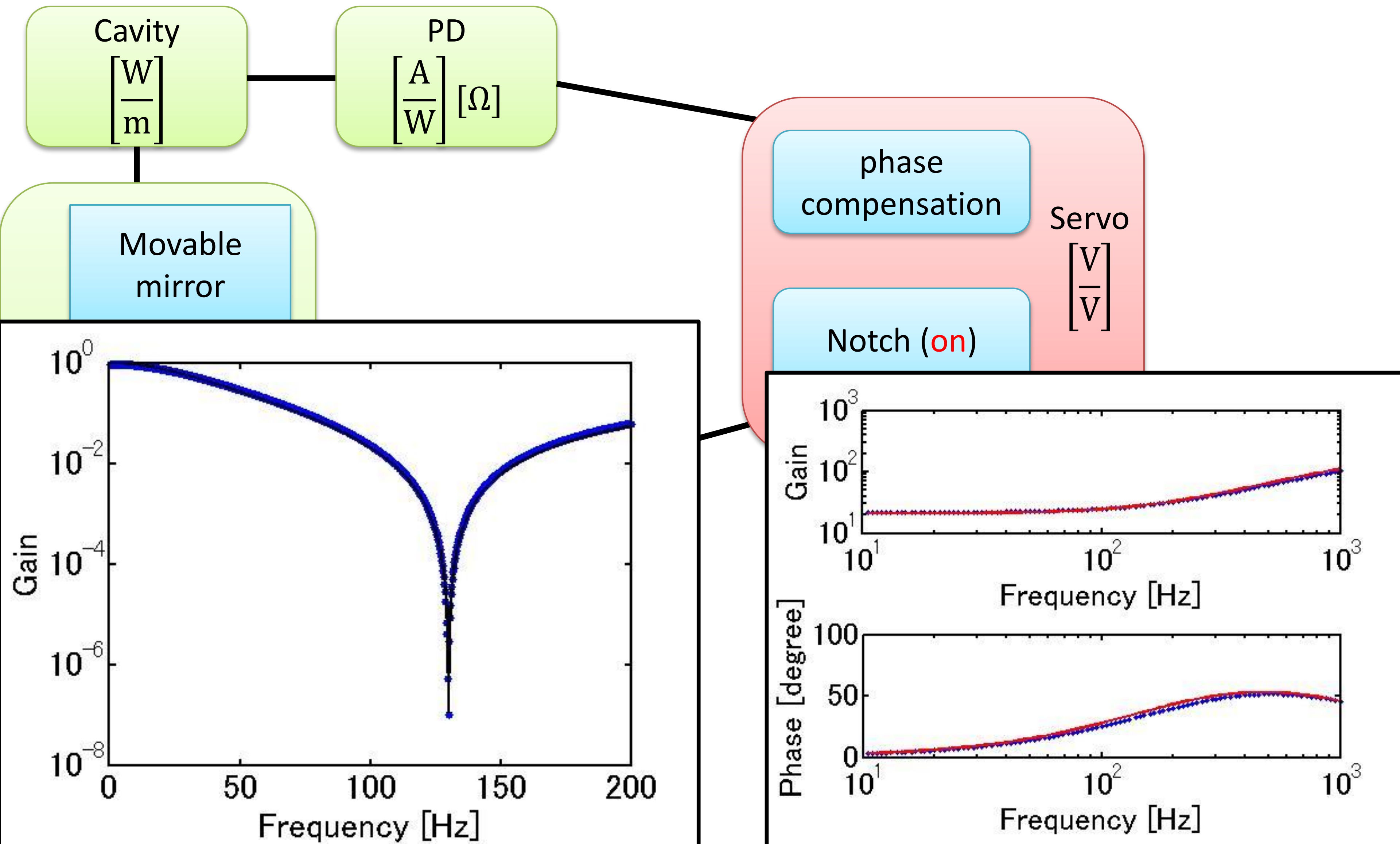
Open-loop transfer function

Calibration

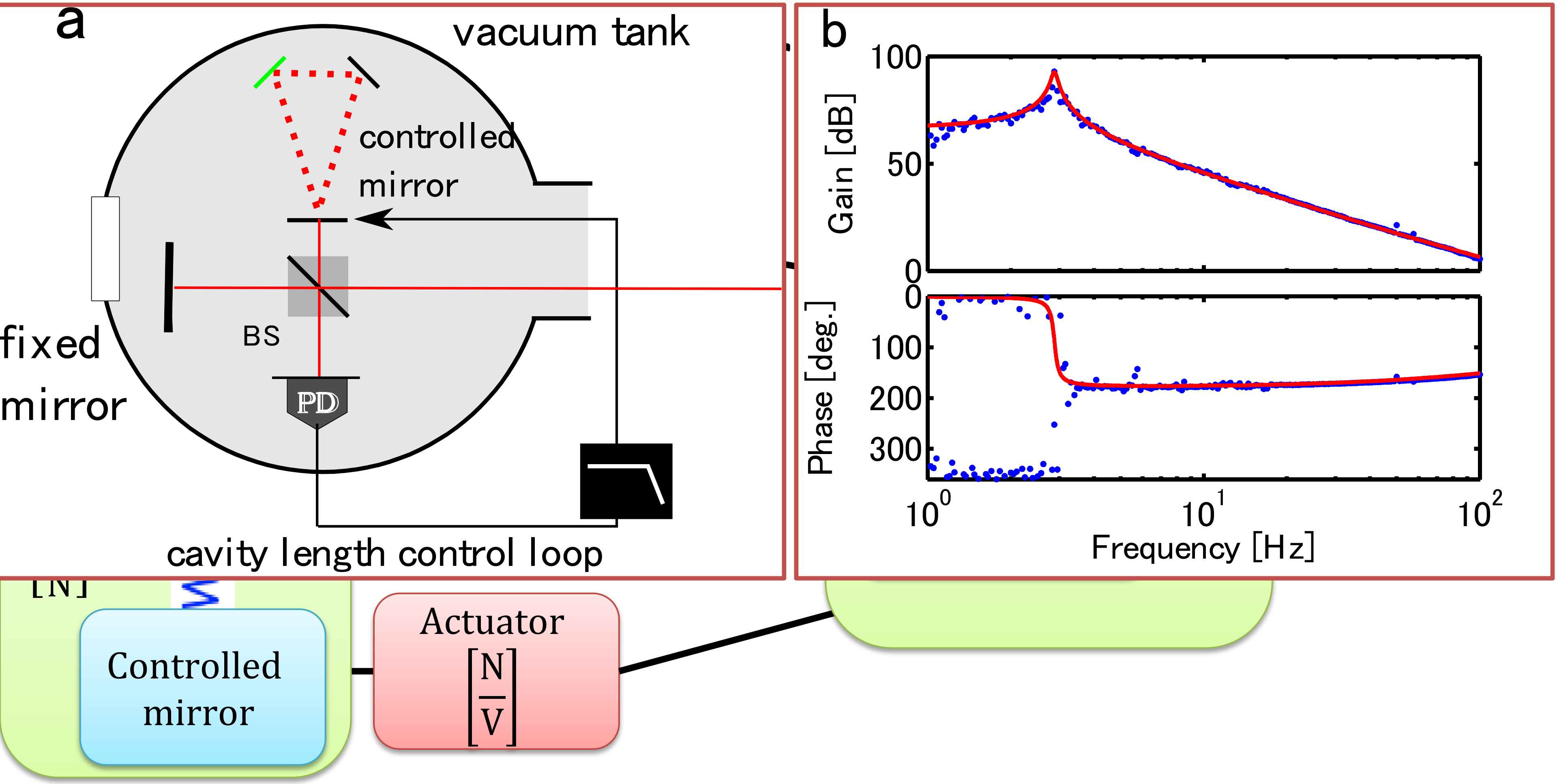


Transfer function

Calibration

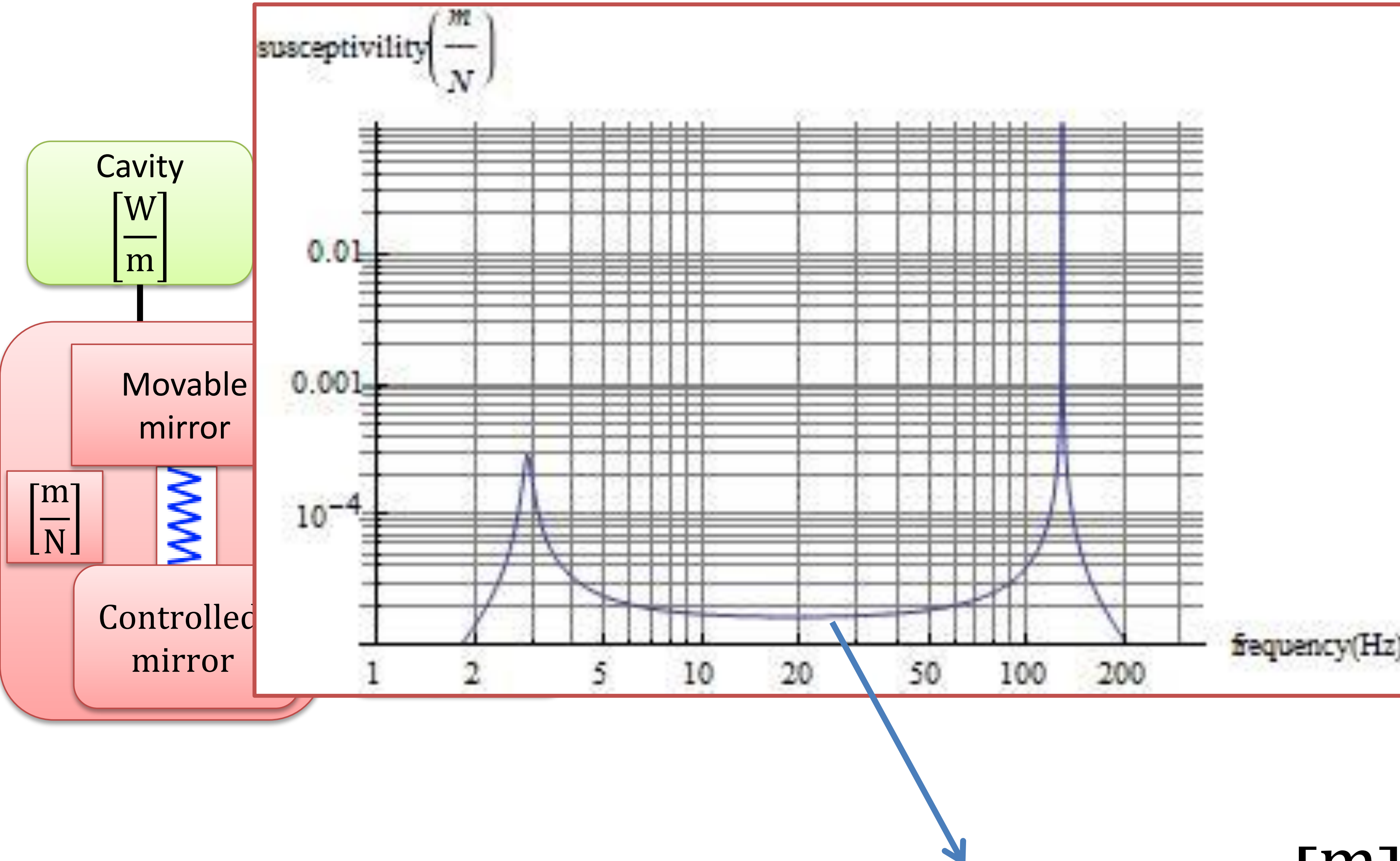


Open-loop function for locking a MI



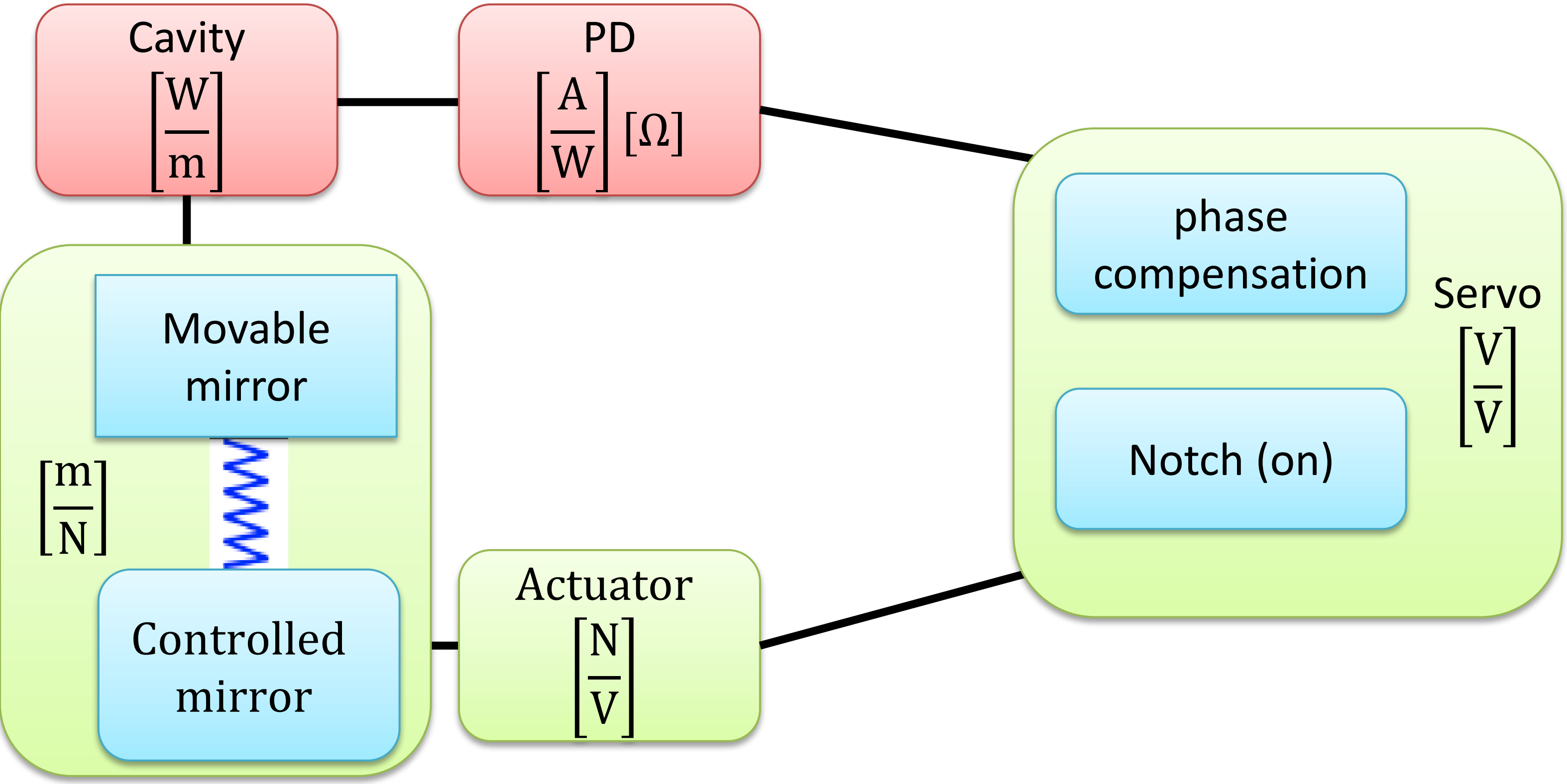
$$(1.4 \pm 0.1) \times 10^{-6} \left[\frac{\mathrm{N}}{\mathrm{V}}\right]$$

The model of a coupled oscillator



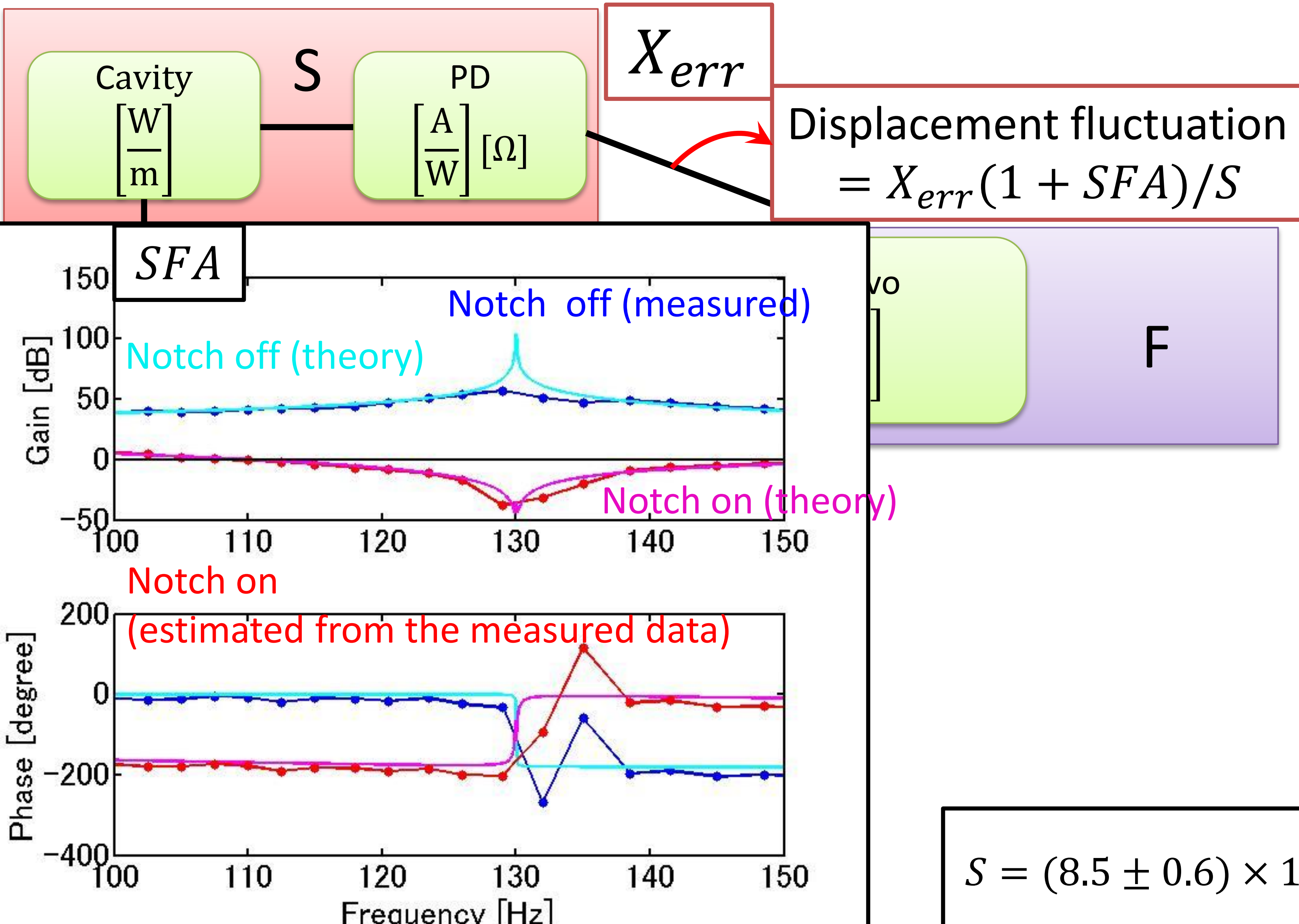
$$1.5 \times 10^{-5} \left[\frac{\mathrm{m}}{\mathrm{N}}\right]$$

Calibration

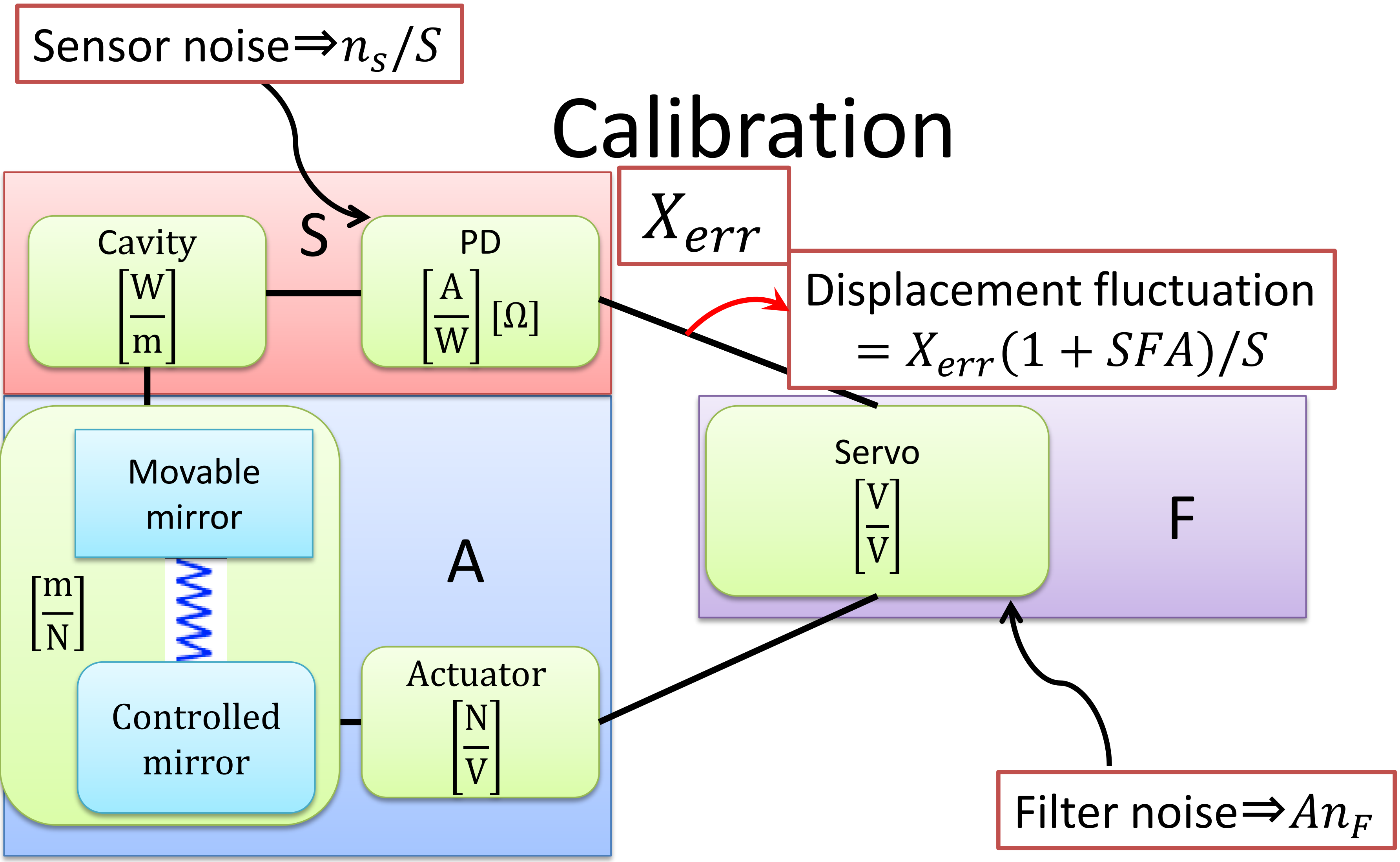


$$(8.5 \pm 0.6) \times 10^{-11} \left[\frac{\mathrm{V}}{\mathrm{m}}\right]$$

Calibration

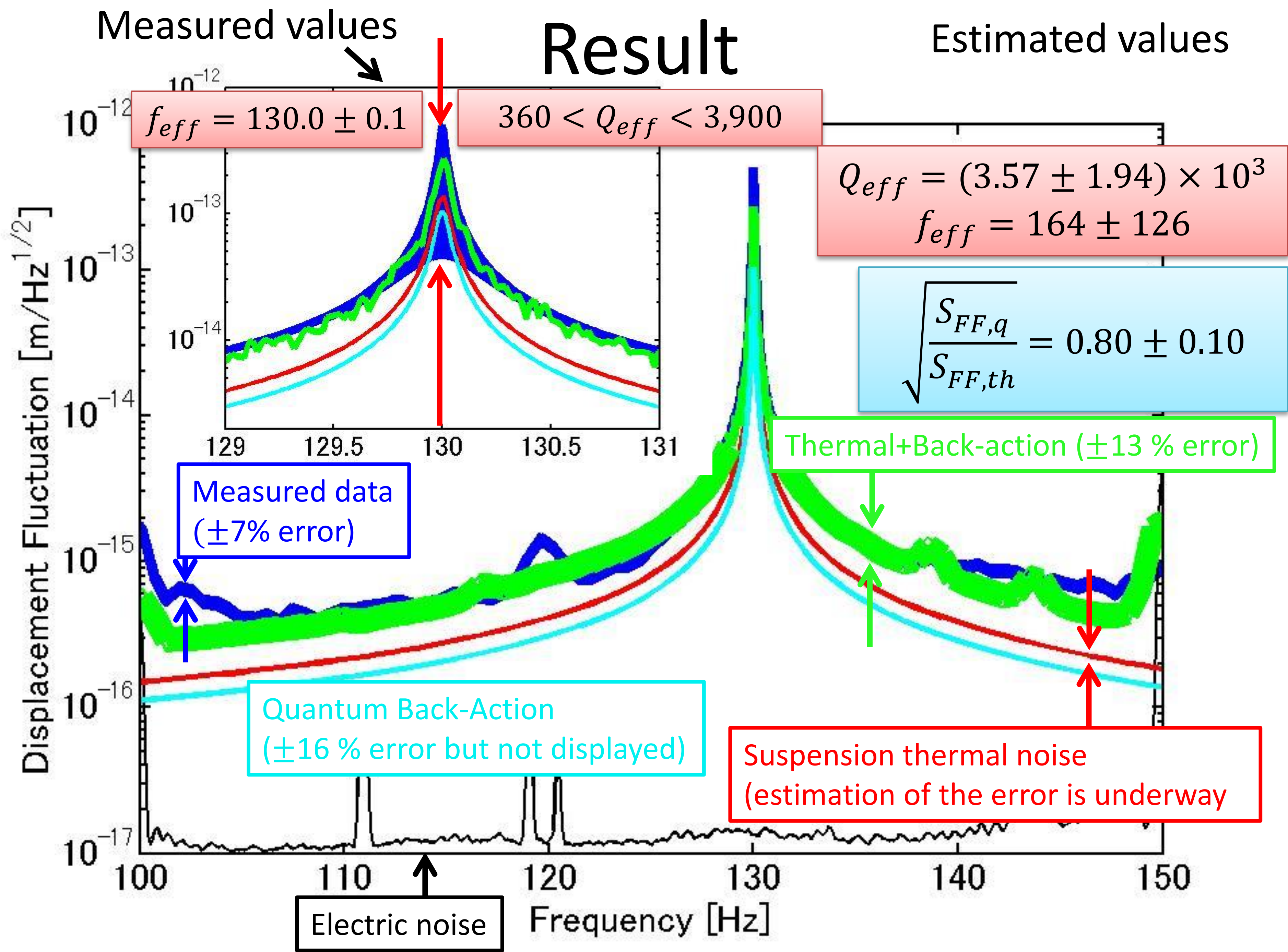


$$S = (8.5 \pm 0.6) \times 10^{-11} \left[\frac{\mathrm{V}}{\mathrm{m}}\right]$$



Sensor noise⇒n_s/S
Calibration
X_{err}
S
Cavity
$\left[\frac{W}{m}\right]$
PD
$\left[\frac{A}{W}\right]$ $[\Omega]$
Displacement fluctuation
$= X_{err}(1 + SFA)/S$
Movable
mirror
$\left[\frac{m}{N}\right]$
A
Servo
$\left[\frac{V}{V}\right]$
F
Controlled
mirror
Actuator
$\left[\frac{N}{V}\right]$
Filter noise⇒An_F

Result



Measured values
Estimated values
$f_{eff} = 130.0 \pm 0.1$
$360 < Q_{eff} < 3{,}900$
$Q_{eff} = (3.57 \pm 1.94) \times 10^3$
$f_{eff} = 164 \pm 126$
$\sqrt{\frac{S_{FF,q}}{S_{FF,th}}} = 0.80 \pm 0.10$
Thermal+Back-action (±13 % error)
Measured data
(±7% error)
Quantum Back-Action
(±16 % error but not displayed)
Suspension thermal noise
(estimation of the error is underway
Electric noise
Displacement Fluctuation [m/Hz$^{1/2}$]
Frequency [Hz]

Summary of parameters

Table 6.1: parameters

parameter	symbol	unit	measured value	estimated value
input power (d)	P_{in1}	mW	5.0 ± 0.5	-
input power (s)	P_{in2}	W	0.10 ± 0.01	-
intracavity power (d)	$P_{\mathrm{in1,circ}}$	W	-	3.00 ± 0.34
intracavity power (s)	$P_{\mathrm{in2,circ}}$	W	-	0.61 ± 0.42
photon number (d)	$N_{\mathrm{in1,circ}}$	-	-	$(4.78 \pm 0.66) \times 10^9$
photon number (s)	$N_{\mathrm{in2,circ}}$	-	-	$(9.87 \pm 7.00) \times 10^8$
normalized detuning (d)	$\Delta_{\mathrm{a}}/\kappa$	-	0.048 ± 0.005	-
normalized detuning (s)	$\Delta_{\mathrm{b}}/\kappa$	-	1.30 ± 0.07	-
optomechanical coupling	$g/2\pi$	Hz/m	$(2.8 \pm 0.1)\omega_{\mathrm{c}}$	(design) $2.84\omega_{\mathrm{c}}$
cavity decay rate	$\kappa/2\pi$	Hz	$(1.52 \pm 0.03) \times 10^6$	-
cavity decay rate (in1)	$\kappa_{\mathrm{in1}}/2\pi$	Hz	$(1.30 \pm 0.03) \times 10^6$	-
cavity decay rate (in2)	$\kappa_{\mathrm{in2}}/2\pi$	Hz	$(3.64 \pm 2.46) \times 10^4$	-
finesse	$\mathcal{F}_{\mathrm{p}}$	-	$(1.10 \pm 0.02) \times 10^3$	-
effective resonant frequency	f_{eff}	Hz	130 ± 0.1	164 ± 126
effective quality factor	Q_{eff}	-	360-3,900	$(3.57 \pm 1.94) \times 10^3$
quality factor	Q_{m}	-	4.7×10^5	$< 3.8 \times 10^6$
thermal fluctuating force	$\sqrt{S^{(2)}_{\mathrm{FF,th}}}$	$\mathrm{N}/\sqrt{\mathrm{Hz}}$	-	$(1.44 \pm 0.02) \times 10^{-16}$
quantum back-action force	$\sqrt{S^{(2)}_{\mathrm{FF,q}}}$	$\mathrm{N}/\sqrt{\mathrm{Hz}}$	-	$(1.08 \pm 0.07) \times 10^{-16}$
actuator efficiency	A	N/V	$(1.4 \pm 0.1) \times 10^{-6}$	-
slope of the PDH signal	H	V/m	$(8.5 \pm 0.6) \times 10^{-11}$	-
signal to noise ratio	-	-	-	0.80 ± 0.10

Next Step

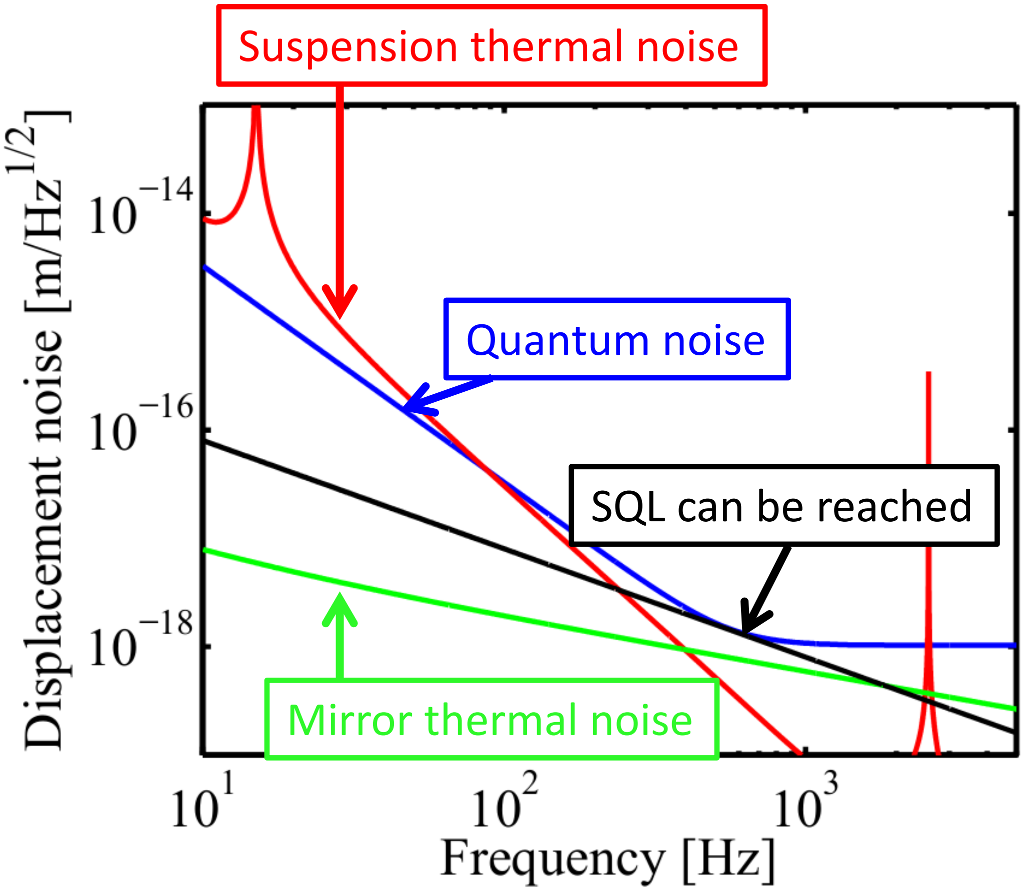
- Reaching the SQL using MZ interferometer

1. Mass 5 mg ⇒ 15 mg
2. Diameter 3 um ⇒ 1 um
3. Length 5 cm ⇒ 2 cm
4. Improve of clamping

(Q-factor will be 8-times)

5. Other material (e.g. CNTF)

(test is underway)



Q-factor will be increased from 4.7×10^5 to 2×10^7

($2 \times 9/2.5 \times 8 \approx 58 > 40$)

Conclusion

- Triangular cavity has potential to reach the SQL.
- At the moment, the ratio of quantum back-action to thermal noise is estimated to be 0.80 ± 0.10.

Next ⇒More validity of the measurement
e.g.) error of the Q-factor,
freq. noise,
dependence of the laser power, and
correlation measurement

Improve of the pendulum
⇒ reaching the SQL