GWPO seminar

Kawamura Lab. ICRR

NAGANO Koji

Abstract

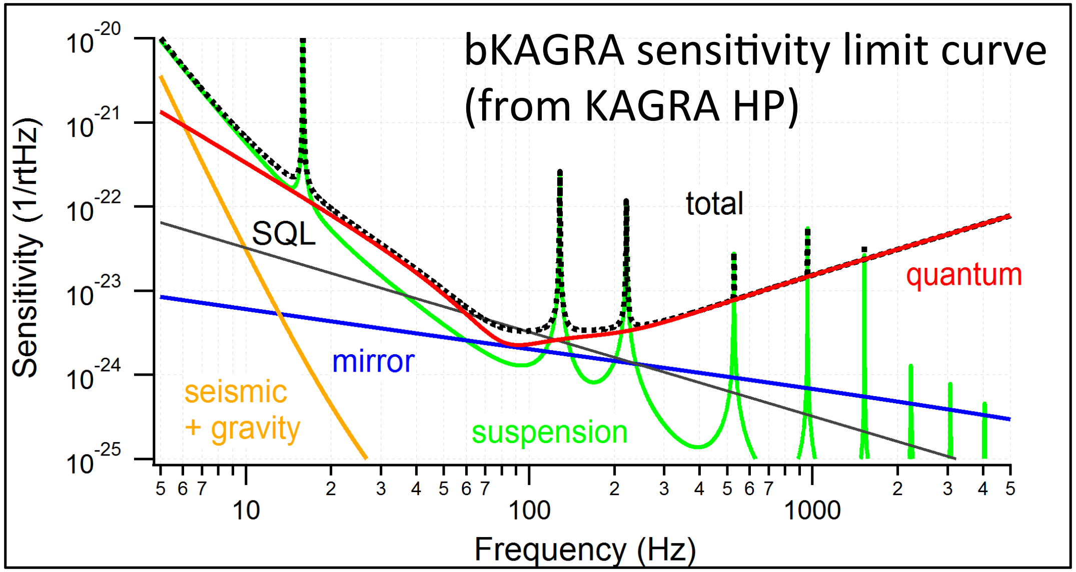
- I'm studying quantum noise, especially radiation pressure noise, at ICRR. In this talk, at first I'm going to explain that sources of quantum noise is vacuum fluctuation. After that I show experimental setup with a suspended 23 mg mirror at ICRR and current sensitivity is limited by laser frequency noise and PD dark noise. Finally, I show that with new method, which is so-called remote excitation, the rotational resonant frequency of the tiny mirror can be measured precisely.

Outline

1. Introduction
2. What is quantum noise?
3. What is QND measurements?
4. Experimental setup
5. Current sensitivity
6. Rotational instability of the cavity (Sidles-Sigg effect)
7. (Near) future plans

Introduction

- The goal sensitivity of bKAGRA is limited mostly by the quantum noise.
- In order to achieve a better sensitivity, demonstrating the reduction of quantum noise is essential.

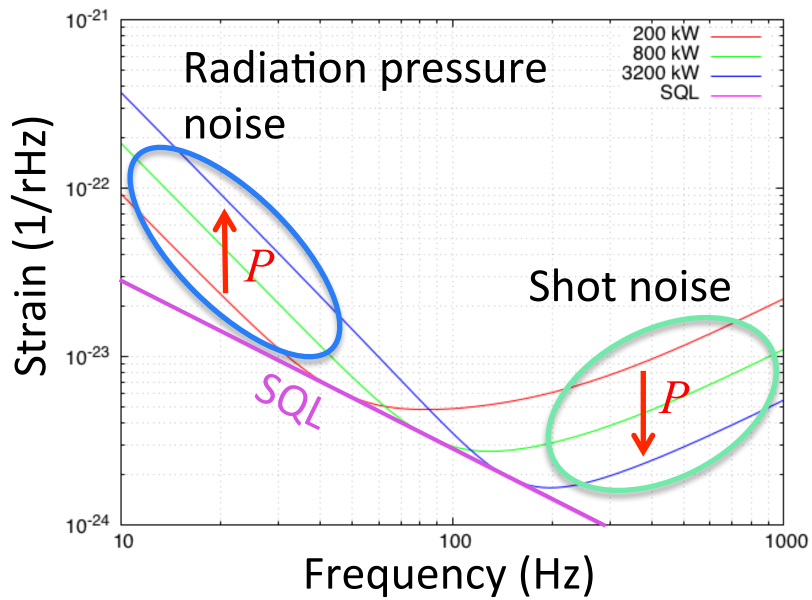


Quantum Noise

- Quantum noise is composed of two elements:
  1. Shot noise $\propto \sqrt{P}$
  2. Radiation pressure noise $\propto 1/\sqrt{P}$

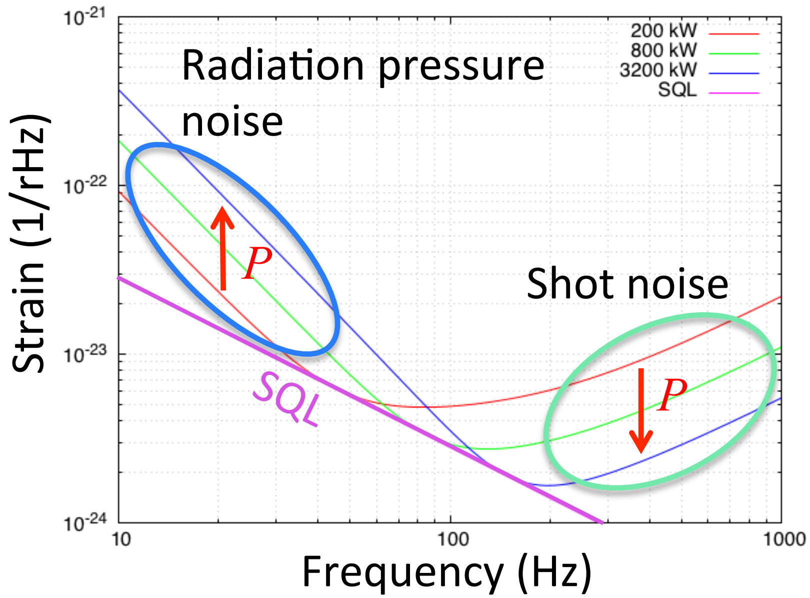
  (in terms of SNR)

  (Here P is circulating power in the cavity.)
- These two noises cannot be reduced simultaneously with "ordinary" measurements. = Gravitational wave detectors have the limit of the sensitivity called standard quantum limit (SQL).



Quantum Noise

- What is "ordinary" measurements?
  - For example, measurements with changing laser power. With this methods, the sensitivity beyond SQL cannot be achieved.



- In order to reduce quantum noise, we should use "non-ordinary" measurements!!

Sources of Quantum Noise

- Before describing “non-ordinary” measurements, let us consider sources of quantum noise (shot noise and radiation pressure noise).

Sources of Quantum Noise

<u>Quasi-quantum treatment</u>

- Source of quantum noise is the fluctuation of the photon number N ($\propto P$).
  - Stochastic error of N is $\sqrt{N}$.
- Radiation pressure noise is generated when the number of photons which are reflected on the mirror and disturbs the mirror fluctuates.
- Shot noise is generated when the photon number measured at photo-detectors fluctuates.

Sources of Quantum Noise

<u>Quasi-quantum treatment</u>

- Source of quantum noise is the fluctuation of the photon number N ($\propto P$).

Fluctuation of the photon number behaves as **displacement noise**

- Radiation pressure noise is generated when the number of photons which are reflected on the mirror and disturbs the mirror fluctuates.
- Shot noise is generated when the photon number measured at photo-detectors fluctuates.

Fluctuation of the photon number behaves as **measurement noise**

Sources of Quantum Noise

Quasi-quantum treatment

- When the stochastic error of the photon number is considered in terms of displacement noise, the error is called radiation pressure noise.
- When the stochastic error of the photon number is considered in terms of measurement noise, the error is called shot noise.

Sources of Quantum Noise

Quantum optical treatment

- From now, quantum noise is treated in the quantum optical way.
- At first, let us consider the fluctuation of the laser light using the optical phase plane as follows:

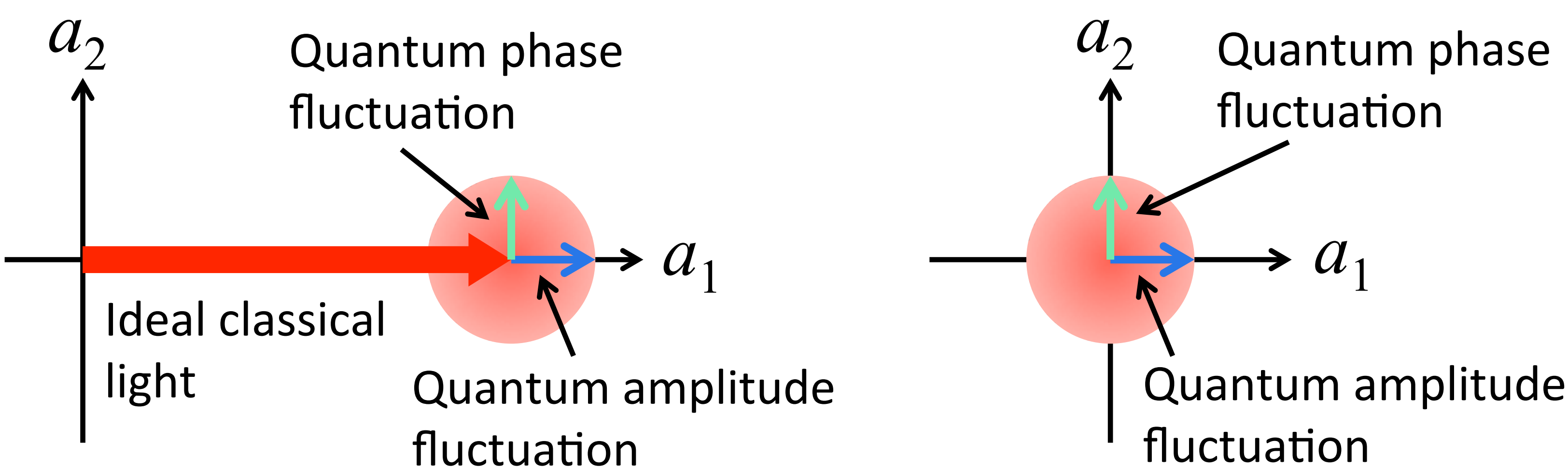
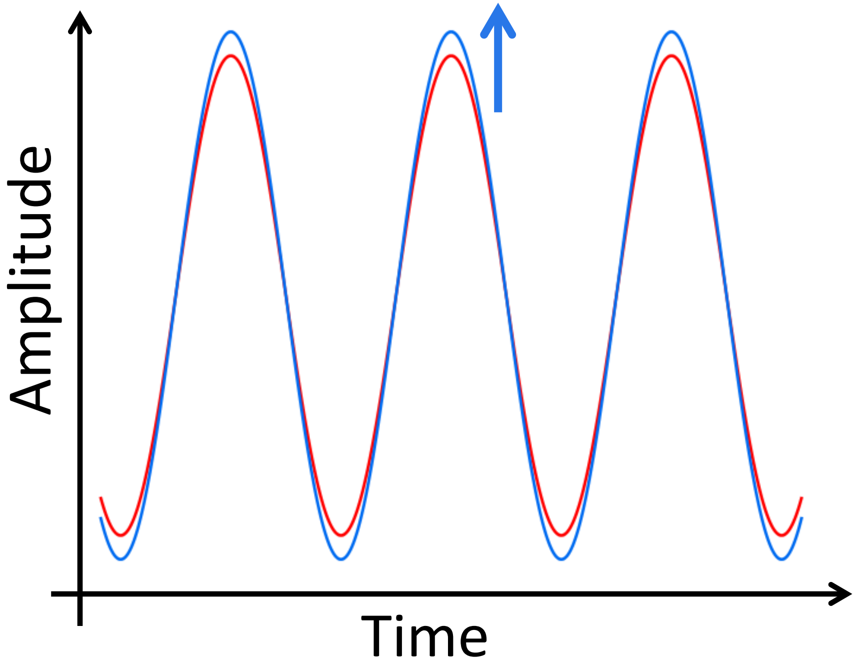


Figure: (left) fluctuation of the light. (right) fluctuation of vacuum field. Here, a_1 and a_2 are defined as amplitude quadrature and phase quadrature, respectively.

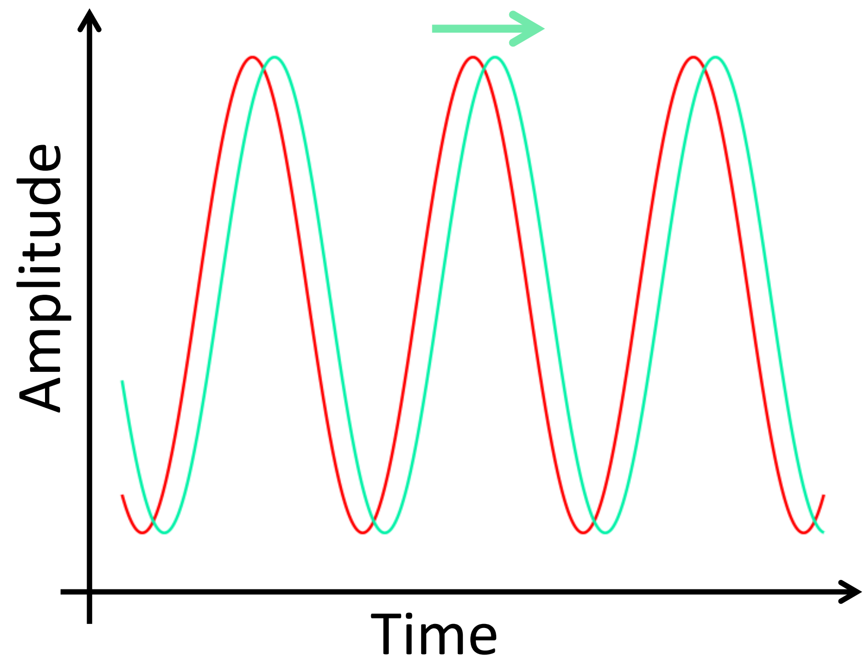
Sources of Quantum Noise

Quantum optical treatment

- Amplitude fluctuation



- Phase fluctuation



Sources of Quantum Noise

<u>Quantum optical treatment</u>

- In gravitational wave detectors, signals are obtained as phase shifts.
- Thus the phase fluctuation of the light has the same phase as the signal to be measured. (= phase quadrature)
- The amplitude fluctuation has the quadrature phase to the signal. (= amplitude quadrature)

(The reason why “quadrature” is used to describe the elements of optical phase plane is, I think, that phase “phase” is very awkward.)

Sources of Quantum Noise

<u>Quantum optical treatment</u>

- In gravitational wave detectors, signals are

Measurement noise → **Shot noise**

- Thus the phase fluctuation of the light has the same phase as the signal to be <u>measured</u>. (= phase quadrature)
- The amplitude fluctuation has the quadrature phase to the signal. (= amplitude quadrature)

(What kind of noise is this? → This is displacement noise.

c → This is **radiation pressure noise**!

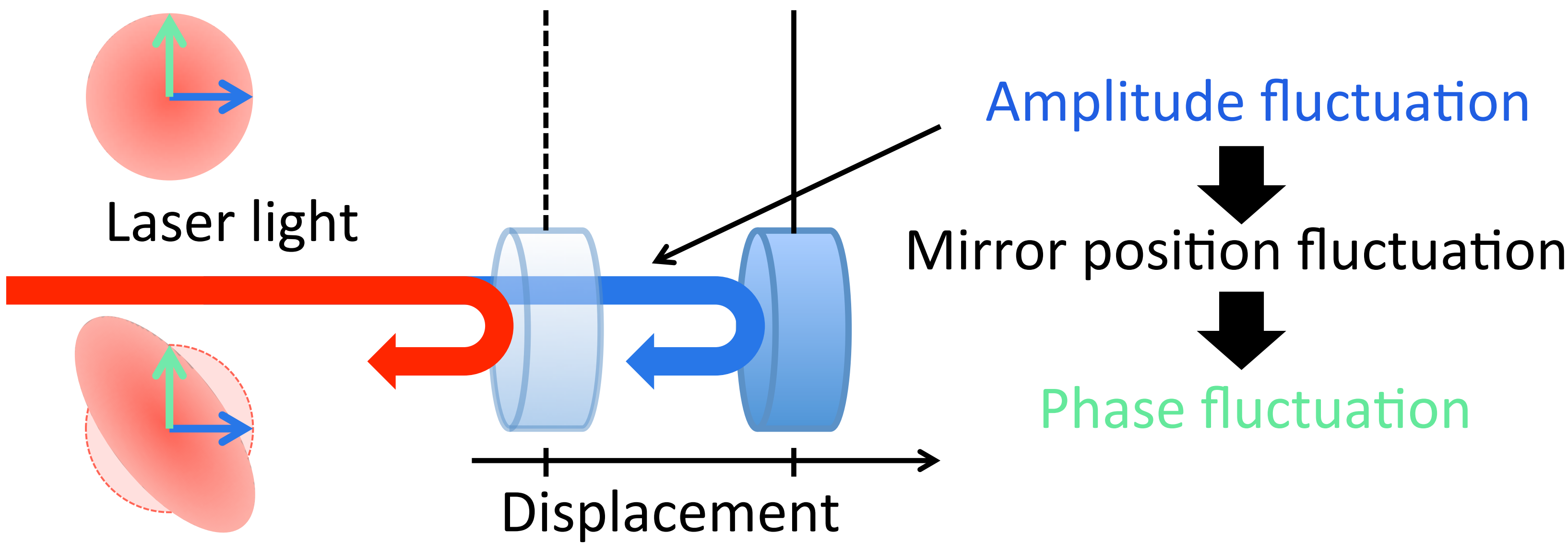
think, that phase "phase" is very awkward.)

Sources of Quantum Noise

<u>Quantum optical treatment</u>

- Amplitude fluctuation makes the mirror reflecting laser light fluctuate because of radiation pressure as below figure.

  → Amplitude fluctuation generates phase quadrature noise.

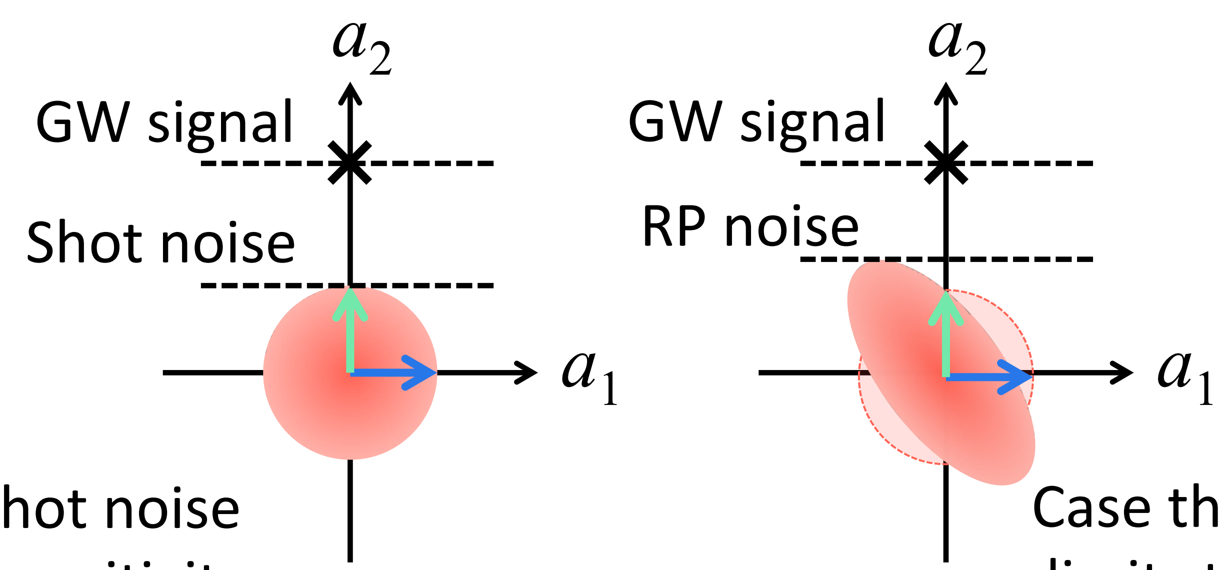


Sources of Quantum Noise

<u>Quantum optical treatment</u>

- Shot noise level is constant. So SNR $\propto \sqrt{P}$.
- Radiation pressure (RP) noise $\propto \frac{P}{mf^2}$. So SNR $\propto \frac{mf^2}{\sqrt{P}}$.

(Here P is laser power, m is mass of mirror, and f is frequency.)



Case that shot noise limits the sensitivity.

Case that RP noise limits the sensitivity.

Sources of Quantum Noise

Quantum optical treatment

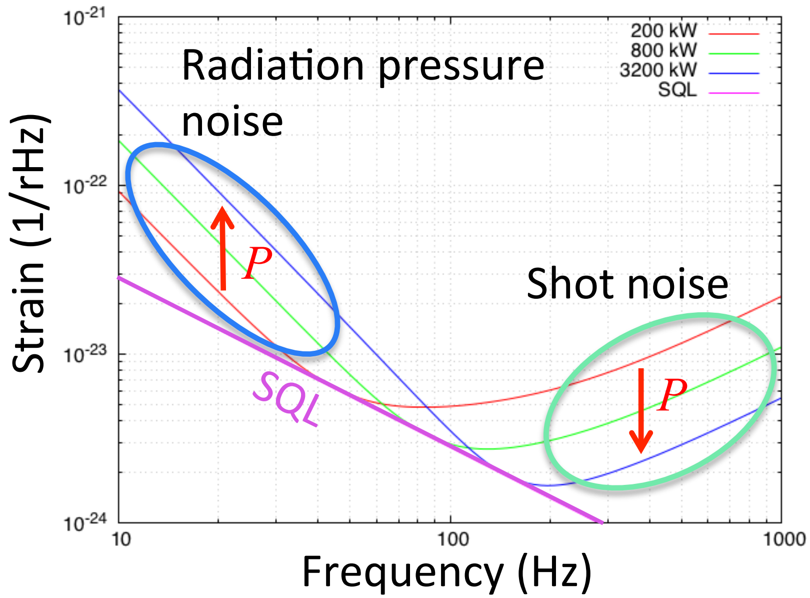
- According to above investigation, the source of quantum noise is the vacuum fluctuation.
- Of the noises from the vacuum fluctuation,
  – the noise caused by amplitude quadrature fluctuation is called radiation pressure noise.
  – the noise caused by phase quadrature fluctuation is called shot noise.

(Note that the vacuum field is input from dark port and this is the very source of quantum noise of gravitational wave detectors.)

Quantum Noise

Remind

- What is "ordinary" measurements?
  - For example, measurements with changing laser power. With this methods, the sensitivity beyond SQL cannot be achieved.



- In order to reduce quantum noise, we should use "non-ordinary" measurements!!

QND Measurements

- "Non-ordinary" measurements, with which the sensitivity beyond SQL can be achieved, is called **q**uantum **n**on-**d**emolition (QND) measurements.
- Very naively, the difference between QND measurements and "ordinary" measurements can be explained as follows:
  - "Ordinary" measurements: When a value is measured, the measurement disturbs the value and make an error of the measurement.
  - QND measurements: the measurement disturbs only the conjugate value of the measured value. So the measured value is kept "clean".

QND Measurements

- "Non-ordinary" measurements, with which the sensitivity beyond SQL can be achieved, is called **q**uantum **n**on-**d**emolition (QND) measurements.
- Very naively, the difference between QND measurements and "ordinary" measurements can be explained as follows:
  - "Ordinary" measurements: When a value is measured, the measurement disturbs the value and make an error of the measurement.
  - **Amplitude quadrature** **Phase quadrature** ɔs only the conjugate value of the measured value. So the measured value is kept "clean".

QND Measurements

- Examples of QND measurements
  1. Input squeezed light from the dark port and measure the signal with a filter cavity
  2. Use optical spring
  3. Measure the ponderomotive squeezed light with homodyne detection
- Of these methods, optical spring and poderomotive squeezing are planed to use in KAGRA.

QND Measurements

- Examples of QND measurements
  1. Input squeezed light from the dark port and measure the signal with a filter cavity
  2. Use optical

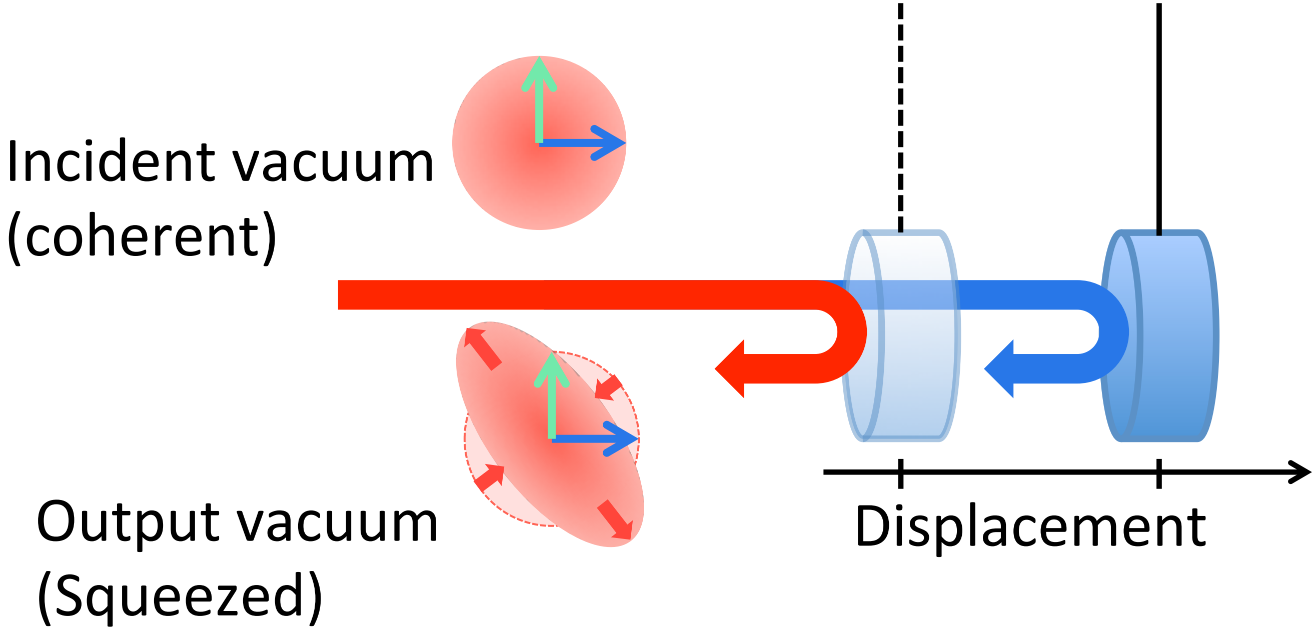
     I'm studying this!
  3. Measure the ponderomotive squeezed light with homodyne detection
- Of these methods, optical spring and poderomotive squeezing are planed to use in KAGRA.

QND Measurements

- What is the measurement of ponderomotive squeezed light with homodyne detection?
- This question can be divided into two components.
  1. What is ponderomotive squeezed light?
  2. What is homodyne detection?

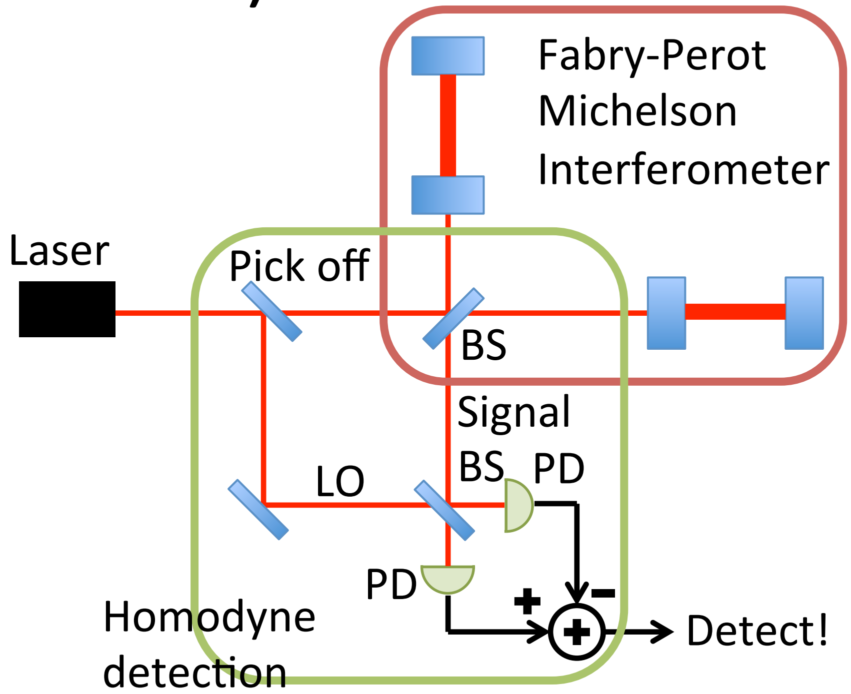
Ponderomotive Squeezing

- "Ponderomotive Squeezing" is squeezing of vacuum fluctuation's amplitude quadrature into its phase quadrature with mirrors by radiation pressure force.
- How much vacuum field is squeezed is $\propto \dfrac{P}{mf^2}$.



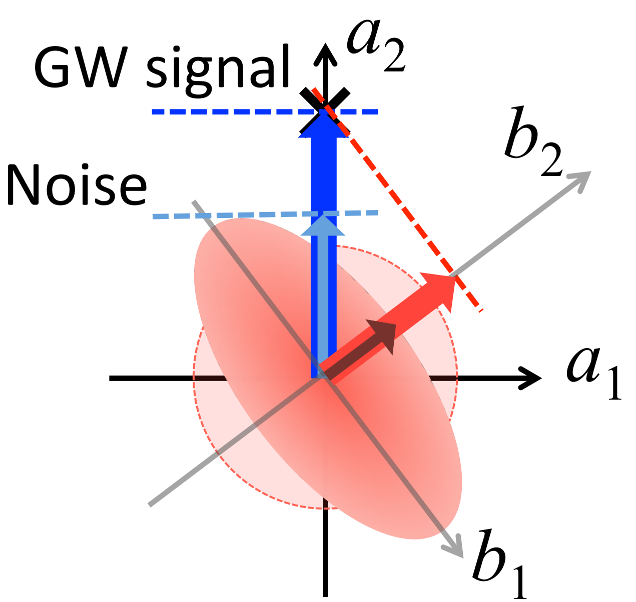
Homodyne Detection

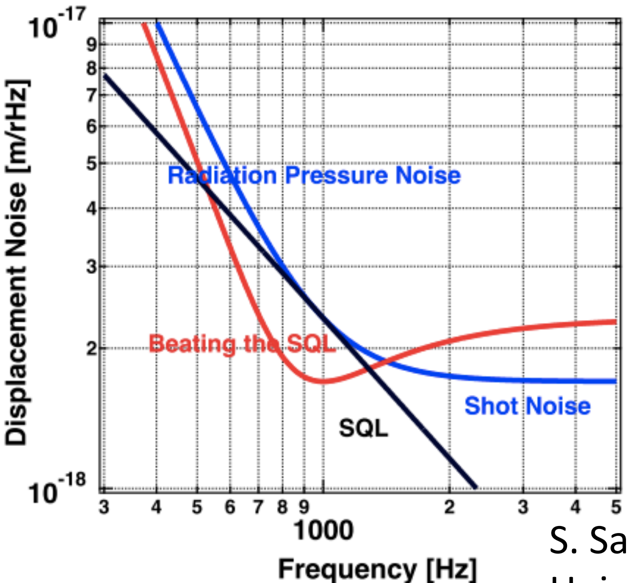
- "Homodyne detection" is to select a measurement quadrature to improve SNR. (In ordinary measurements, the measurement quadrature is phase quadrature.)
- Homodyne detection is performed by making the output signal from dark port interfere with local oscillator (LO).



Reduction of Quantum Noise

- Using ponderomotive squeezing and homodyne detection, SQL can be beaten.
- In the new measurement quadrature (b_2), GW signals decrease but noises are more reduced.
  → <u>**SNR will be improved!!**</u>





S. Sakata, Ochanomizu Univ., Ph.D. thesis

Experimental Setup

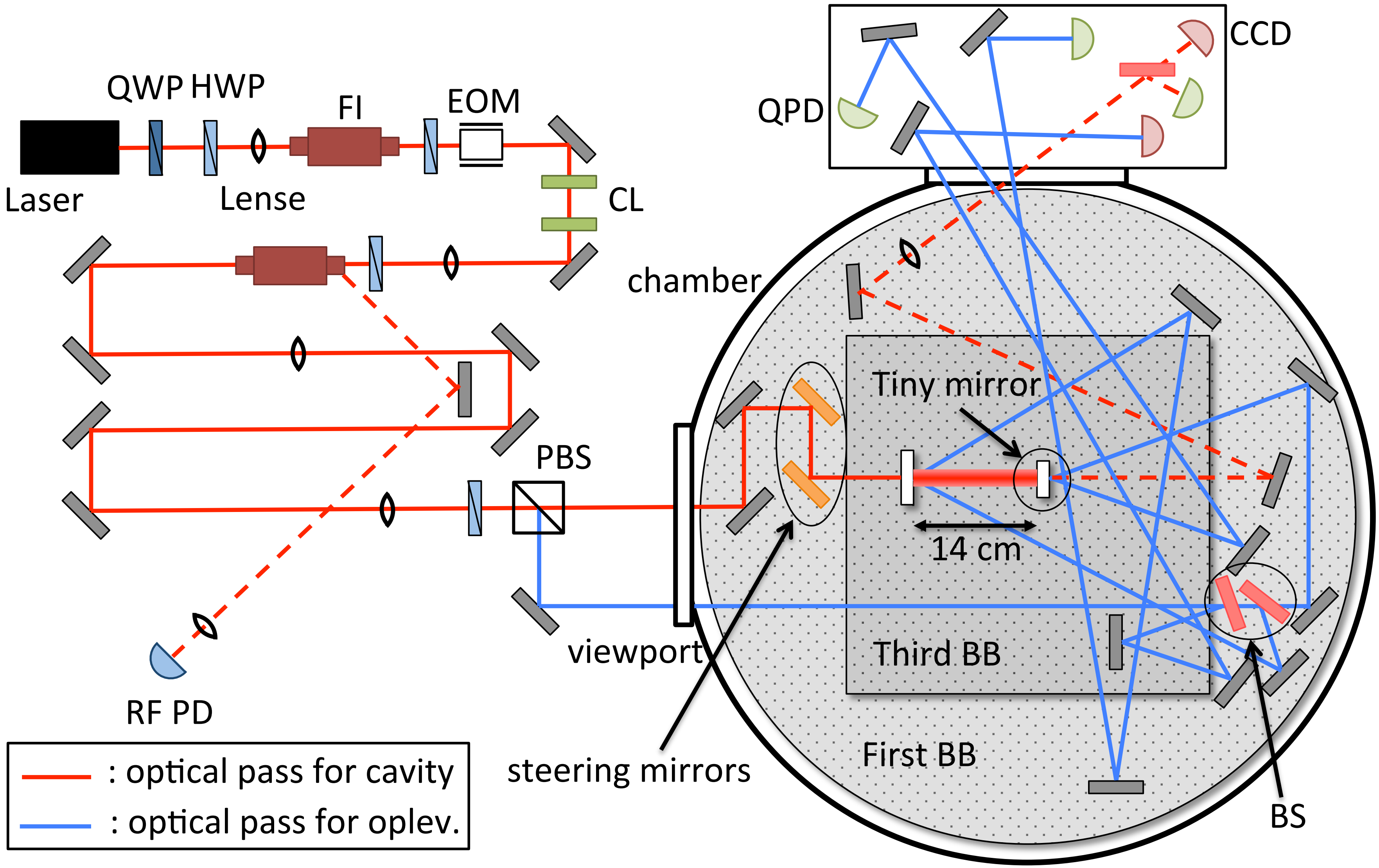
- I have a experiment at ICRR for demonstrating technique of quantum noise reduction, especially radiation pressure noise reduction.
- For demonstrating the technique, first of all, radiation pressure noise which is not reduced should be measured.
- Thus I have a experiment for measuring radiation pressure noise in wide range of frequency.

Experimental Setup

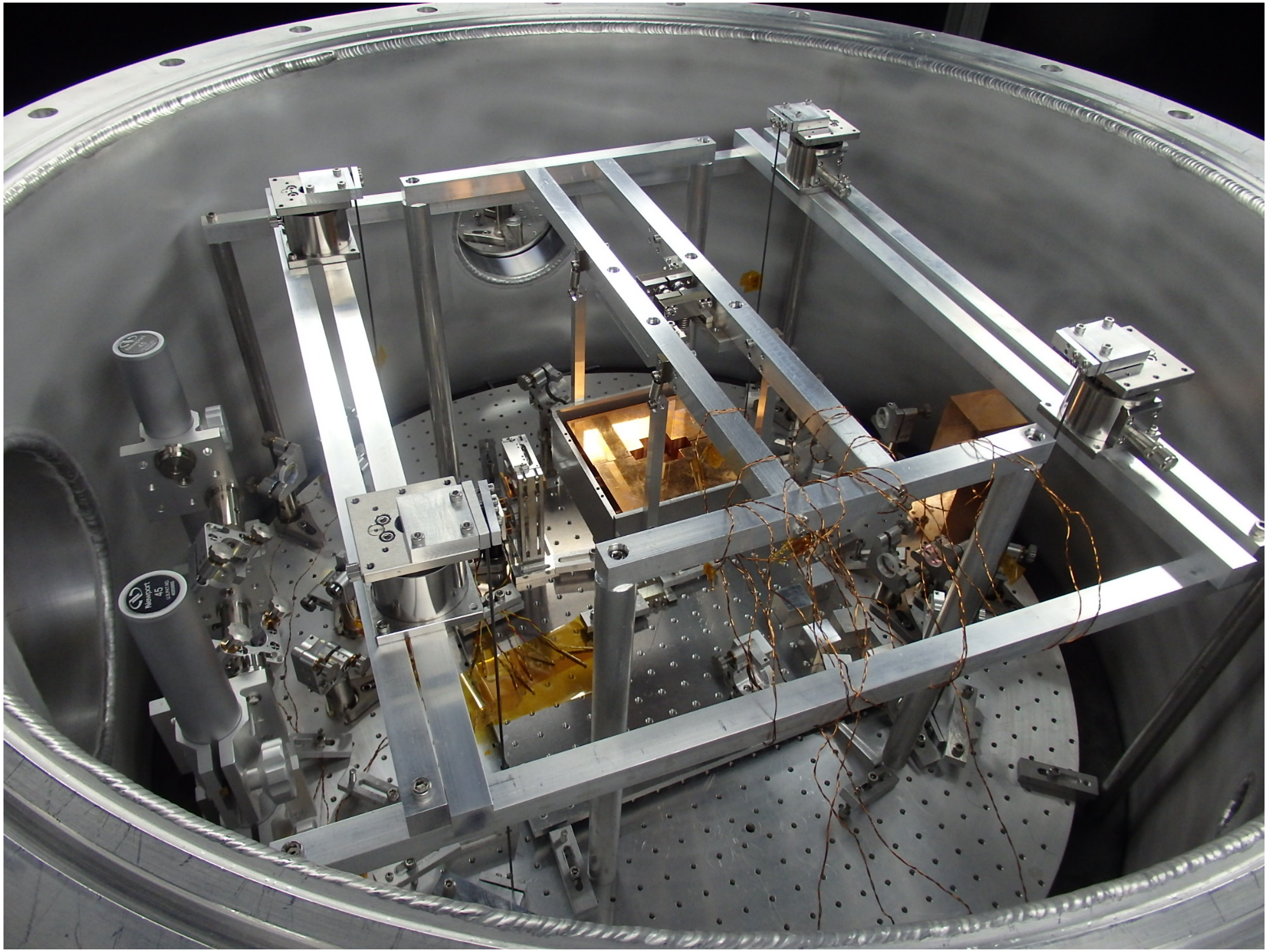
- For measuring radiation pressure noise, our experimental setup is devised as follows:
  - Suspended tiny mirrors (23 mg)
  - High finesse (~10^4) optical cavities (not yet)
  - Fabry-Perot Michelson interferometer (not yet)
- First and second one is used for enhancing radiation pressure noise.
  - Recall that radiation pressure noise is $\propto \frac{P}{mf^2}$.

  First one (→ m) Second one (→ P)
- Third one has the purpose for reducing the common-mode noise, such as classical laser amplitude noise.

Experimental Setup

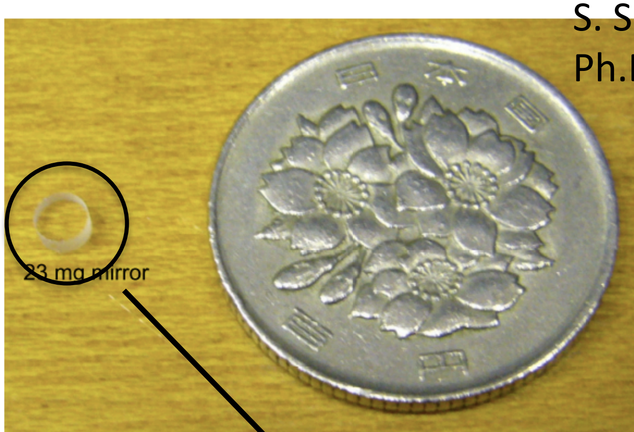


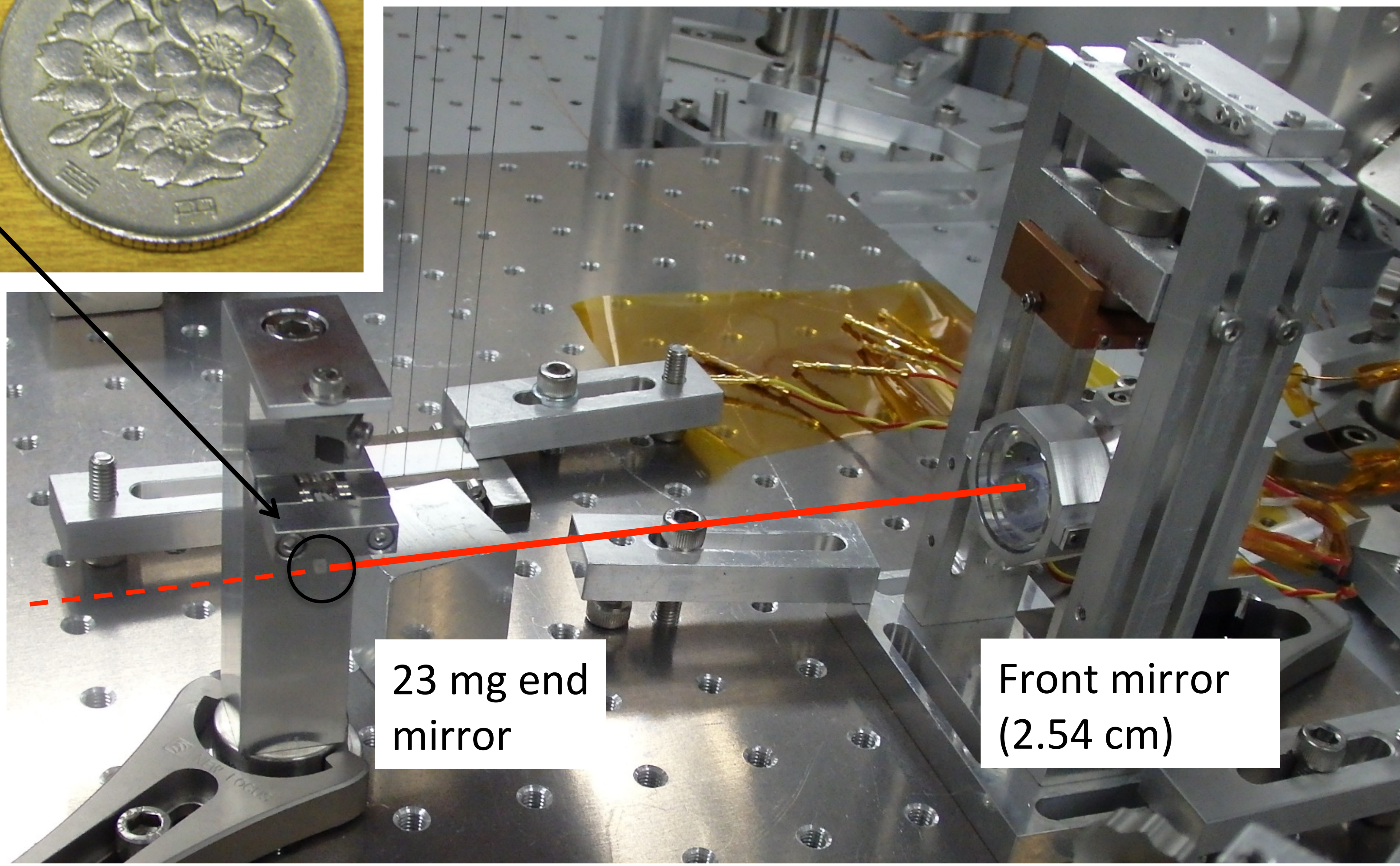
Experimental Setup



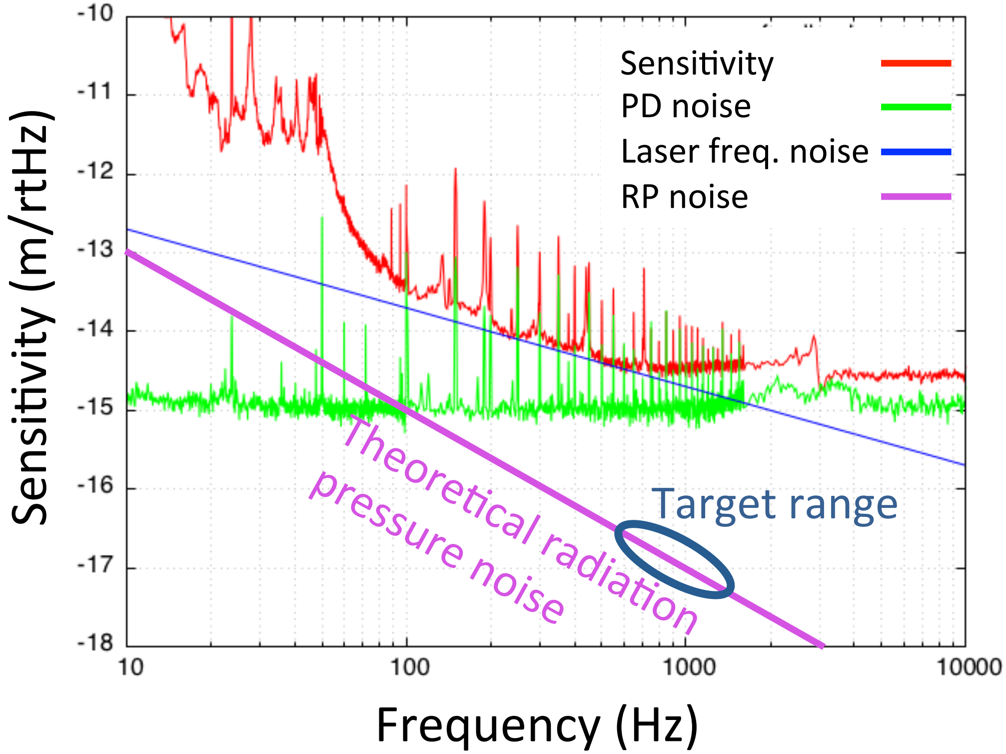
Experimental Setup

S. Sakata, Ochanomizu Univ.
Ph.D. Thesis (2008)





Current Sensitivity

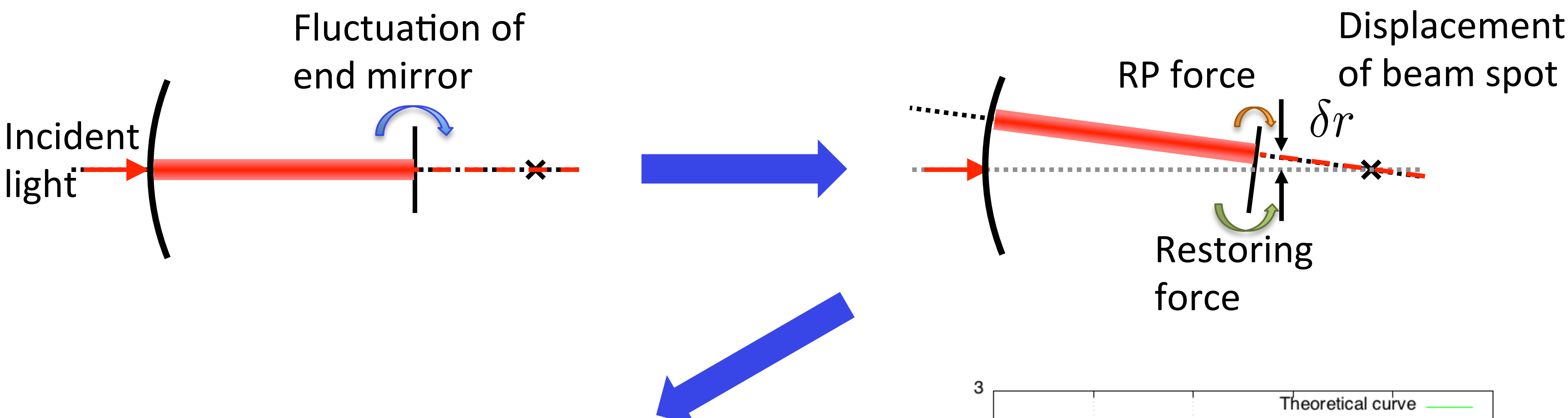


- Current sensitivity is limited by laser frequency noise (100 – 1000 Hz) and dark noise of the photo detector (1000 Hz –).

Current Problems

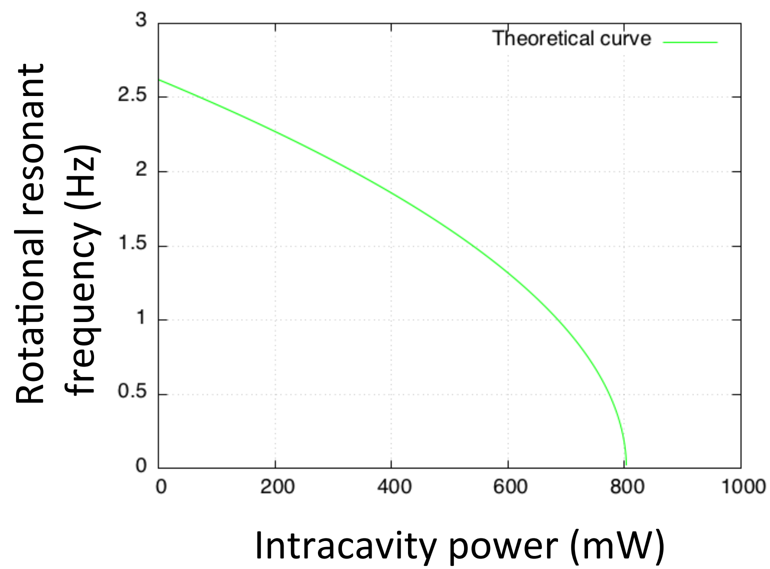
- Now I cannot make laser power increase because of rotation instability due to radiation pressure applied to the tiny end mirror.
  - This effect is called Sidles-Sigg effect.
- This instability should be avoid using a rotational control system for enhancing and measuring radiation pressure noise.

Sidles-Sigg Effect



- Case1: RP > Restoring force
  → Cavity will be unstable.
- Case2: RP < Restoring force
  → **Resonant frequency will be decrease.**

I measured this case.

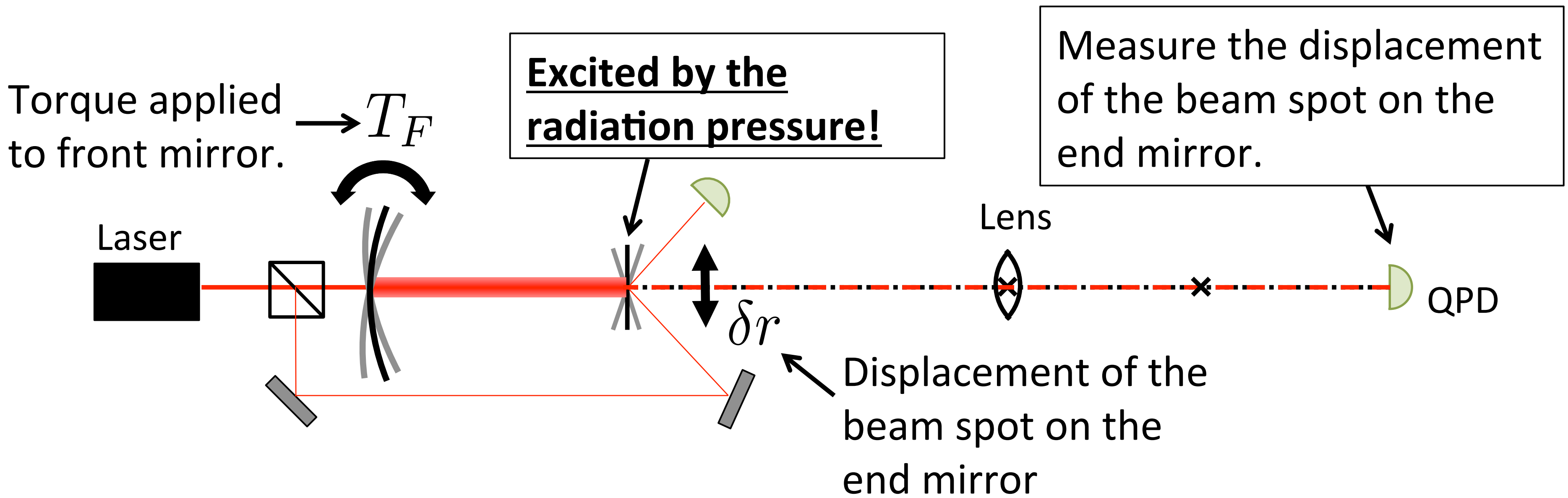


Sidles-Sigg Effect

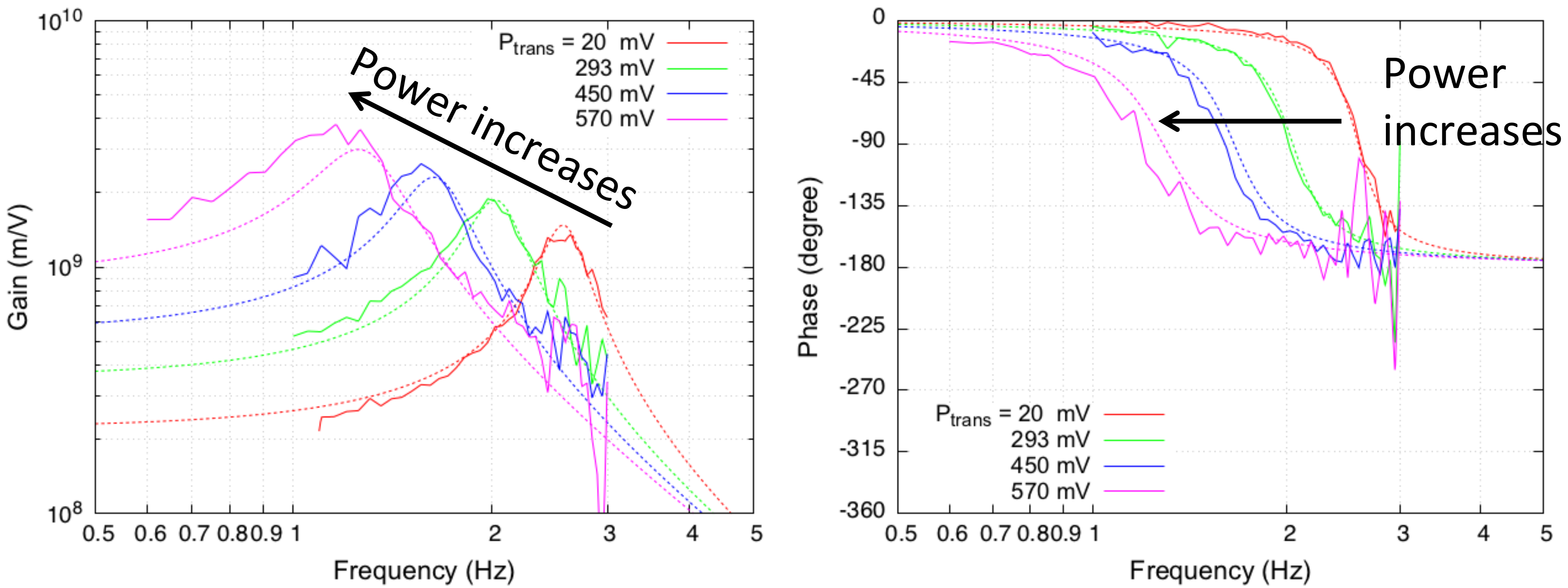
- To measure the decrease of resonant frequency, the transfer function from the torque applied to the end mirror to the angle of the end mirror should be measrued.
- However, the end mirror has no conventional actuators because of the space constraint and the end mirror cannot be excited easily.
- For solving this problem, I invented a new method for measuring Sidles-Sigg effect precisely with remote excitation on the mirror using the radiation pressure of the resonant light in the cavity.
  - I call this new method remote excitation.

Sidles-Sigg Effect

- The conceptual figure of remote excitation is shown in below.
- The front mirror is excited, and then the beam spot on the end mirror is moved and the end mirror is excited by the radiation pressure.

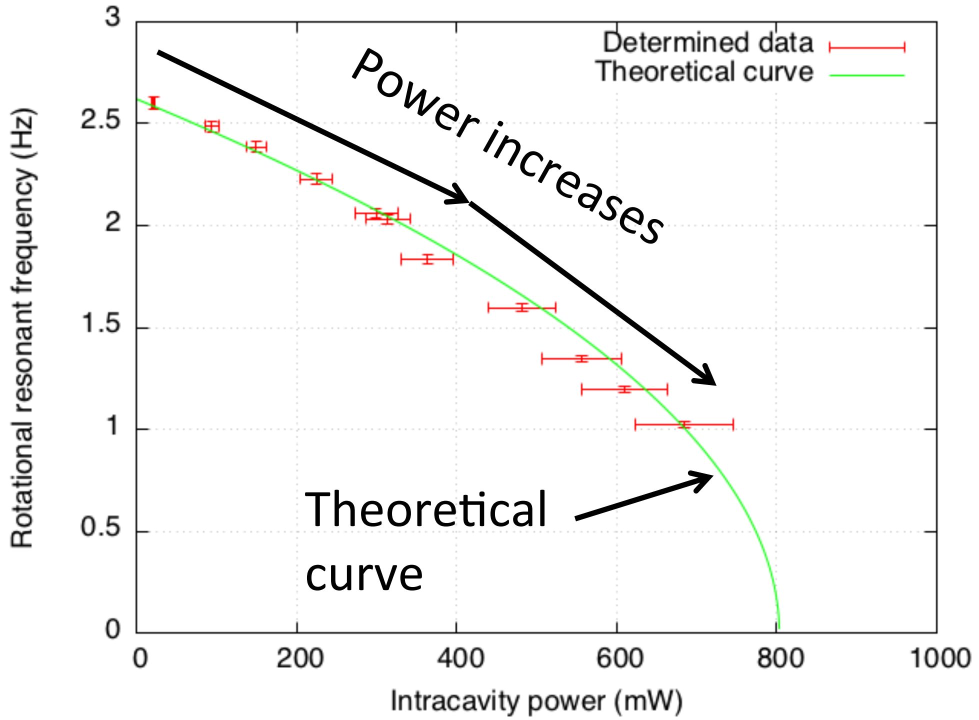


Sidles-Sigg Effect



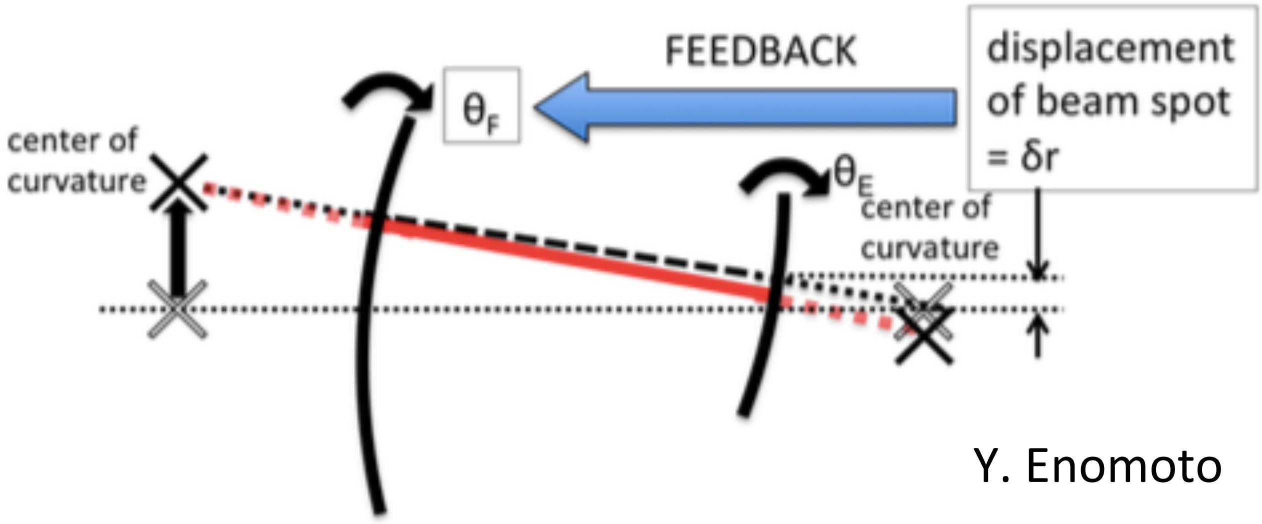
- Transfer functions from torque applied to the end mirror to angle of the end mirror measured with remote excitation.

Sidles-Sigg Effect



- Measured resonant frequencies of the end mirror.
- This figure shows the resonant frequency decreases with increase of the laser power.

Rotational Control System



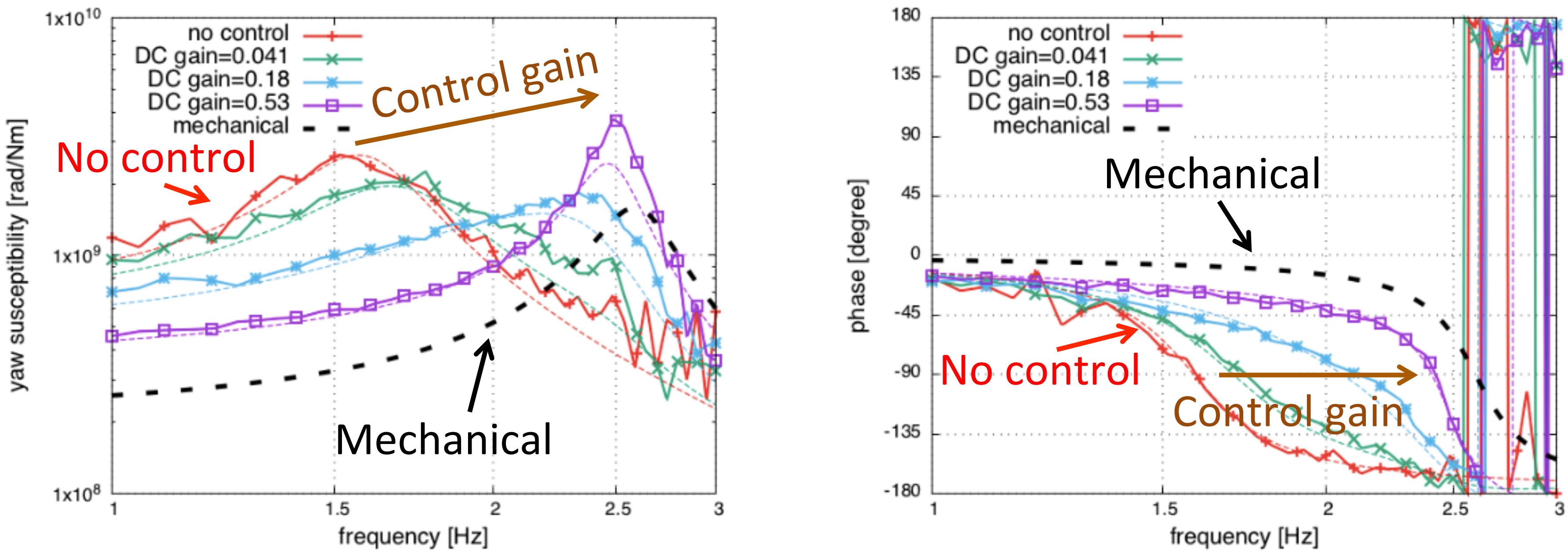
Y. Enomoto

- We designed a rotational control system from displacement of beam spot on the end mirror to the angle of the front mirror for avoiding the Sidles-Sigg effect.
- This feedback control system keeps the beam spot on the end mirror at the optical center of the end mirror.
  - In such case, radiation pressure torque is not generated.

Rotational Control System

- How to see if the control system works well?
  - When the instability occurs, the rotational resonant frequency decreases. On the other hand, when the instability is avoided, the rotational resonant frequency should increase (return to the mechanical resonant frequency.)
  - According to the above investigation, if we can measure the increase of the rotational resonant frequency of the end mirror, the rotational control system is found to work well!

Rotational Control System



- This figure shows the increase (or returning) of the rotational resonant frequency of the end mirror with increase of the control gain of the rotational resonant frequency.

(Near) Future Plans

- What I must do is
  - to stabilize the laser frequency for improving sensitivity (100 – 1000 Hz),
  - to make the resonant type of PD for improving sensitivity (1000 Hz –),
  - to re-design the electronic filter of the rotational control system for avoiding anti-dumping effect,
  - to demonstrate the rotational control system works well at high laser power where the radiation pressure force is larger than restoring force of the end mirror.

Future plans

- I'm going to fabricate the same Fabry-Perot cavity as the cavity now used and set up a Fabry-Perot Michelson interferometer with the two cavities.
- With the FPMI, I'm expected to measure radiation pressure noise in wide frequency range.
- After that, I plan to setup the homodyne detection and demonstrate the reduction of radiation pressure noise!!