Development of a stable high power Fabry-Perot cavity for quantum non-demolition measurement

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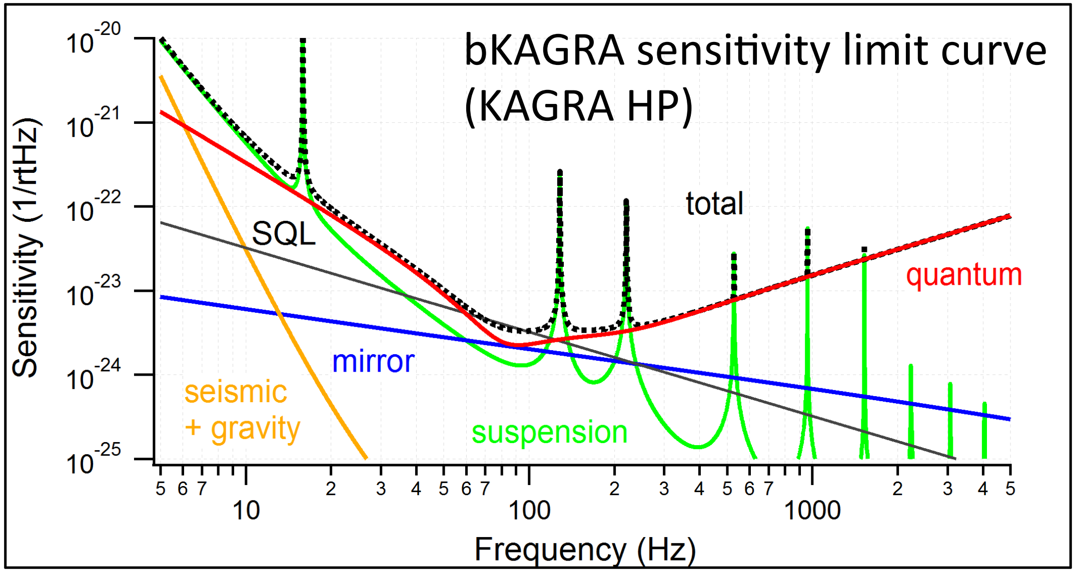
Introduction

- Goal sensitivities of gravitation wave detectors are limited mostly by the quantum noise.
- In order to achieve a better sensitivity, demonstrating the reduction of quantum noise is essential.



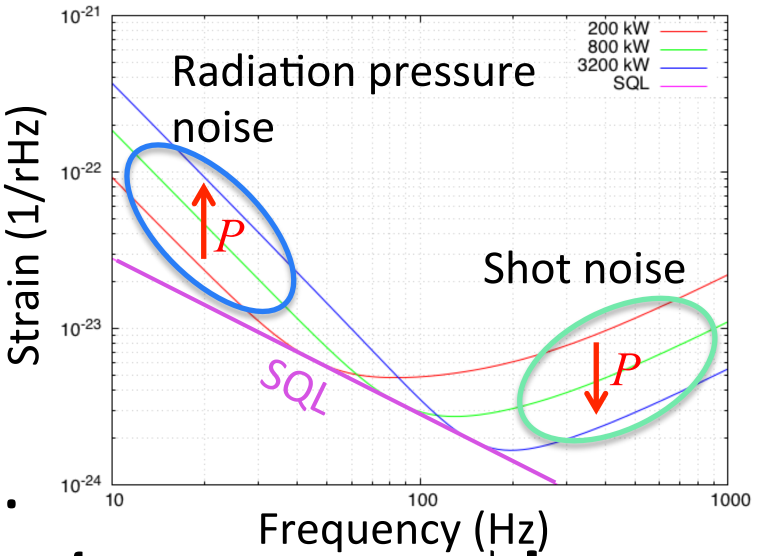
bKAGRA sensitivity limit curve (KAGRA HP)

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 a kind of limit of the sensitivity called standard quantum limit (SQL).



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

Quantum Noise

- Such “non-ordinary” measurements which reduce quantum noise are called **q**uantum **n**on-**d**emolition (QND) measurements.
- From now I want to explain mechanism of QND measurements.
- However, to explain them, quantum noise must be treated as quantum optical phenomena.
- So I will do a bit of explanation of sources of quantum noise in terms of quantum optics now.

Sources of Quantum Noise

Quantum optical treatment

- To come right to the point, the source of quantum noise is vacuum fluctuation.
- Vacuum fluctuation can be understood using the following optical phase plane.

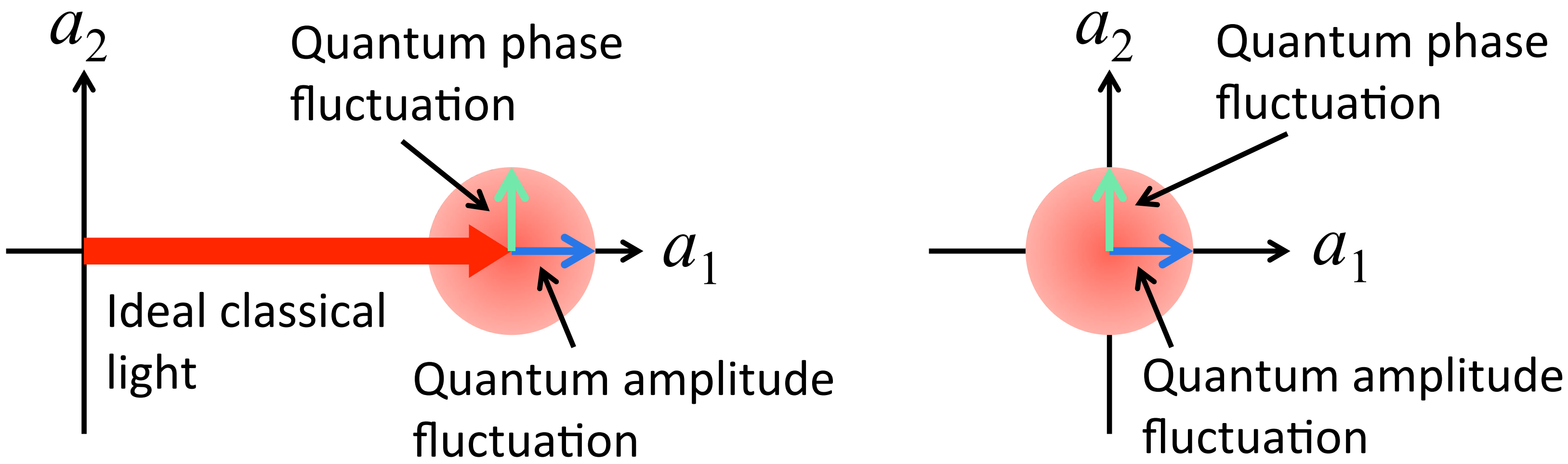
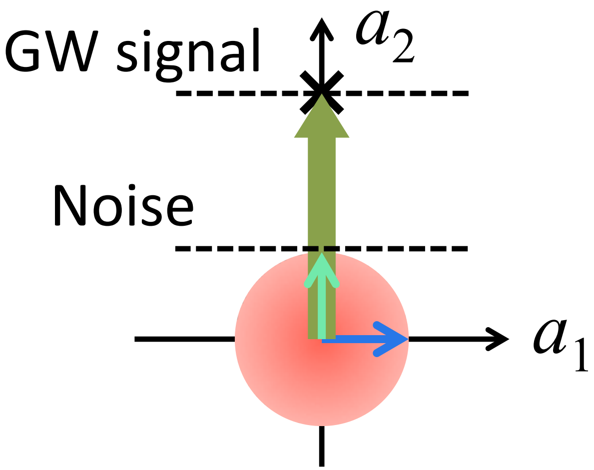


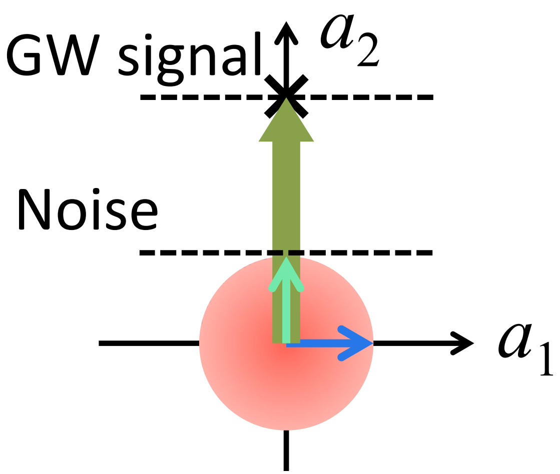
Figure: (left) fluctuation of the light. (right) fluctuation of vacuum field. Here, a_1 and a_2 are defined as amplitude quadrature and phase quadrature, respectively.

Sources of Quantum Noise

- At anti-symmetric port, when interferometers are operated at dark fringe, there is no classical light (except leak light for DC readout).
- In gravitational wave detectors, signals are obtained as phase shifts.
- Thus, naively, output field from interferometer will be like a following figure.



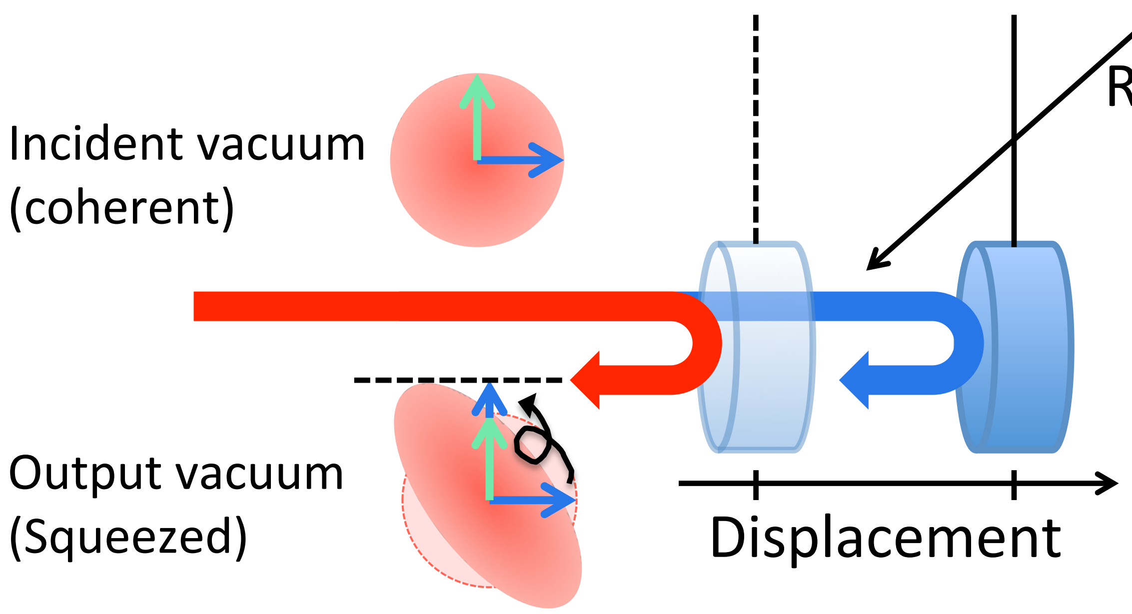
Sources of Quantum Noise



- According to the right figure, the phase fluctuation of the light has the same quadrature as the signal to be measured. The amplitude fluctuation has the conjugate quadrature.
- When we define shot noise and radiation pressure noise as sensing noise and displacement noise, respectively, **phase fluctuation is regarded as shot noise**.
- Then what will amplitude fluctuation be?
  → **Amplitude fluctuation will be radiation pressure noise.**

Sources of Quantum Noise

- The way amplitude fluctuation will be radiation pressure noise is understood as the following figure.



Amplitude fluctuation

⬇

Radiation pressure fluctuation

⬇

Mirror position fluctuation

⬇

Optical path length fluctuation

⬇

Phase fluctuation

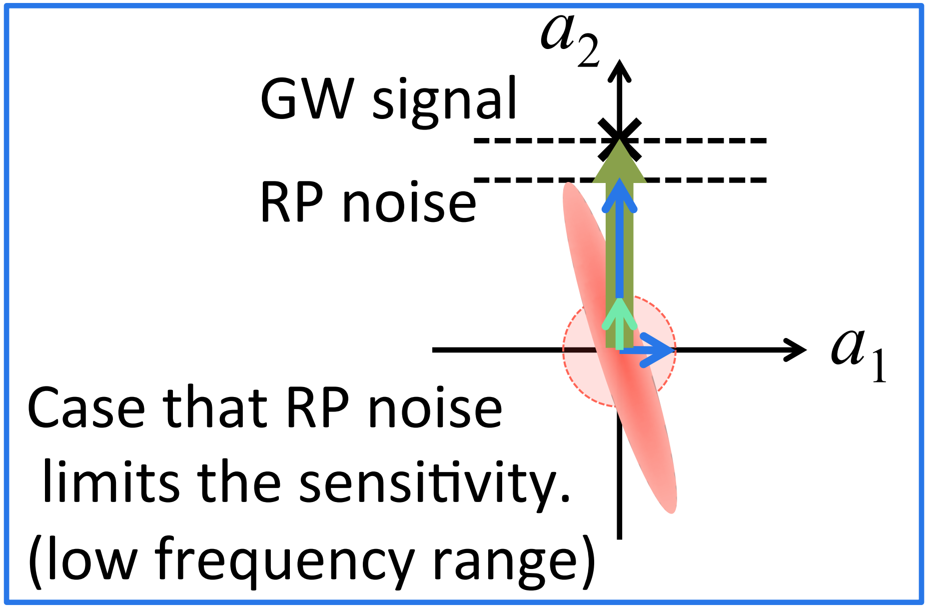
= **RP noise**

Sources of Quantum Noise

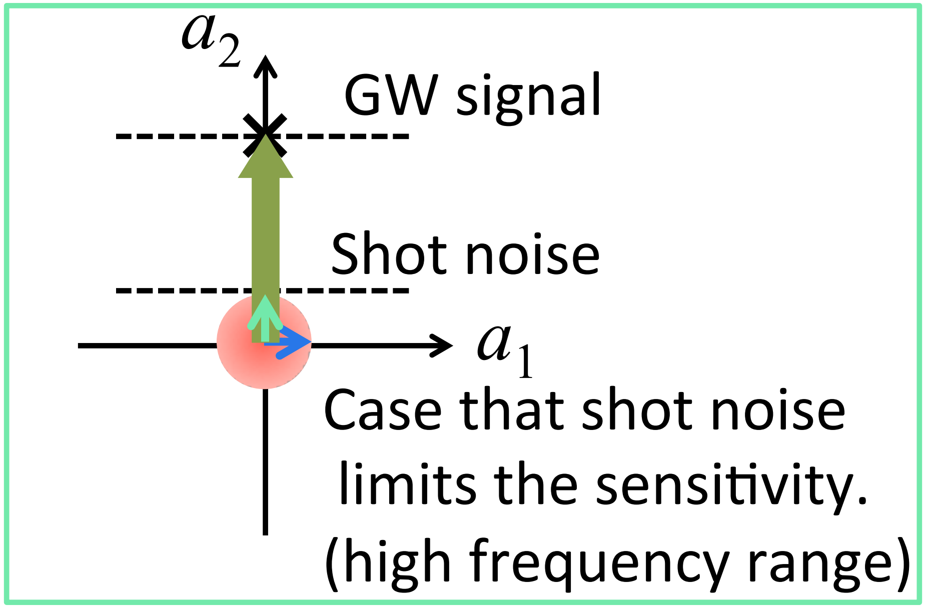
- Therefore,
  - shot noise level is constant and signal is $\propto \sqrt{P}$. So SNR $\propto \sqrt{P}$.
  - radiation pressure (RP) noise $\propto \boxed{\frac{P}{mf^2}}$. So SNR $\propto \frac{mf^2}{\sqrt{P}}$.

This expression came from just EOM of the mirror.

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



Case that RP noise limits the sensitivity. (low frequency range)



Case that shot noise limits the sensitivity. (high frequency range)

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 fluctuation is called radiation pressure noise.
  - – the noise caused by phase fluctuation is called shot noise.

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

QND Measurements

- Now, let me back to explanation of QND measurements for reducing quantum noise.
- 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”.

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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
- In KAGRA, of these methods, optical spring and poderomotive squeezing are planed to use.

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
  3. Measure the ponderomotive squeezed light with homodyne detection

I’m studying this!

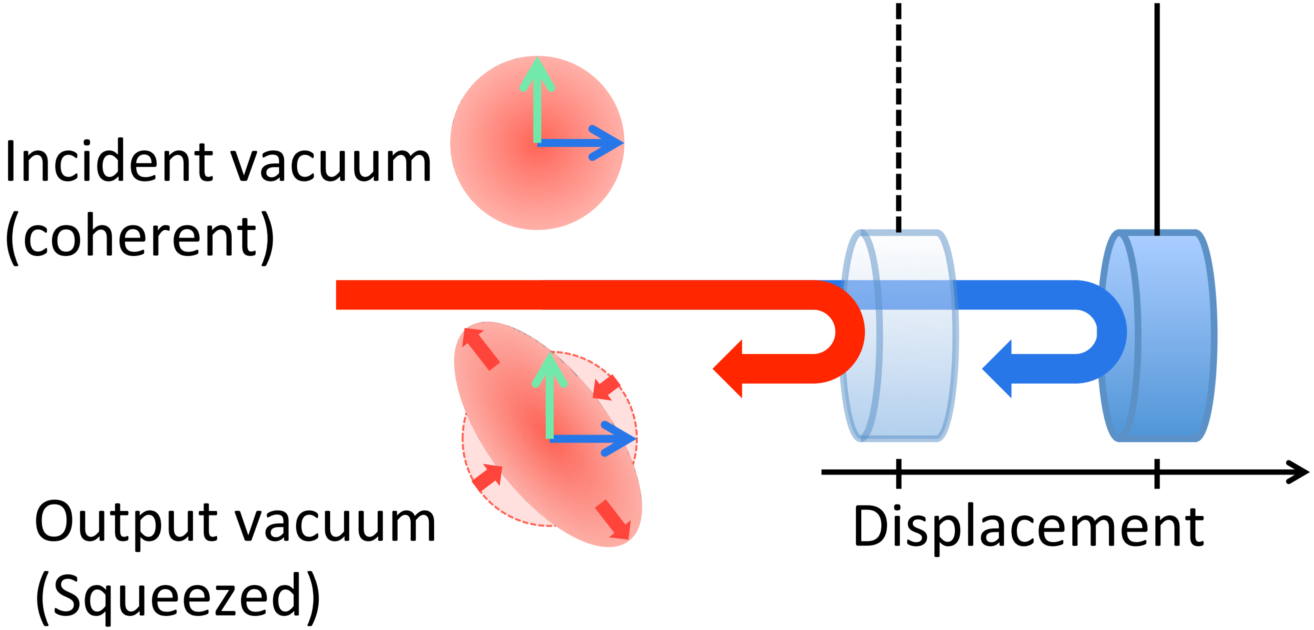
- In KAGRA, of these methods, optical spring and poderomotive squeezing are planed to use.

QND Measurements

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

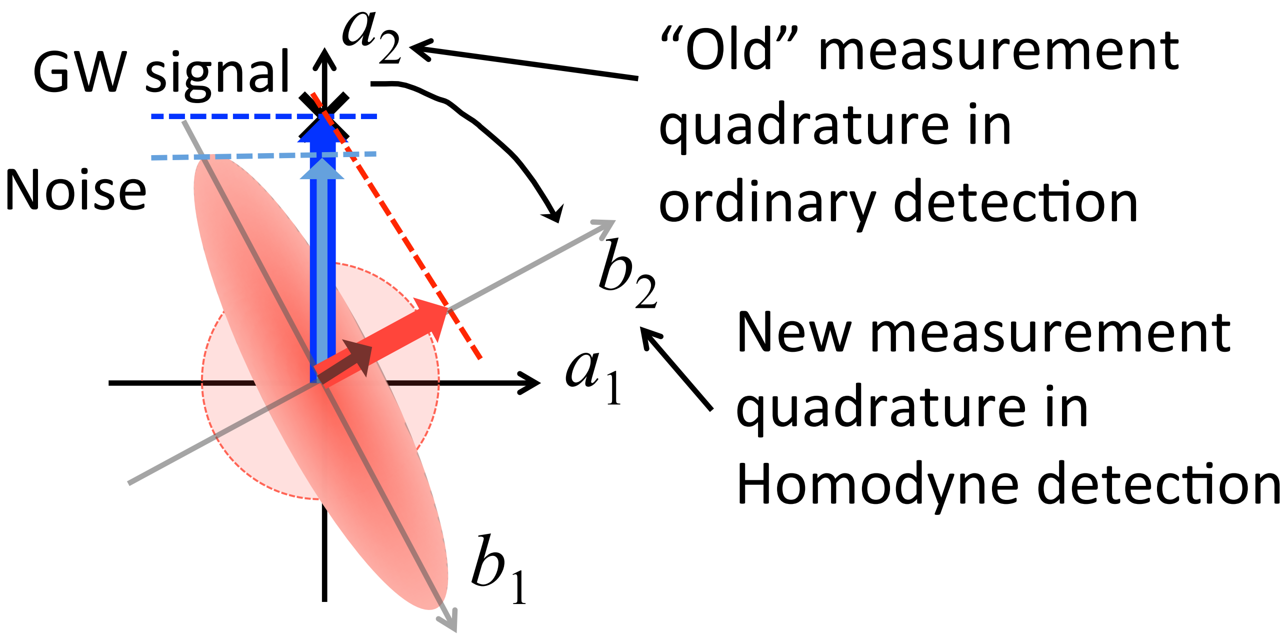
Ponderomotive Squeezing

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



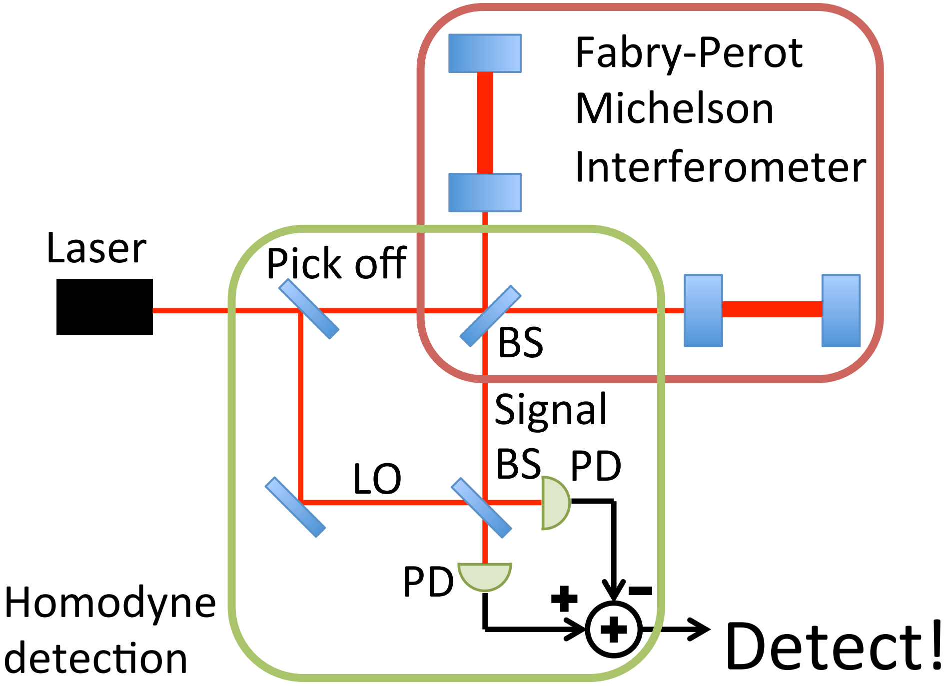
Homodyne Detection

- “Homodyne detection” is to select a measurement quadrature to improve SNR. (In ordinary measurements, the measurement quadrature is phase quadrature.)



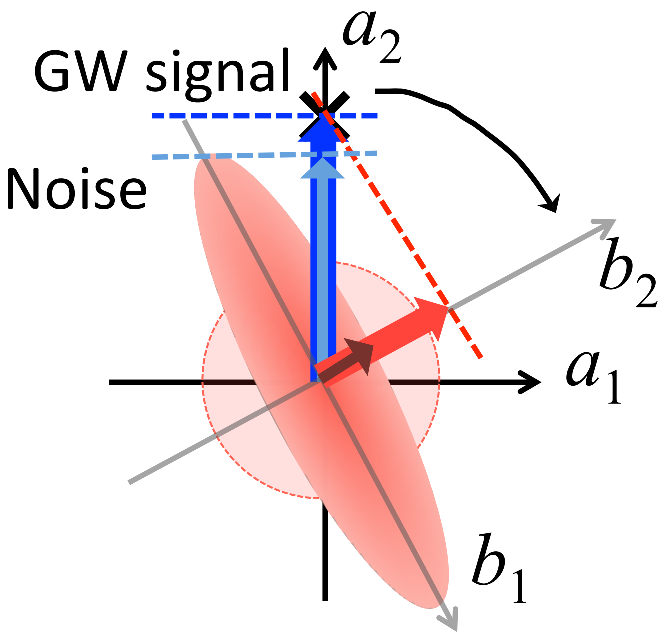
Homodyne Detection

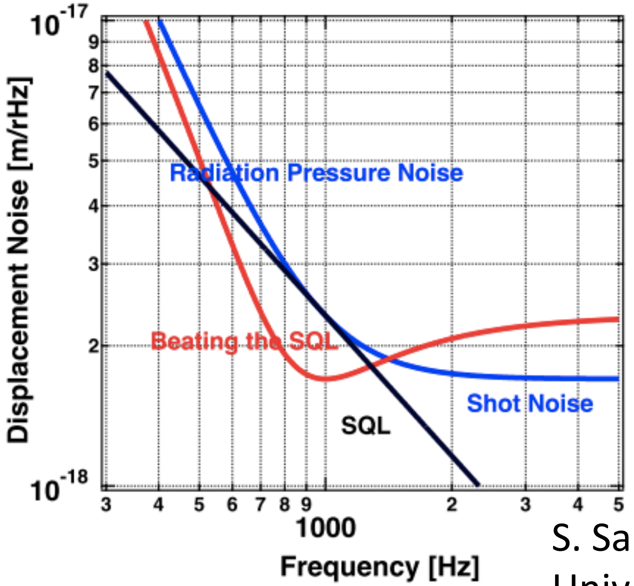
- Homodyne detection is performed by making the output signal from dark port interfere with local oscillator (LO).



Reduction of Quantum Noise

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

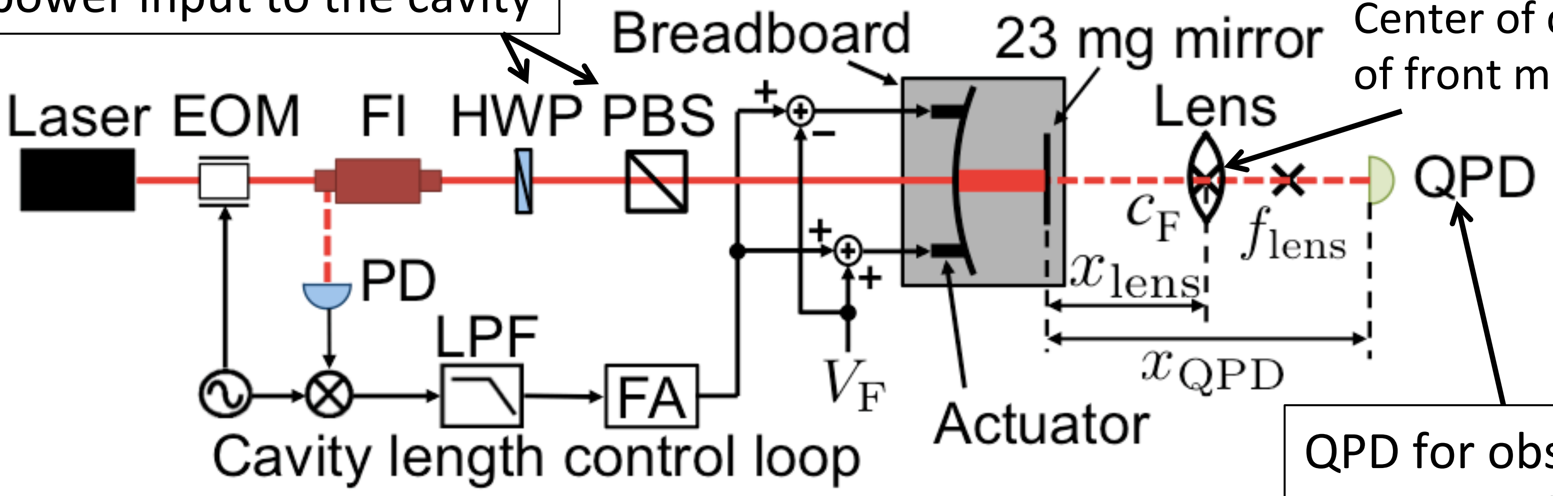
- For measuring radiation pressure noise, our experimental setup is devised as follows:
  - Suspended tiny mirrors (23 mg)
  - High finesse (~10^4) optical cavities (not yet)
  - Fabry-Perot Michelson interferometer (not yet)
- First and second one is used for enhancing radiation pressure noise.

  First one Second one

  - Recall that radiation pressure noise is $\propto \frac{\overset{\text{Second one}}{\boxed{P}}}{\underset{\text{First one}}{\boxed{m}} f^2}$.
- Third one has the purpose for reducing the common-mode noise, such as classical laser amplitude noise.

Experimental Setup

These are used for changing laser power input to the cavity

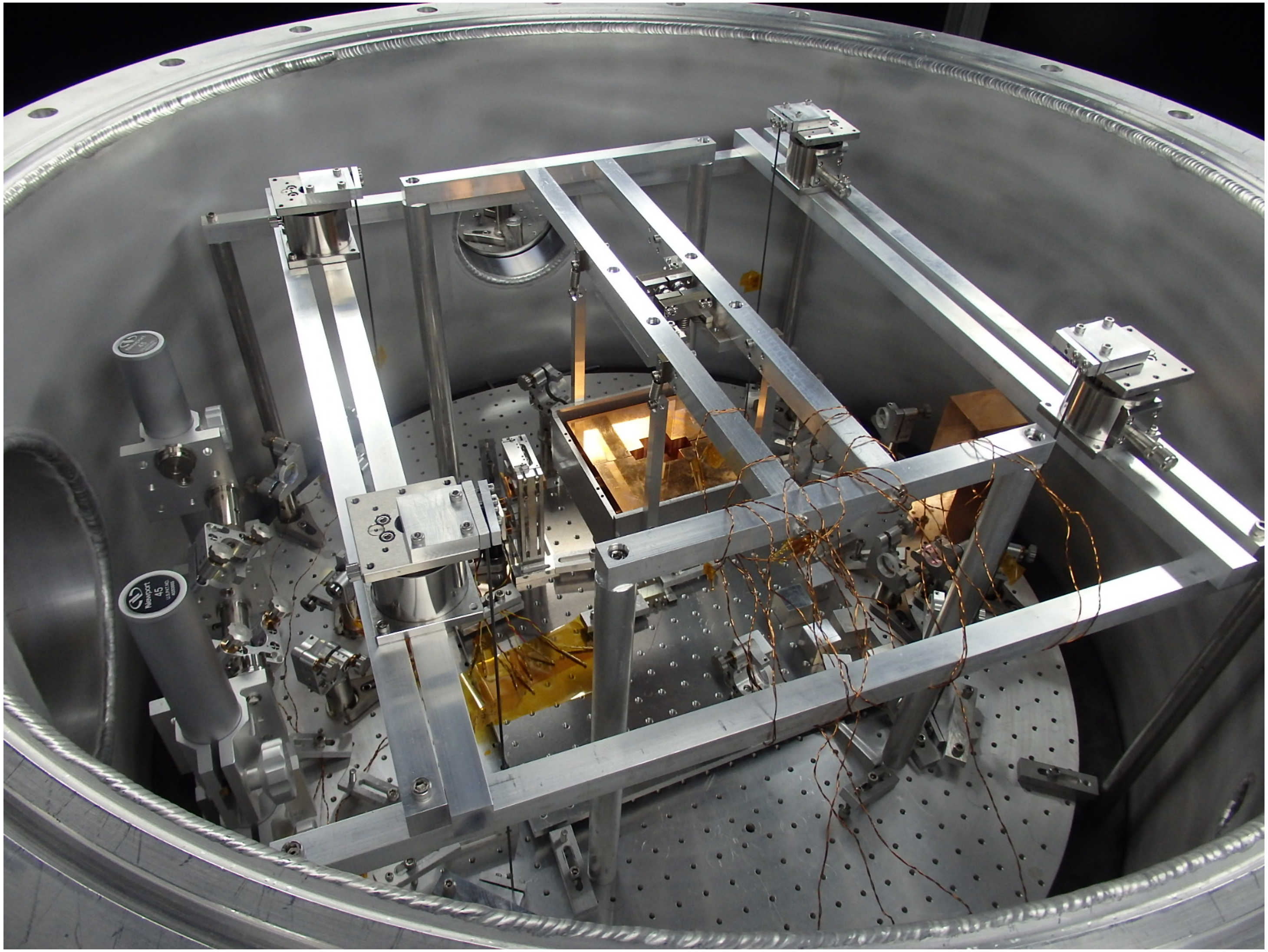


Center of curvature of front mirror

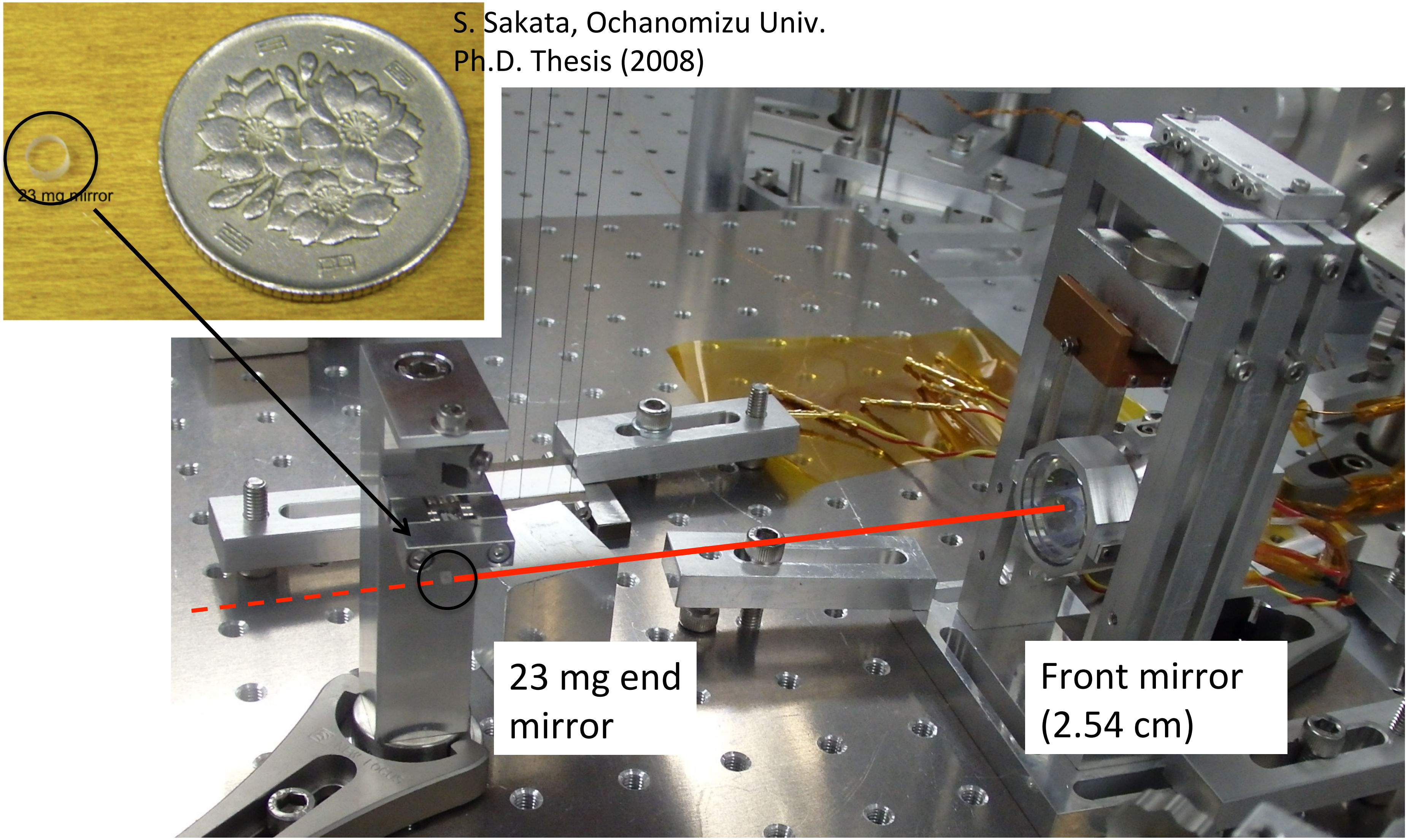
QPD for observing transmitted light

- Status of each component
  - End mirror: diameter is 3 mm, flat, **mass is 23 mg**.
  - Front mirror: diameter is 2.54 cm, radius of curvature is 1 m, mass is 55 g.
  - Cavity: length is 14 cm, finesse is about 400, set in vacuum chamber.

Experimental Setup

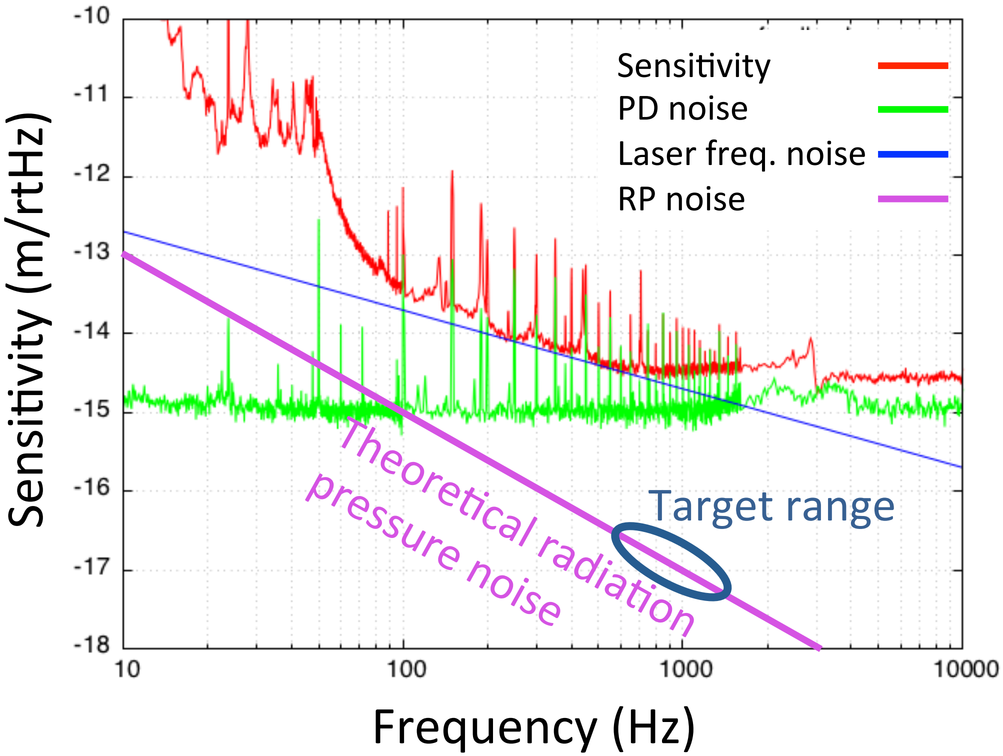


Experimental Setup



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

Current Sensitivity

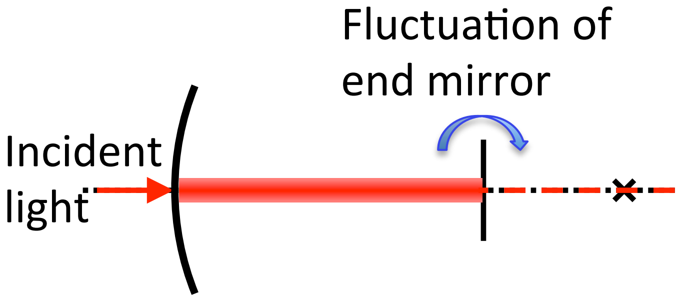


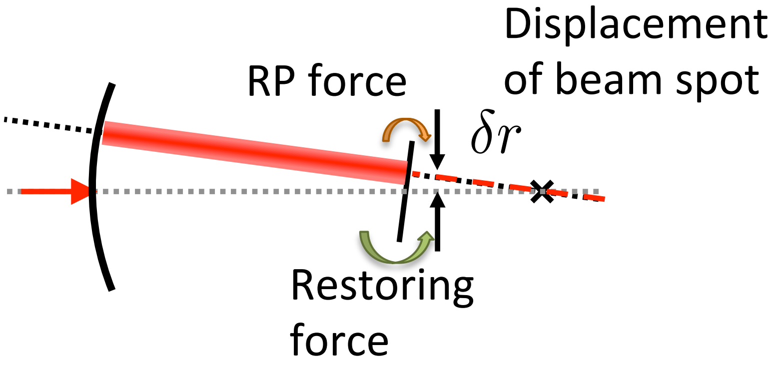
- Current sensitivity is limited by laser frequency noise (100 – 1000 Hz) and dark noise of the photo detector (1000 Hz –).

Current Problems

- Now we want to increase laser power for measuring radiation pressure noise.
- However, we 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 measuring radiation pressure noise.

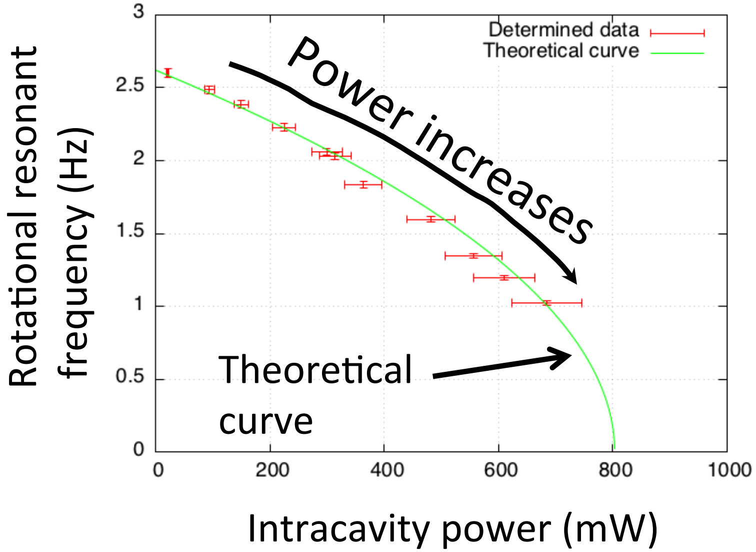
Sidles-Sigg Effect



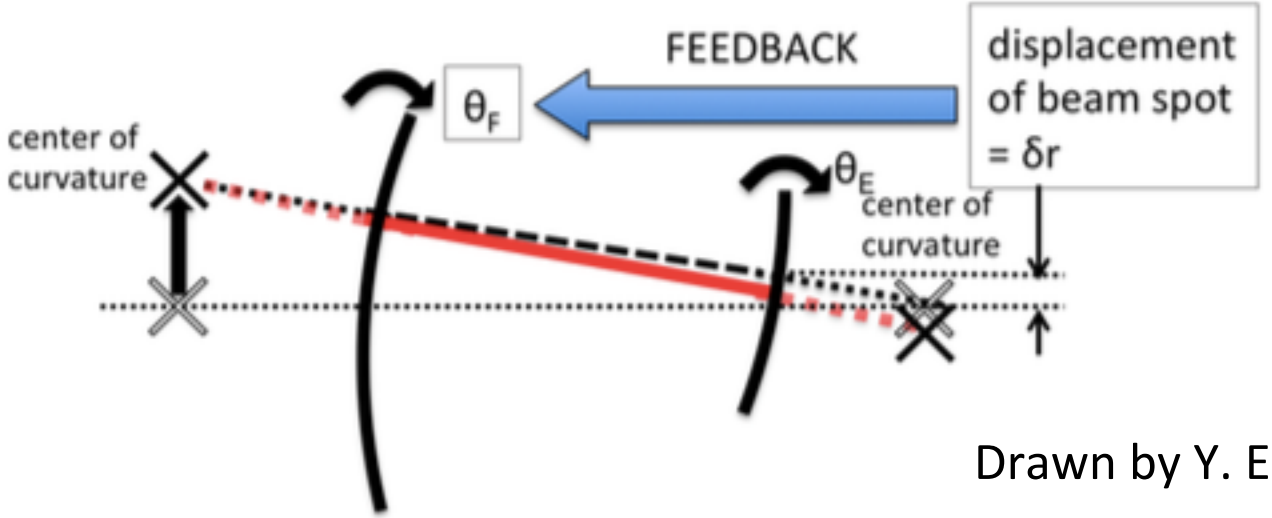


- Case1: RP > Restoring force
  → Cavity will be unstable.
- Case2: RP < Restoring force
  → **Resonant frequency will decrease.**

I have measured this case.



Rotational Control System

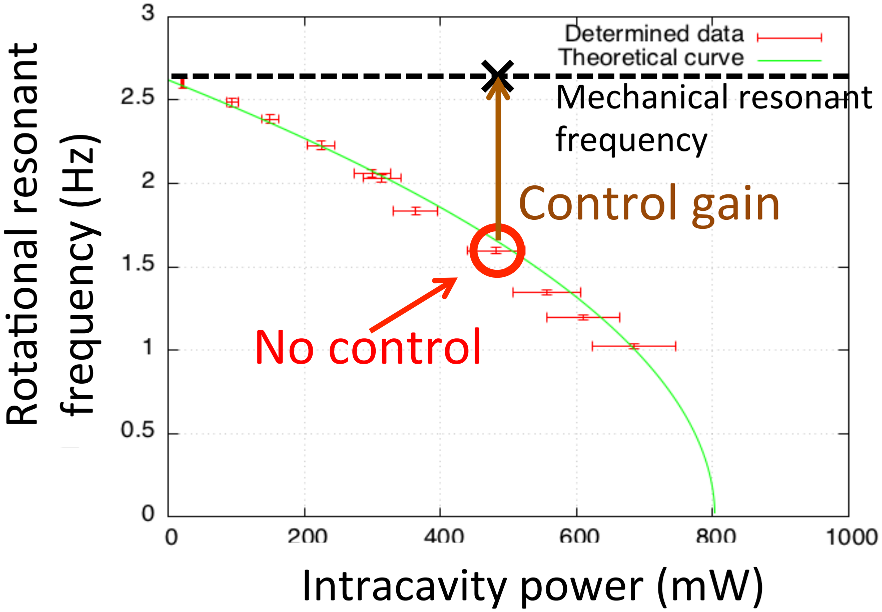


Drawn by Y. Enomoto

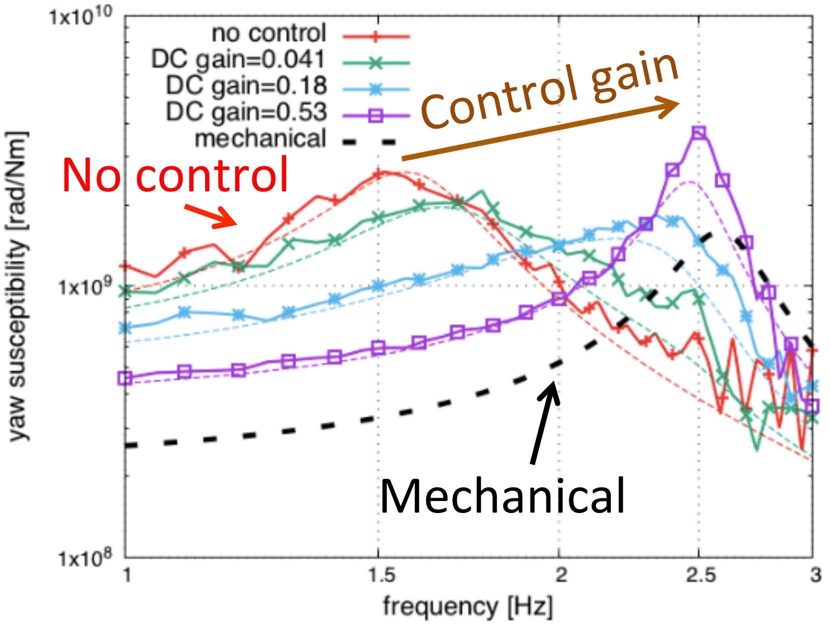
- We designed a rotational control system from displacement of the beam spot on the end mirror to the angle of the front mirror for keeping the beam spot in a certain point for avoiding the Sidles-Sigg effect.
- This feedback control system keeps the beam spot on the end mirror at the optical center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

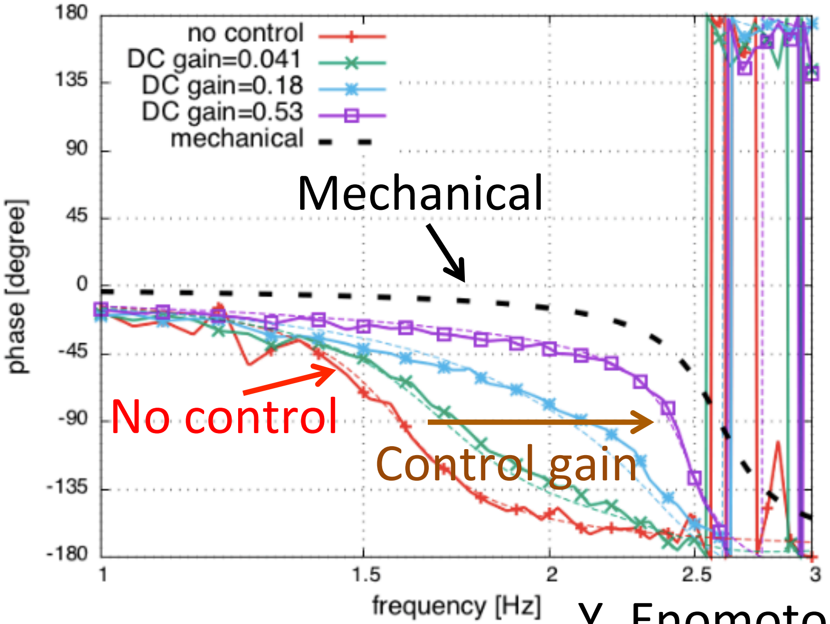
Rotational Control System

- 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 does not decrease (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





Y. Enomoto

- 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 control system.

(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 type of 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!!