Study on optical levitation of a mg-scale mirror
(光輻射圧による鏡の光学浮上技術の開発)

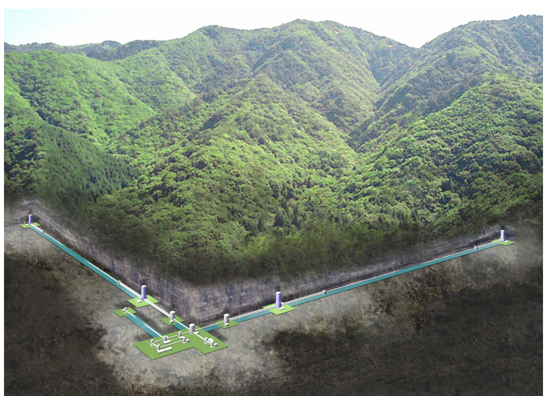
UTokyo, KAGRA Observatory, ICRR

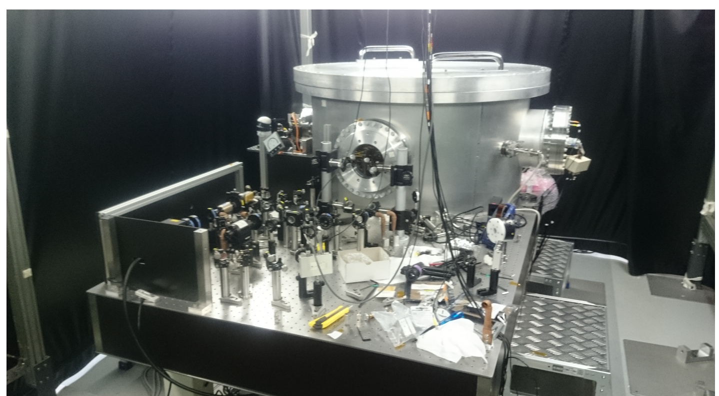
Koji Nagano (長野 晃士)

(With a lot of support from Shotaro Wada, Takuya Kawasaki, Yuta Michimura, Takafumi Ushiba, Nobuyuki Matsumoto, and Masaki Ando)

Self introduction

- NAGANO Koji (D1)
- Mainly in Hongo campus (table top).
- Study topics
  - Gravitational wave detector
    - Input-output optics (IOO)
    - Main interferometer (MIF)
  - Opto-mechnical system
  - Macroscopic quantum mechanics





Abstract

- We are studying quantum noise in the gravitational wave detector and macroscopic quantum mechanics.
- For these studies, interferometer which is dominated by quantum effect should be prepared although it can be hidden easily by environmental (classical) disturbance.
- To avoid environmental disturbance induced by ordinary mechanical suspension system, we proposed new technique, optical levitation of the mirror.
- In this talk, optical levitation will be introduced and current experimental status will be reported.

Schematic of optical levitation.

Outline

1. Introduction
2. Optical Levitation
3. Current status
4. Summary

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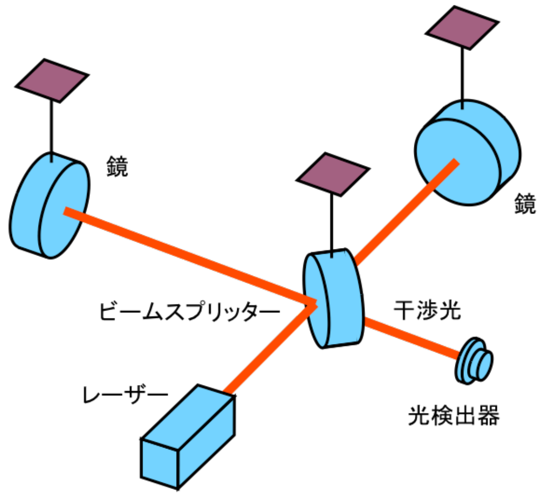
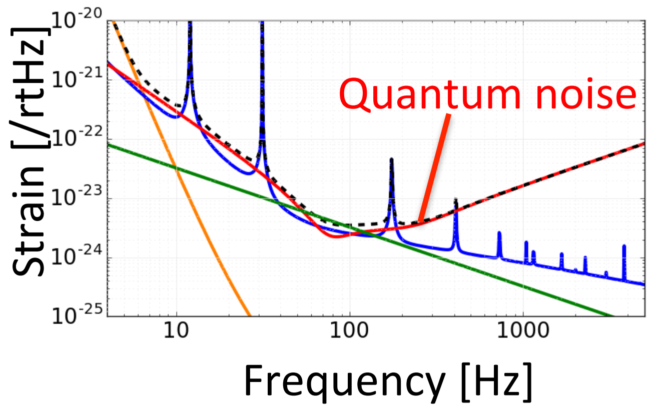
Introduction

- Laser interferometer is a very precise position measurement device and used to <u>detect gravitational waves</u>.
- One of the major noise sources of the interferometers is quantum fluctuation of light.
- Thus, <u>we need to know the features of the quantum mechanics (QM) deeply to reduce the quantum noise (QN) and improve the sensitivity of interferometers.</u>



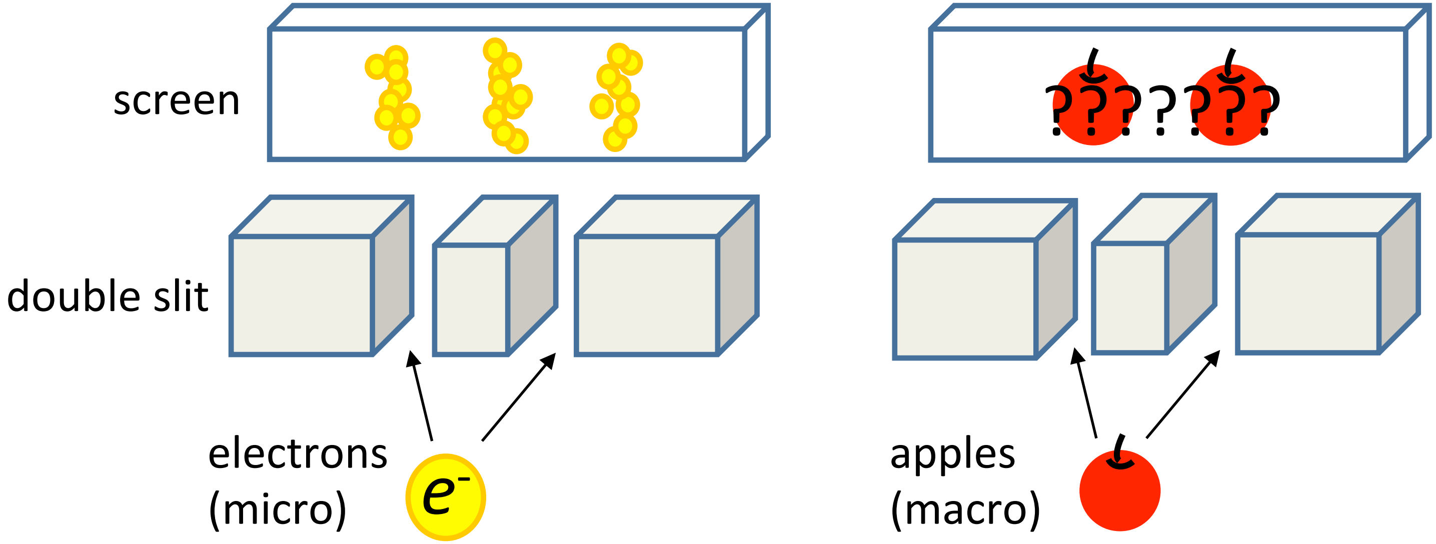
Michelson interferometer.
(Made by S. Kawamura)



KAGRA latest estimated sensitivity.

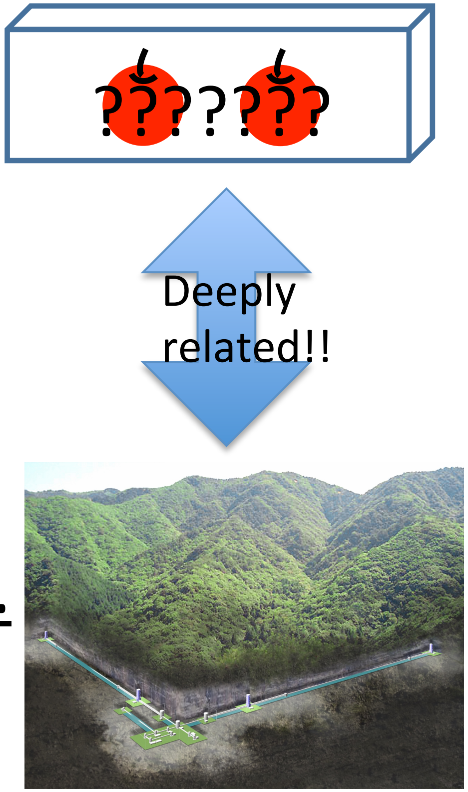
Introduction

- In addition, this QN study leads to answer to one the most fundamental question of physics: "***In the macroscopic world, does quantum mechanics hold?***"
- Surprisingly, we cannot answer this question although QM is successful in the microscopic world, such as electrons, atoms, and so on.



Introduction

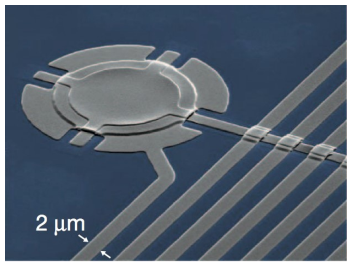
- In the macroscopic world, we have not seen quantum effect, such as super position.
- Is this because,
  - Just classical noise (CN) is large?
  - We need **<u>macroscopic quantum mechanics</u>**?
- To confirm the situation, we should make <u>various mass-scale systems which is dominated by quantum effect.</u>
- This is also necessary for the **<u>development of the reduction technique of QN of GW detectors.</u>**



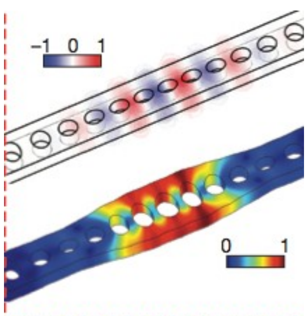
Introduction

- Prior works

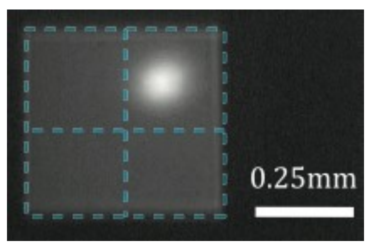
Planck mass (~ 22 ug)



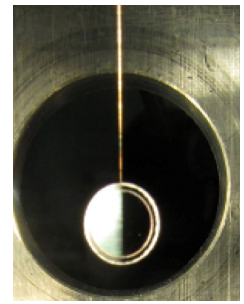
membrane, 48 pg, Teufel+ (2011)



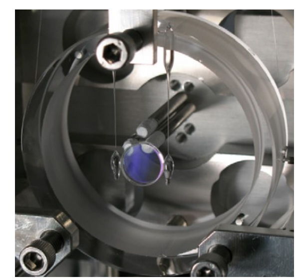
nanomechanical oscillator, 311 fg, Chan+ (2011)



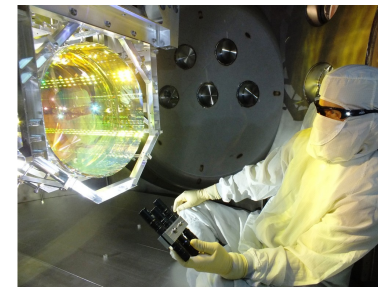
membrane, 7 ng, Peterson+ (2016)



suspended mirror, 5 mg, Matsumoto+ (2014)



suspended mirror, 1 g, Neben+ (2012)



suspended mirror, 23--40 kg, GW detector (aLIGO, AdV, KAGRA)

fg pg ng ug mg g kg mass

Introduction

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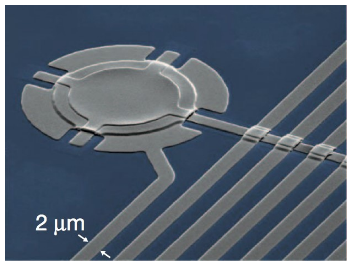
QN dominant



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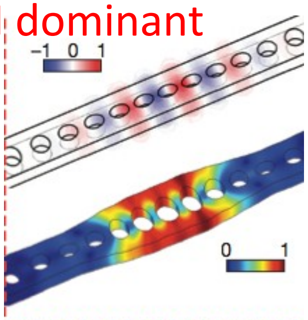

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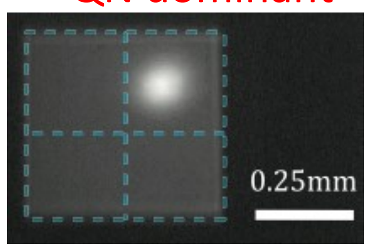

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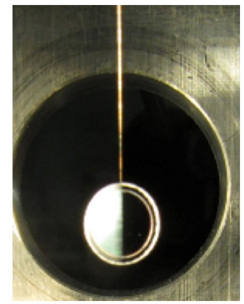

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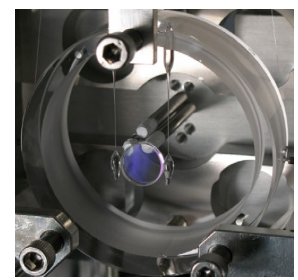

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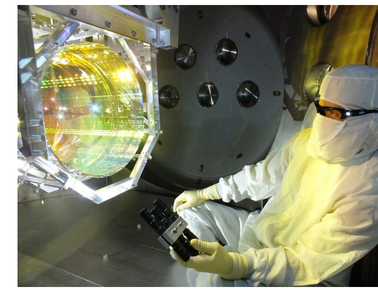

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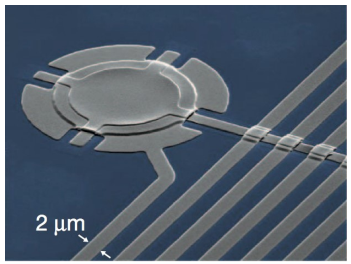

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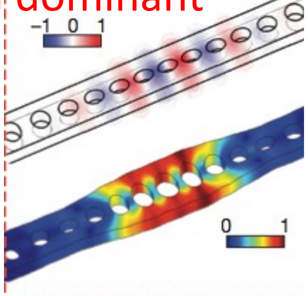

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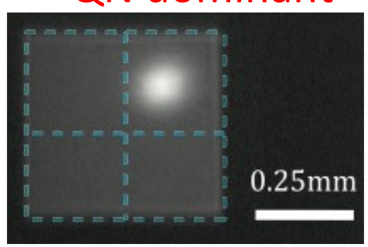

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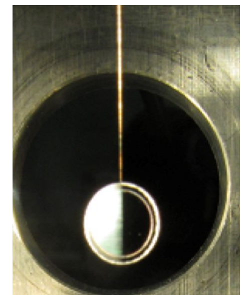

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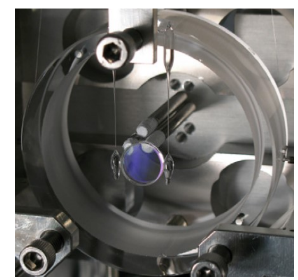

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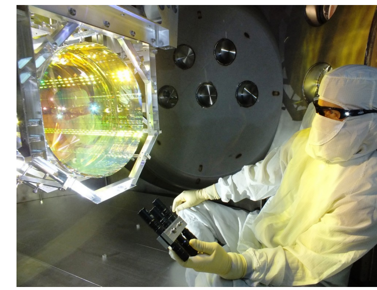

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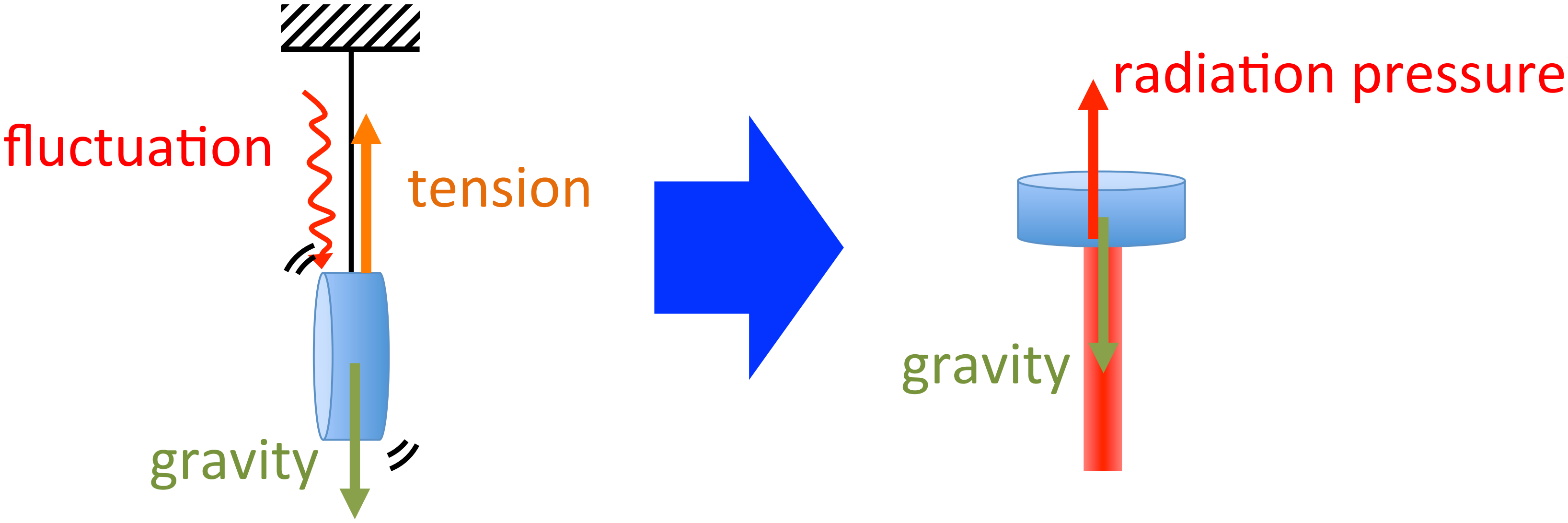
Optical levitation

- Suspension system (for seismic isolation) may introduce additional classical thermal disturbance and can hide quantum effect.
- To avoid the thermal effect, new technique to support mirror using only optical radiation which is called as <u>optical levitation</u> was proposed.



Optical levitation

Levitate the mirror only by optical radiation pressure

↓

Isolate the system from the environment and make the system dominated by quantum effect

↓

Study quantum noise in interferometers

↙ ↘

Improve sensitivity of gravitational wave detectors

Test of macroscopic quantum mechanics

Optical levitation

Study quantum noise in interferometers

Improve sensitivity of gravitational wave detectors

- See QN, in especially radiation pressure noise in advance of large scale detector.
- Develop the reduction technique of quantum in table top experiment.
- Leads to increasing of GW event ratio.

Test of macroscopic quantum mechanics

- Realize entanglement between the macroscopic mirror which can be seen!!
- Test of quantum gravity theory or objective collapse theory.
- Ultimately, lead to jointed theory of QM and GR.

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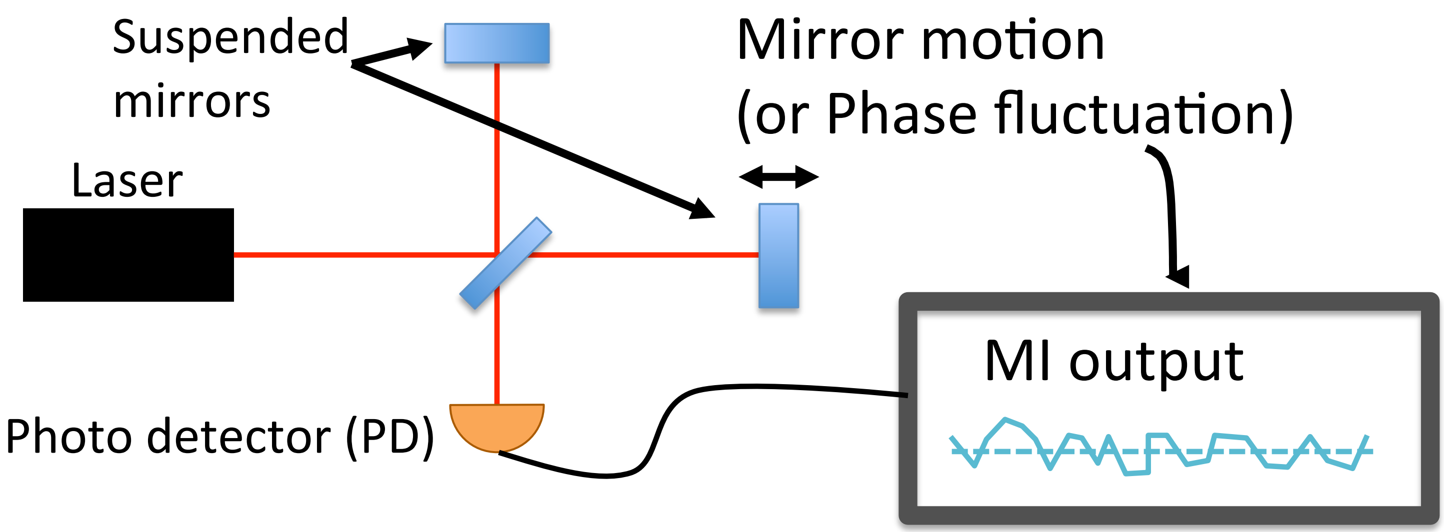
Laser interferometer

- Michelson interferometer (MI) is a device which convert phase change to power change as a signal.

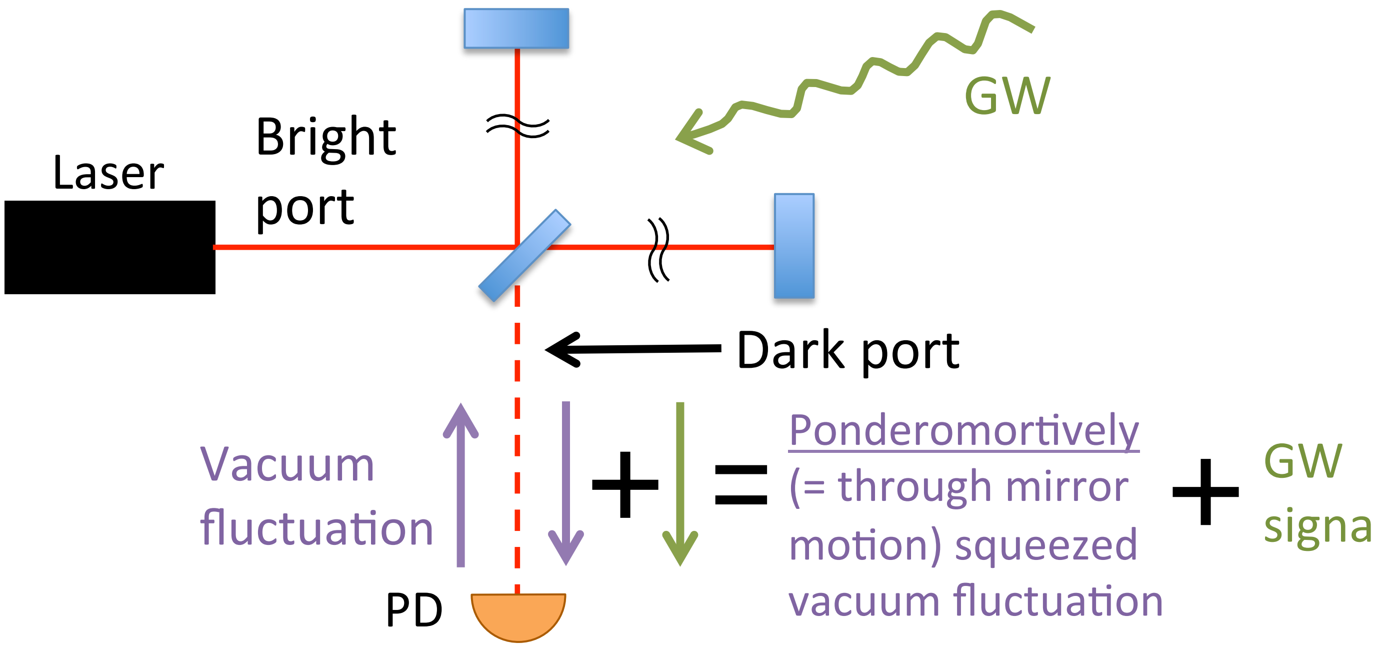
= Phase fluctuation generates signal (or noise).



Quantum noise of GW detector

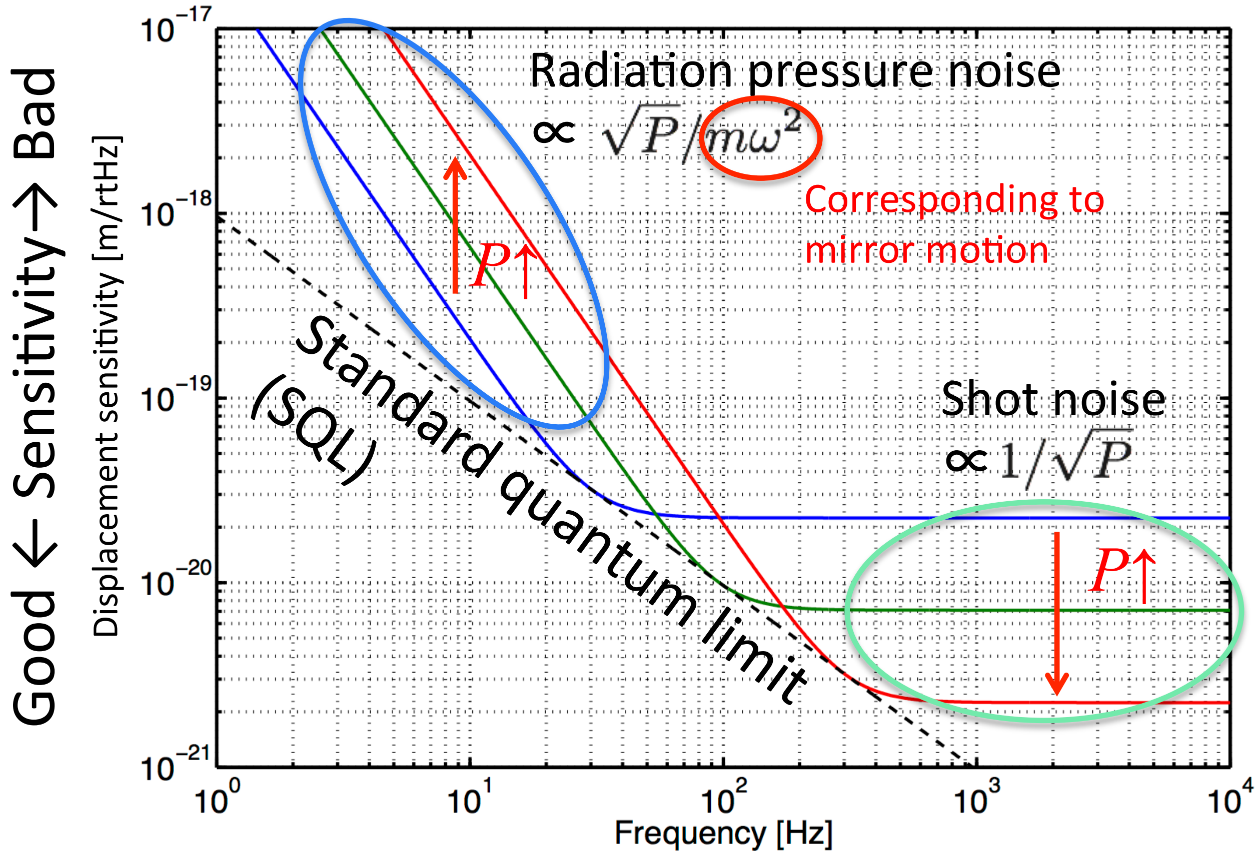
- Quantum noise of laser interferometter

= QN is caused by vacuum fluctuation induced from signal port (= dark port).



Quantum noise of GW detector

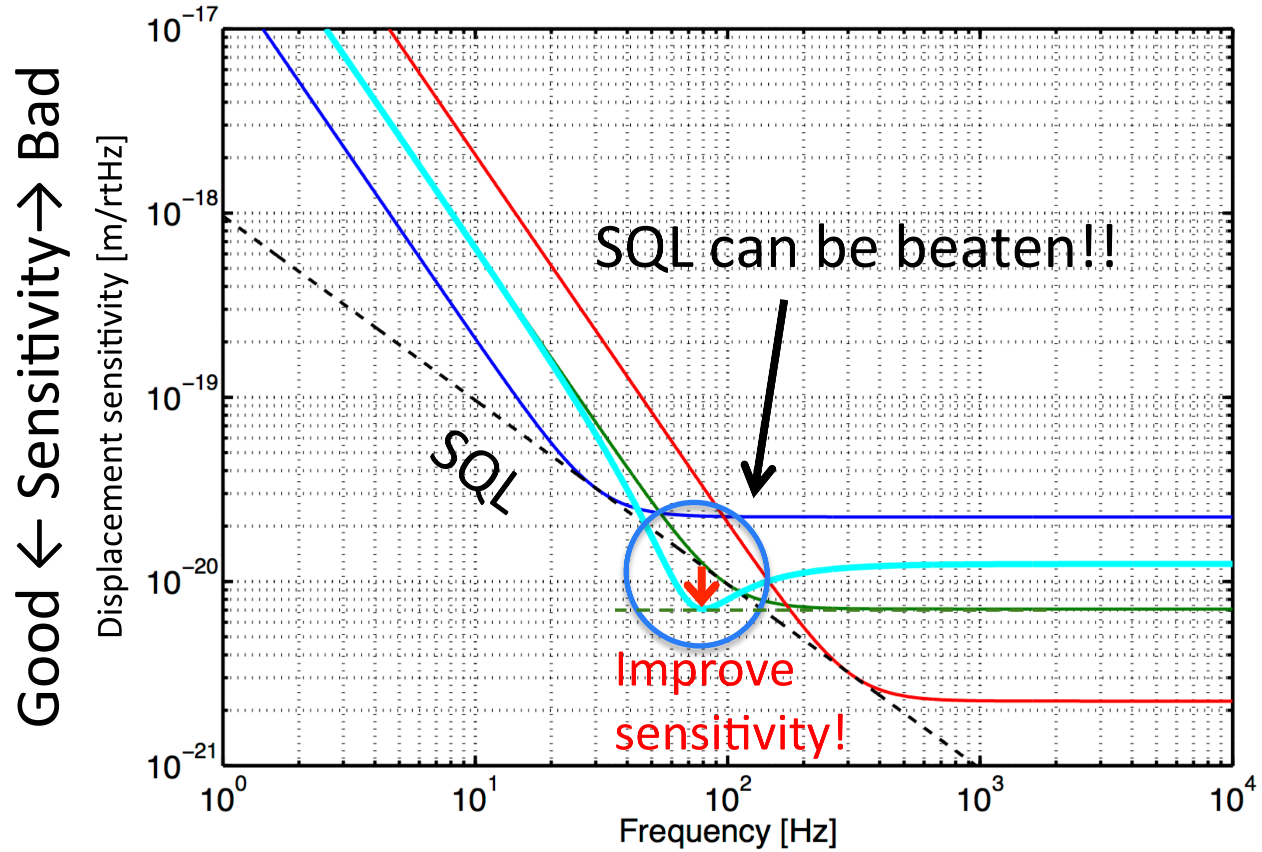
- QN of ordinary ("classical") interferometers



Quantum noise of GW detector

- QN of ~~ordinary ("classical")~~ interferometers

with homodyne detection = quantum measurement technique



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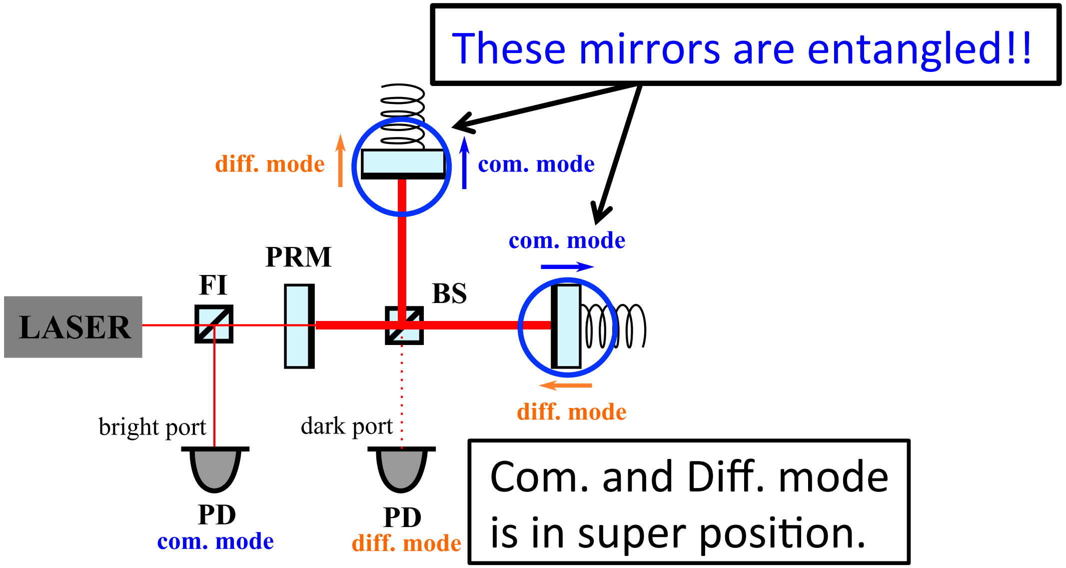
Macroscopic quantum mechanics

- If we can prepare two mirrors whose motion was dominated by quantum effect, the mirrors are entangled.
- Then, we can start to test of macroscopic quantum mechanics.

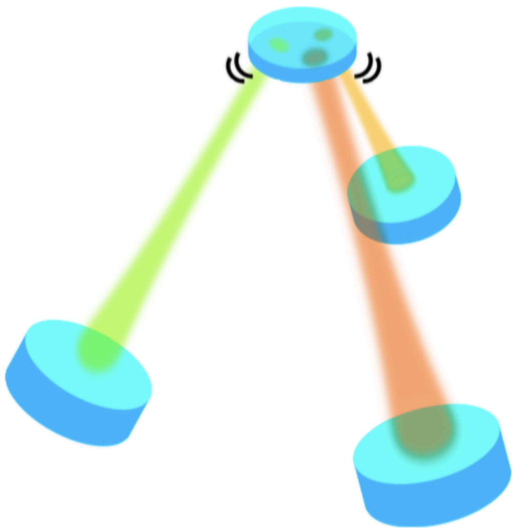


Optical levitation

- So far, two types (or more?) of OLs for mg-scale mirrors have been proposed.

Y. Kuwahara, Master thesis, University of Tokyo (2016)

sandwich type
Y. Michimura+, Opt. Express (2017)



tripod type
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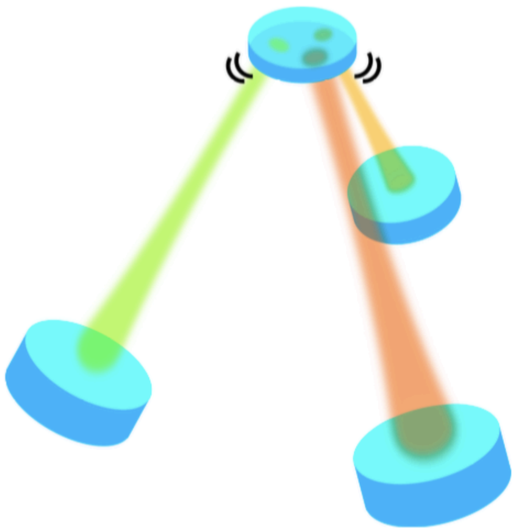

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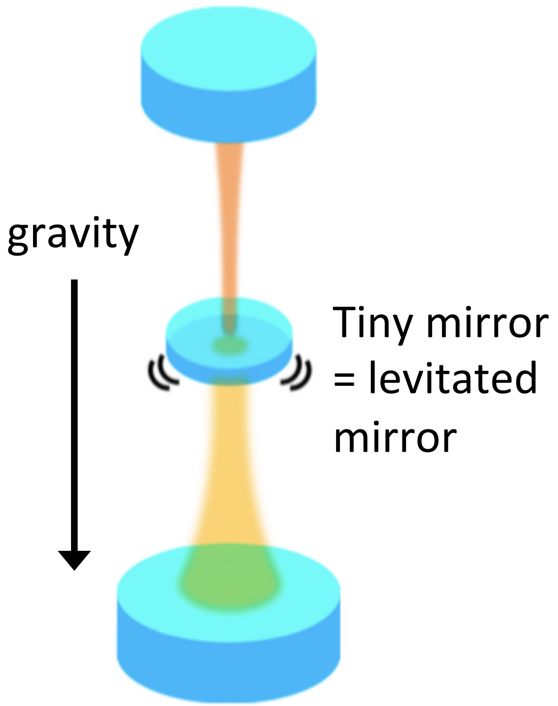
Sandwich type optical levitation

Sandwich type optical levitation

- Inserting a curved tiny mirror (~ 1mg) between two optical cavities allows the tiny mirror to levitate stably.
- Simpler method.
- Quantum noise dominant system can be achieved.
- This is still theoretical proposal [1]. Thus, we need experimental demonstration.

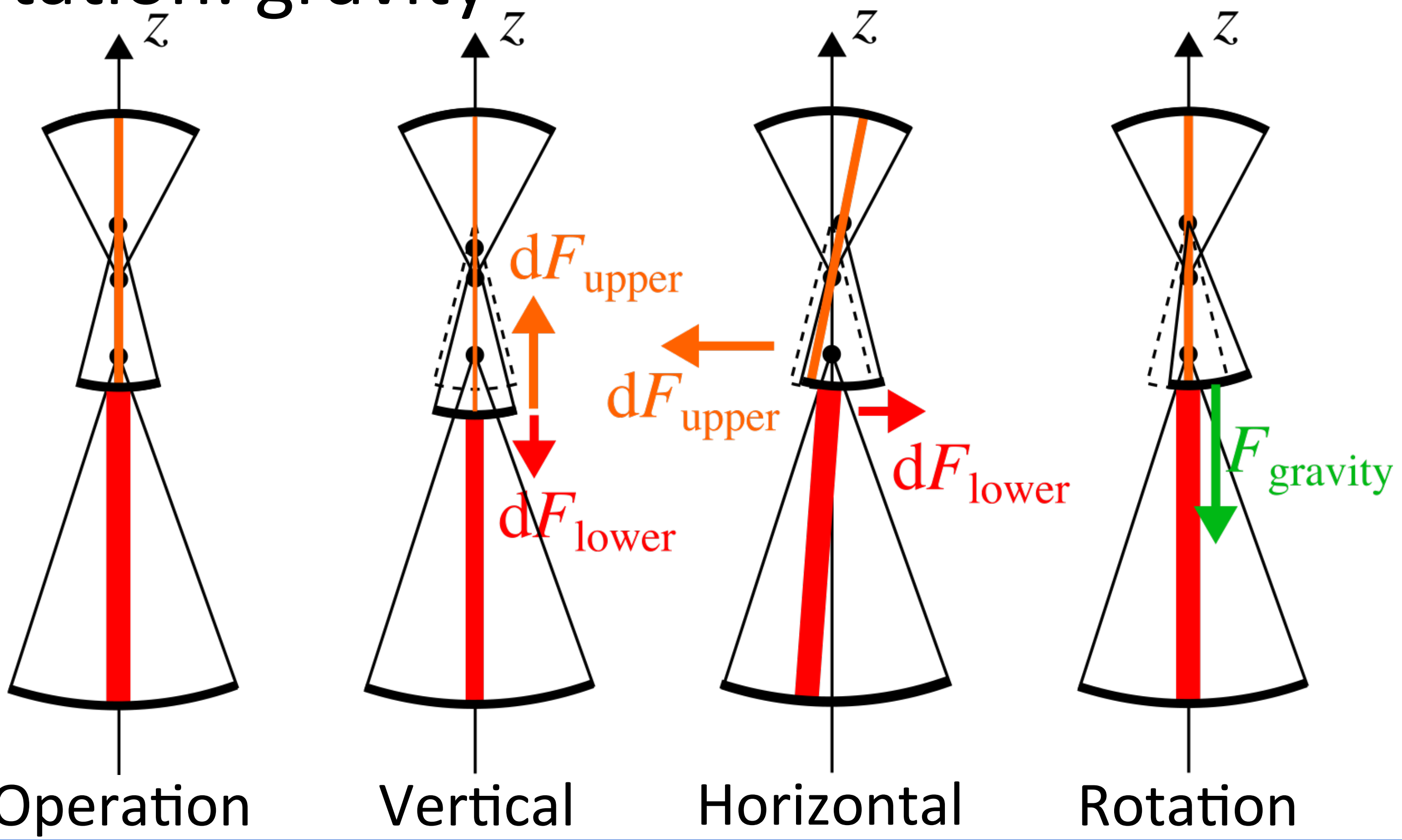
[1] Y. Michimura et al., *Opt. Express*, 2017.



Schematic of the sandwich type optical levitation.

Stability of SW optical levitation

- Vertical: optical spring
- Horizontal: tilt of optical axes
- Rotation: gravity



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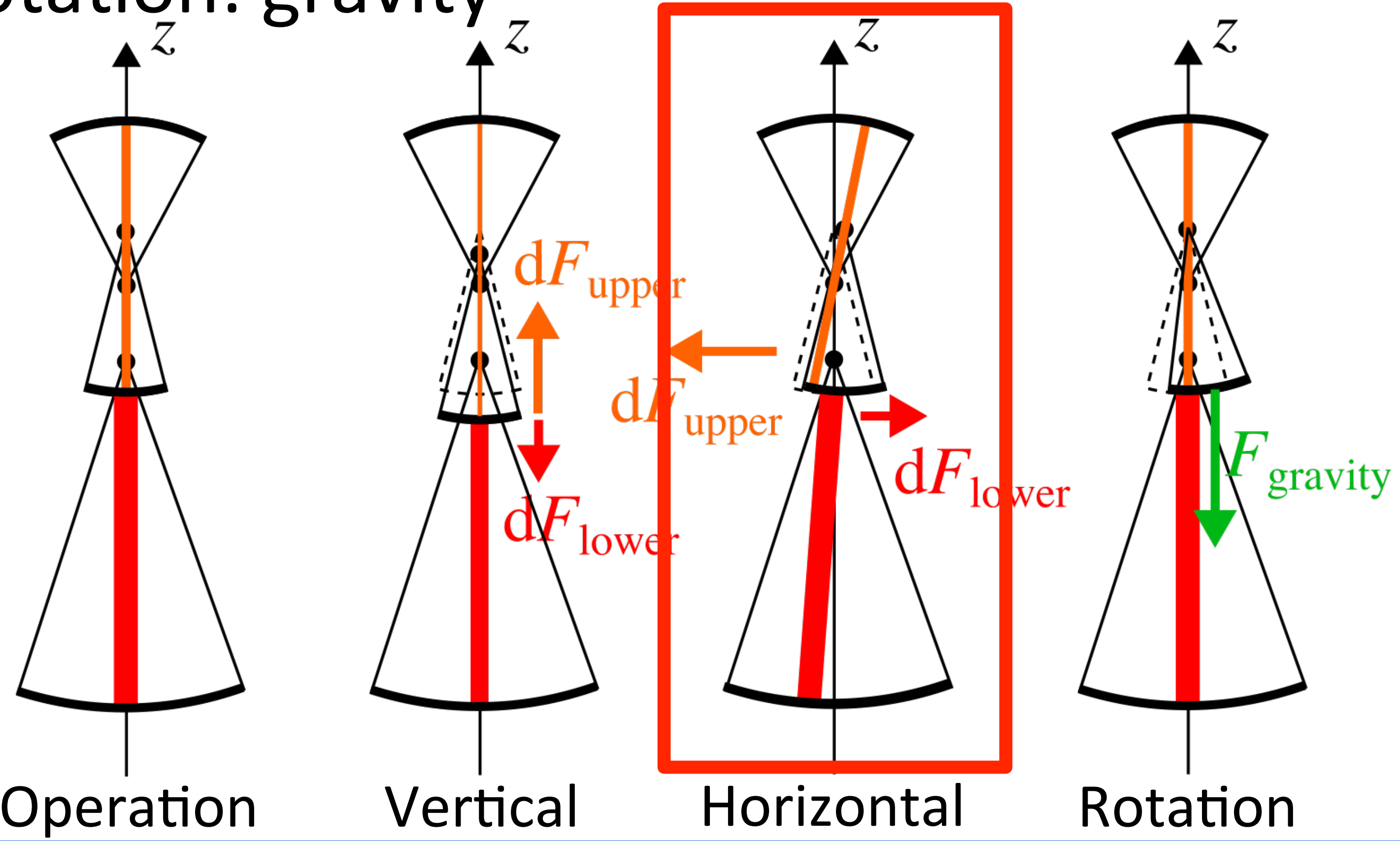
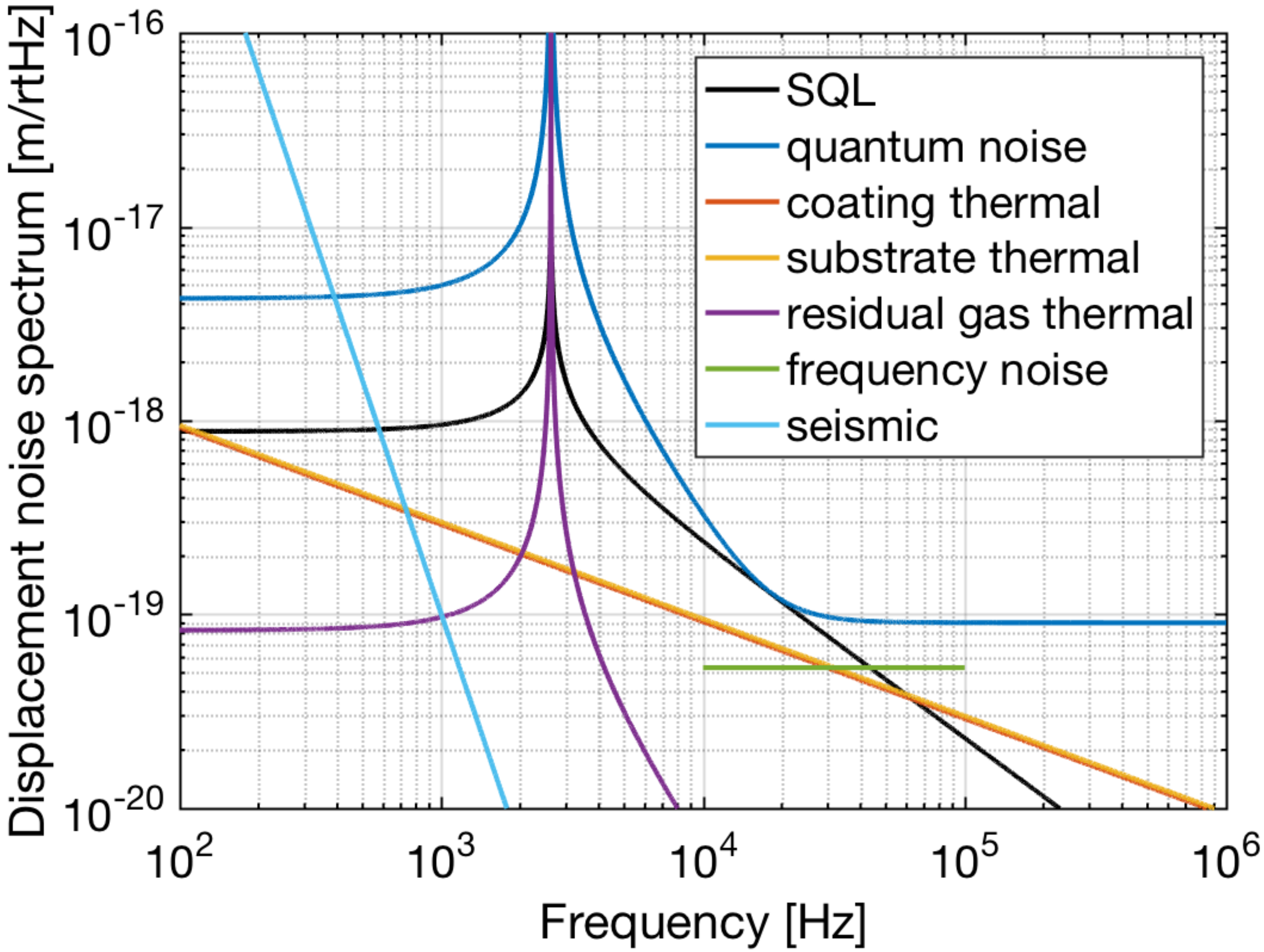


Sensitivity of SW optical levitation

- QN dominate system can be achieved.

Parameters
mirror mass: 1 mg
Finesse: 100
Laser power:
40 W (lower),
10 W (upper)



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Current status

- Challenging points
  - Tiny mg-scale mirror fabrication
    - Evaluation of the tiny mirror property
  - Demonstration of horizontal stability of the sandwich type optical levitation
  - How to reach the actual levitation
  - How to reduce all of the classical noises
  - and so on

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  - Tiny mg-scale mirror fabrication
    - Evaluation of the tiny mirror property
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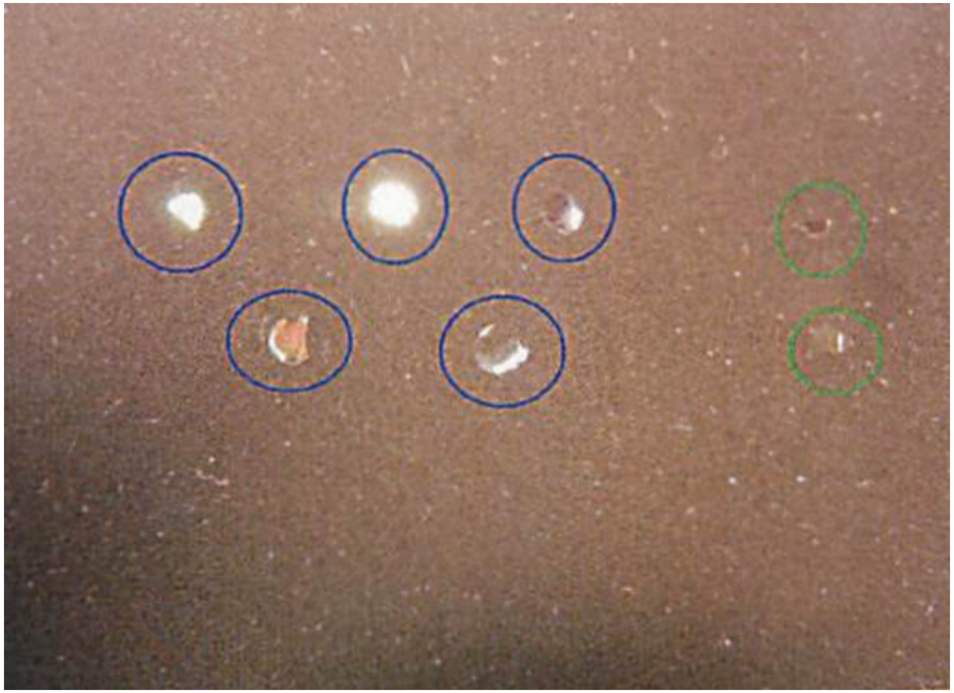
  - How to reduce all of the classical noises
  - and so on

Fabrication of the tiny mirror

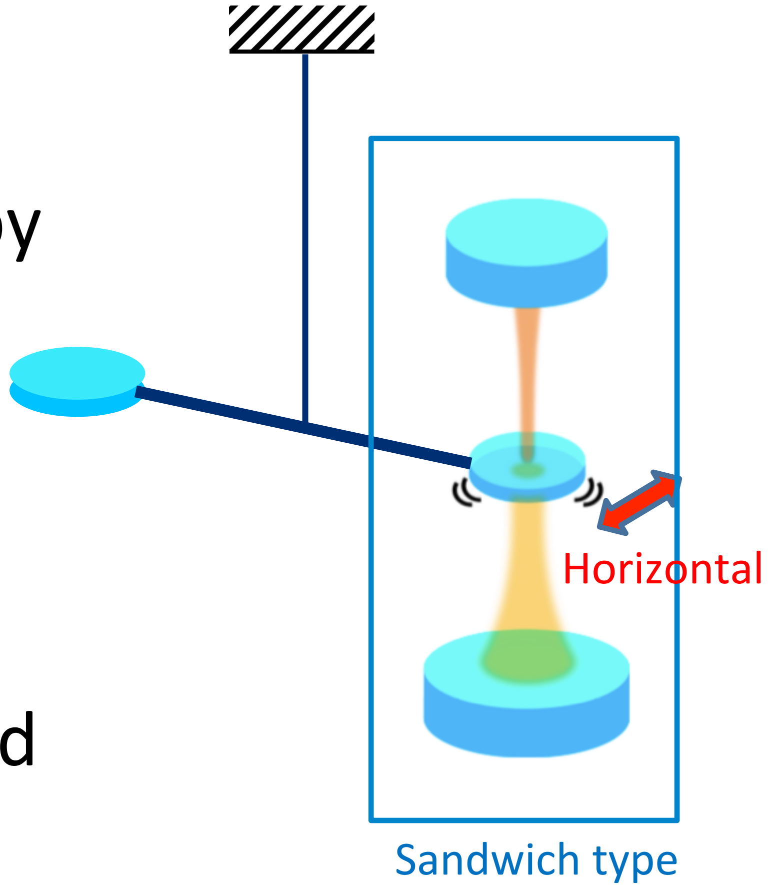
- Specs of tiny mirror
  - mass: 1.6 mg (dia: 3 mm, thick: 0.1 mm)
  - RoC: 30 mm (Convex)
  - Reflectivity: 0.9995
- Although the fabrication is challenging, 1.6 mg mirror has been delivered.
  - However, the mirror without any lack is only one.
- Evaluation of the delivered mirror property is also challenging and on going.



Picture of the mirror after coating. Only one of seven does not have any lack.

Principle demonstration

- We are trying to demonstrate it with a torsion pendulum before the fully optical setup.
- Restoring torque generated by sandwich type configuration will be measured.
- Well sensitive torsion pendulum has been made.
- The setup is being constructed in a vacuum chamber.



Future plan

- We are now testing each component which is needed for sandwich type optical levitation.
- After the current components test, we will integrate them.
- Then, we will try to levitate the mirror optically in the next fiscal year (FY2018).

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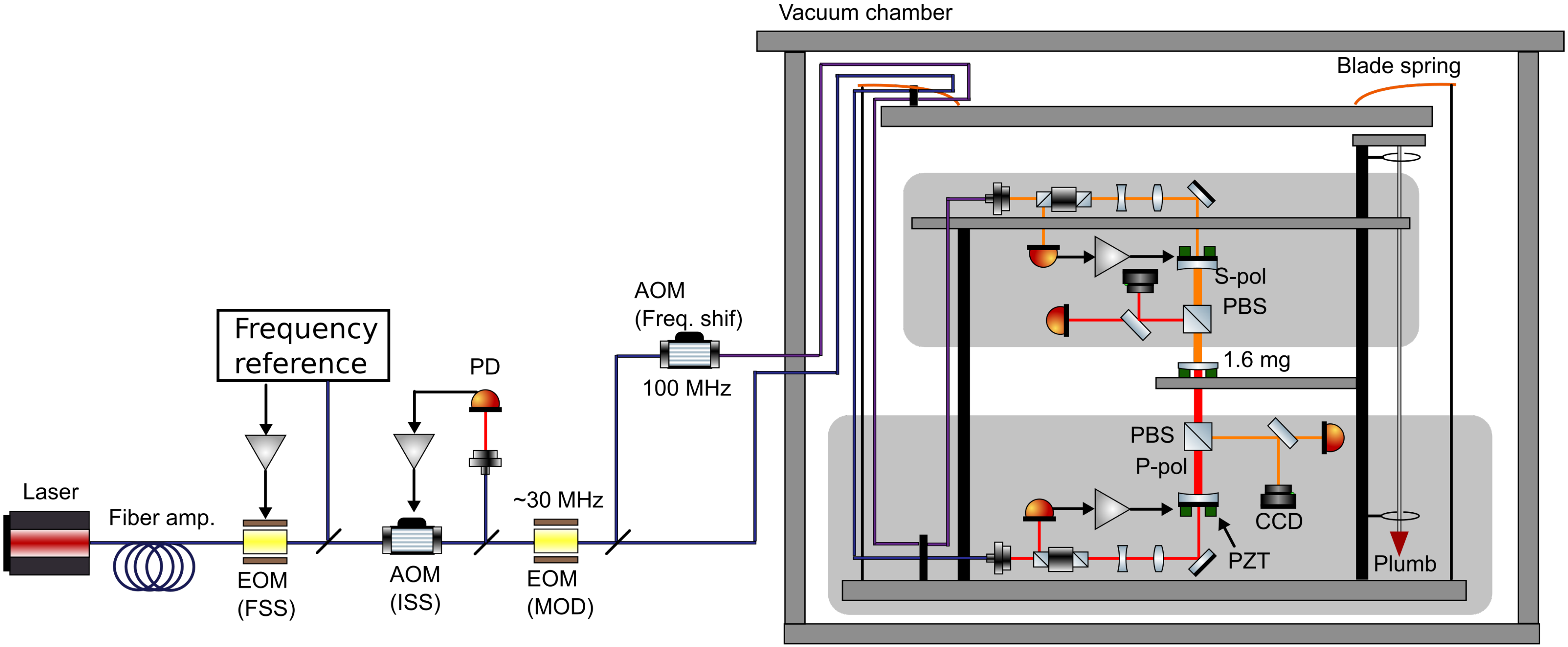
Summary

- For the development of the QN reduction technique in GW detectors and test of macroscopic QM, we are preparing sandwich type optical levitation.
- We are now testing each component.
- We will try to levitate the mirror optically in the next fiscal year (FY2018).

Schematic of the sandwich type optical levitation.

Appendix

Setup


Vacuum chamber
Blade spring
Frequency reference
PD
AOM
(Freq. shif)
100 MHz
S-pol
PBS
1.6 mg
PBS
P-pol
CCD
PZT
Plumb
Laser
Fiber amp.
EOM
(FSS)
AOM
(ISS)
~30 MHz
EOM
(MOD)

Macroscopic quantum mechanics

- ***In the macroscopic world, does quantum mechanics hold?***
- We have not seen quantum effect, such as super position, in the macroscopic world.
- If we can see macroscopic quantum effect, it might lead to the jointed theory between QM and general relativity.