Development plan of Phase-III TOBA toward my Ph.D. thesis

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Contents

- Introduction of TOBA for new members
- Design and previous studies of Phase-III TOBA
- Current status of my experiment
- Plans of my experiment

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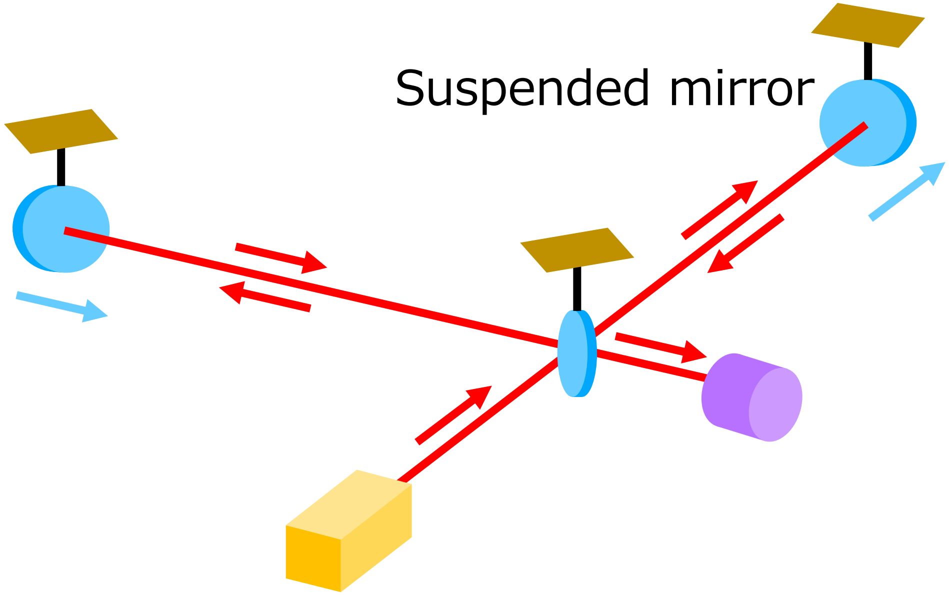
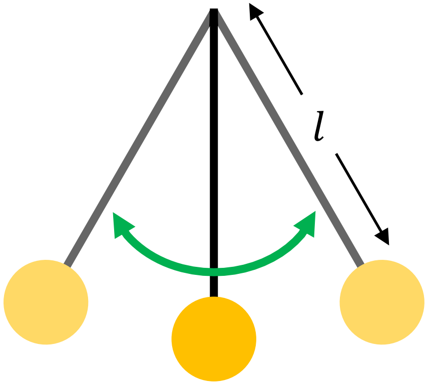
Laser interferometric GW detectors

- LIGO, Virgo, KAGRA
  - Michelson interferometer with suspended mirrors
  - Good sensitivity in 10 Hz-1 kHz
  - Detect mergers of solar mass BHs and neutron stars
- GWs in low freq. have other scientific targets (later), but we cannot use normal pendulum



Mirror behaves as free mass
above resonant frequency

Normal (translational) pendulum



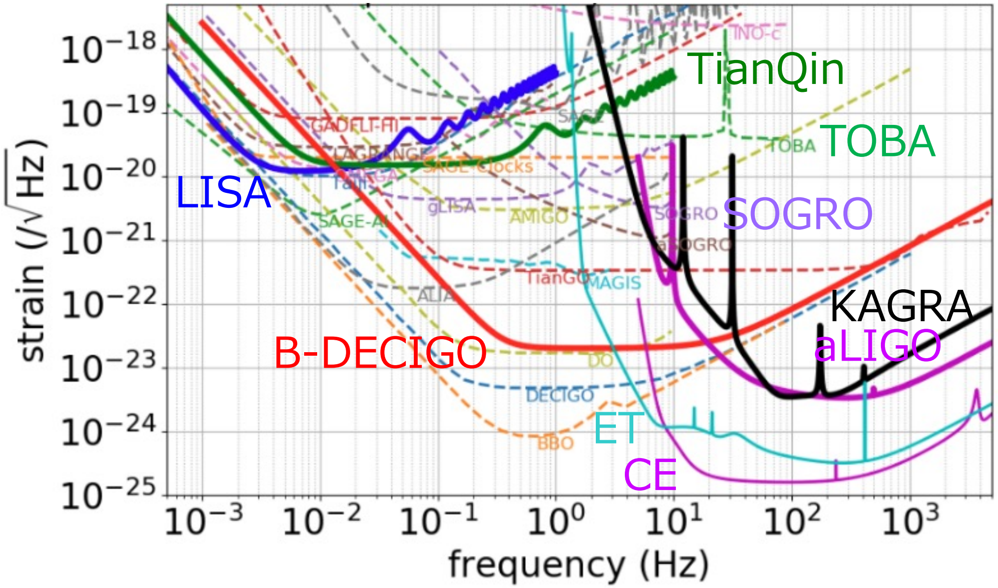
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$

- $f_0 = 0.7\ \mathrm{Hz}$ when $l = 50\ \mathrm{cm}$
- $f_0 = 10\ \mathrm{mHz}$ when $l = 2.5\ \mathrm{km}$

GW detectors in low frequency

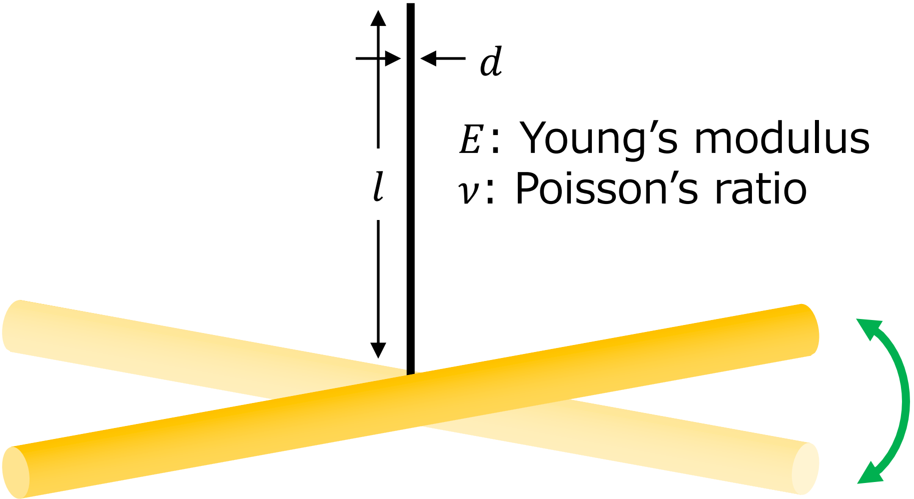
- We have two choices to build GW detectors in low freq.
- Space GW detectors
  - Good sensitivity
  - LISA, DECIGO, TianQin
- Ground-based GW detectors using other principles
  - Inexpensive to develop, easy to maintain
  - Superconducting levitation: SOGRO
  - Atom interferometer: MIGA
  - Torsion pendulums: TOBA, TorPeDo

Michimura-san's seminar



Resonant freq. of torsion pendulum

Torsion pendulum



E: Young's modulus
ν: Poisson's ratio

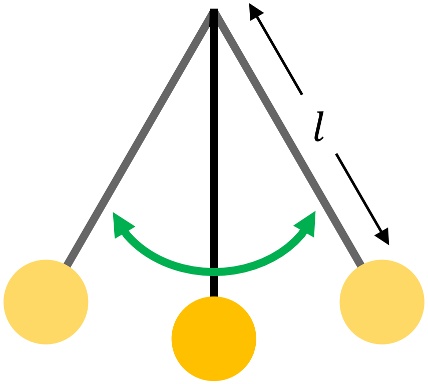
I: moment of inertia

$$f_{\mathrm{Yaw}} = \frac{1}{2\pi}\sqrt{\frac{\pi E d^4}{64 l (1+\nu) I}}$$

- $f_0 = 20\ \mathrm{mHz}$
  when $l = 50\ \mathrm{cm}, d = 0.3\ \mathrm{mm}$,
  $E = 411\ \mathrm{GPa}, \nu = 0.28$ (tungsten),
  $I = 0.016\ \mathrm{kg\ m^2}$
  (aluminum, 30×5×5 cm³)

- Resonant freq. of torsional mode is much lower than translational mode
  → We can detect GW around 0.1 Hz with torsion pendulum

Normal (translational) pendulum



$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$

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TOBA: TOrsion-Bar Antenna

- Ground-based GW detector for low freq. (0.1-10 Hz)
- Aim to detect the differential torsional rotation of two test masses for common mode rejection

2005-2014

2015-Now

Phase-I

Phase-II

Phase-III

Final

Principle test

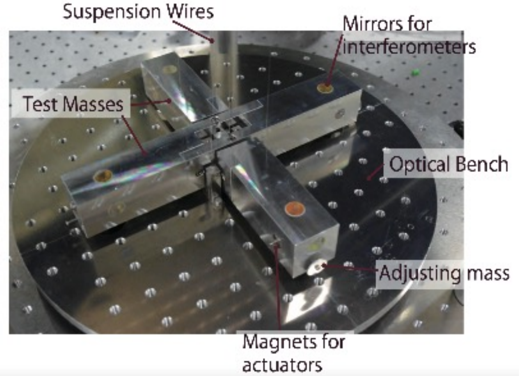
Geophysics / Noise reduction

GW observation

10^{-8} /√Hz (established)
~20 cm bars
Room temp.

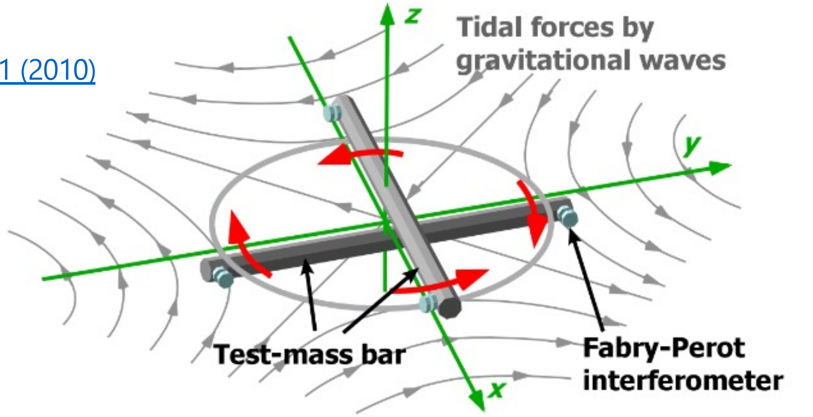
10^{-15} /√Hz (target)
35 cm bars
Cryo. temp. (4 K)

10^{-19} /√Hz (target)
10 m bars
Cryo. temp. (4 K)



K. Ishidoshiro+, PRL 106, 161101 (2011)
A. Shoda+, PRD 95, 082004 (2017)

M. Ando+
PRL 105, 161101 (2010)

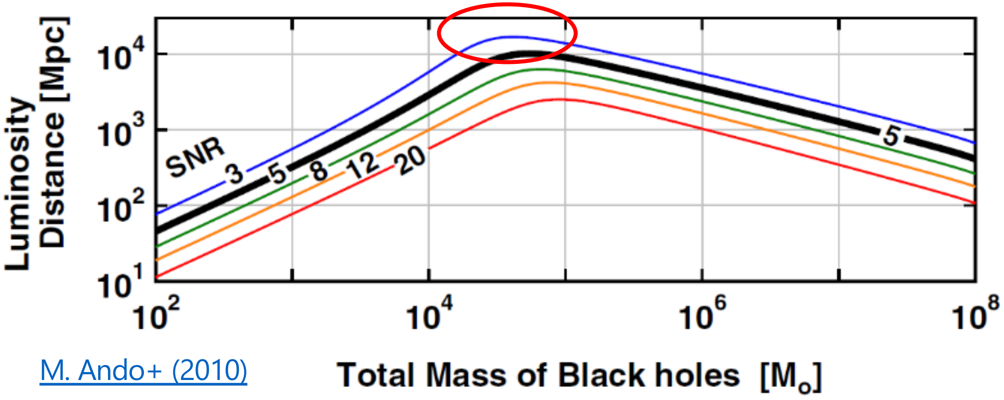


Science of TOBA (GW in low freq.)

- Binary mergers of intermediate mass BHs
  - Within ~1 Mpc (inside the Milky Way Galaxy) (Phase-III)
  - Within ~10 Gpc (10 billion years ago) (Final)

  → Formation process of supermassive BHs
- Stochastic GW background
  - Ω_{GW} ~10^{-7} @ 0.1 Hz (Final)

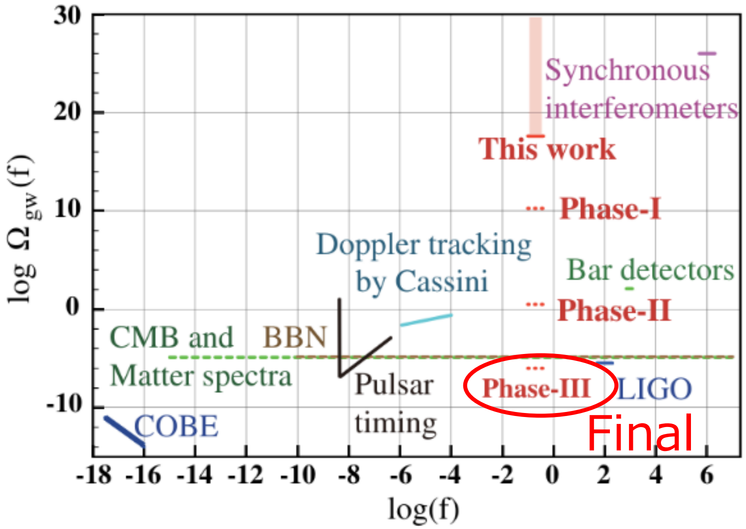
  → Direct exploration of the early universe



10 Gpc for $10^5\ M_\odot$

M. Ando+ (2010)

K. Ishidoshiro+ (2011)



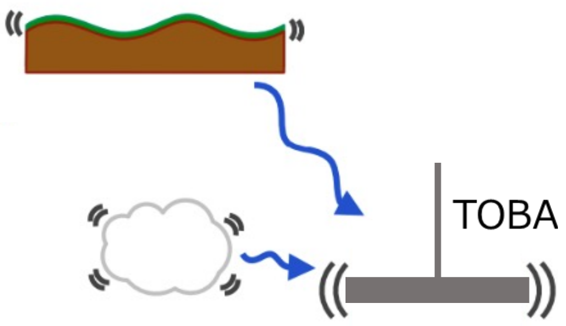
Science of TOBA (Geophysics)

- Newtonian noise: local gravity gradient noise caused by density perturbation of atmosphere and ground
  - First direct detection (Phase-III)

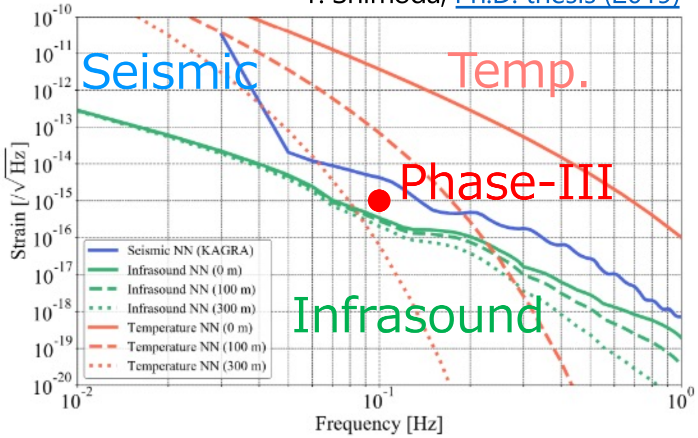
  → Noise reduction of third generation GW detectors

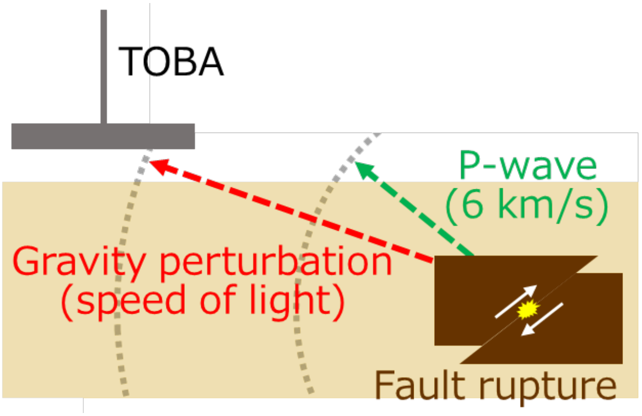
- Earthquake early warning
  - M7 earthquake at a distance of 100 km within 10 sec (Phase-III)

  → Reduction of disaster damage



T. Shimoda, Ph.D. thesis (2019)





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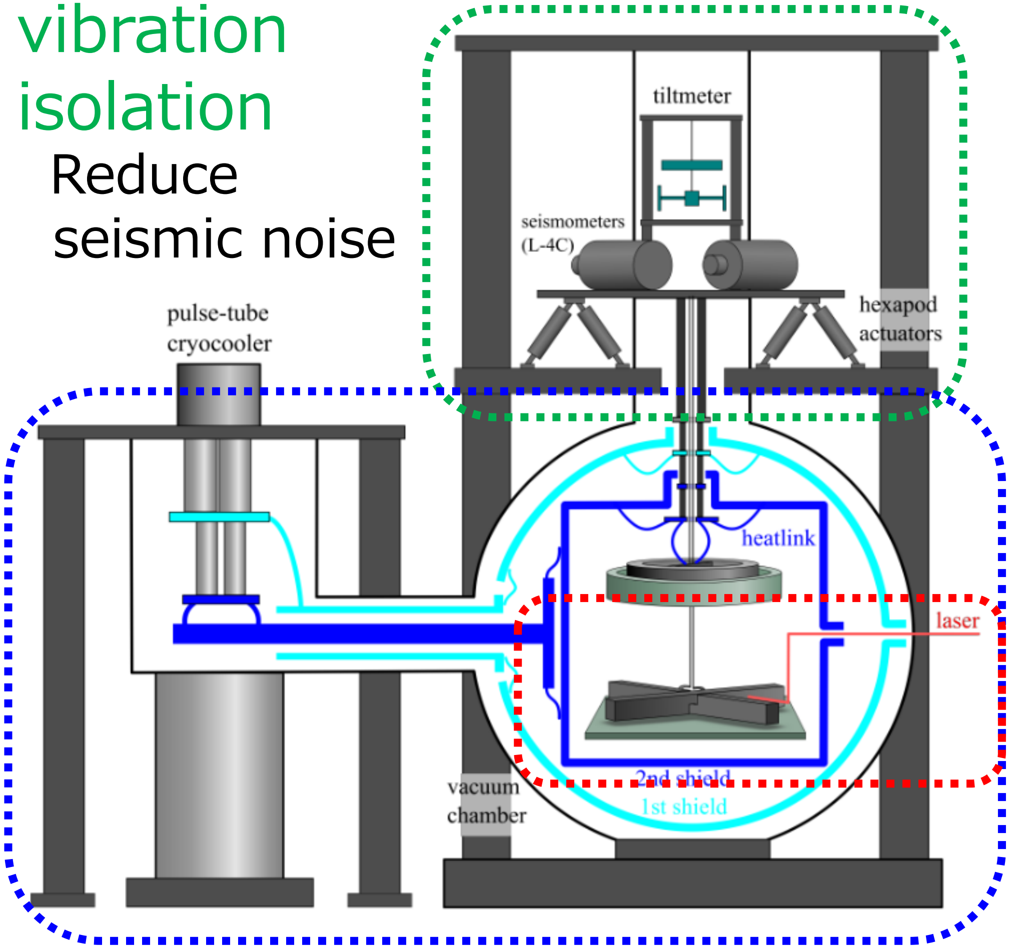
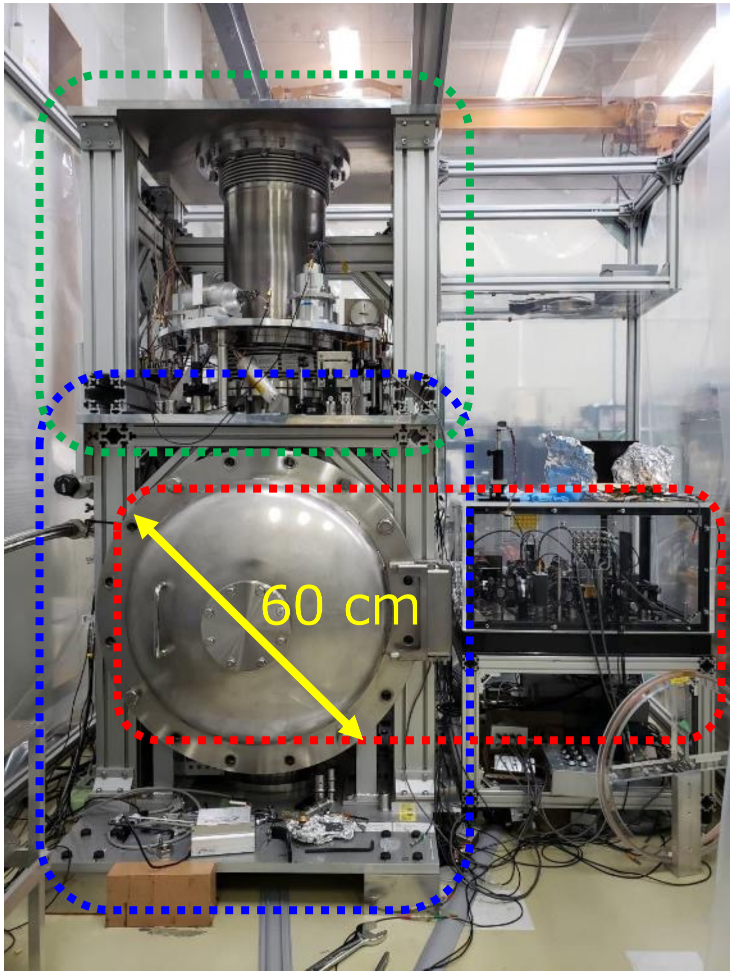
Configuration of Phase-III TOBA

T. Shimoda, Ph.D. thesis (2019)
T. Shimoda+, Int. J. Mod. Phys. D 29, 1940003 (2020)

Active vibration isolation

Reduce seismic noise





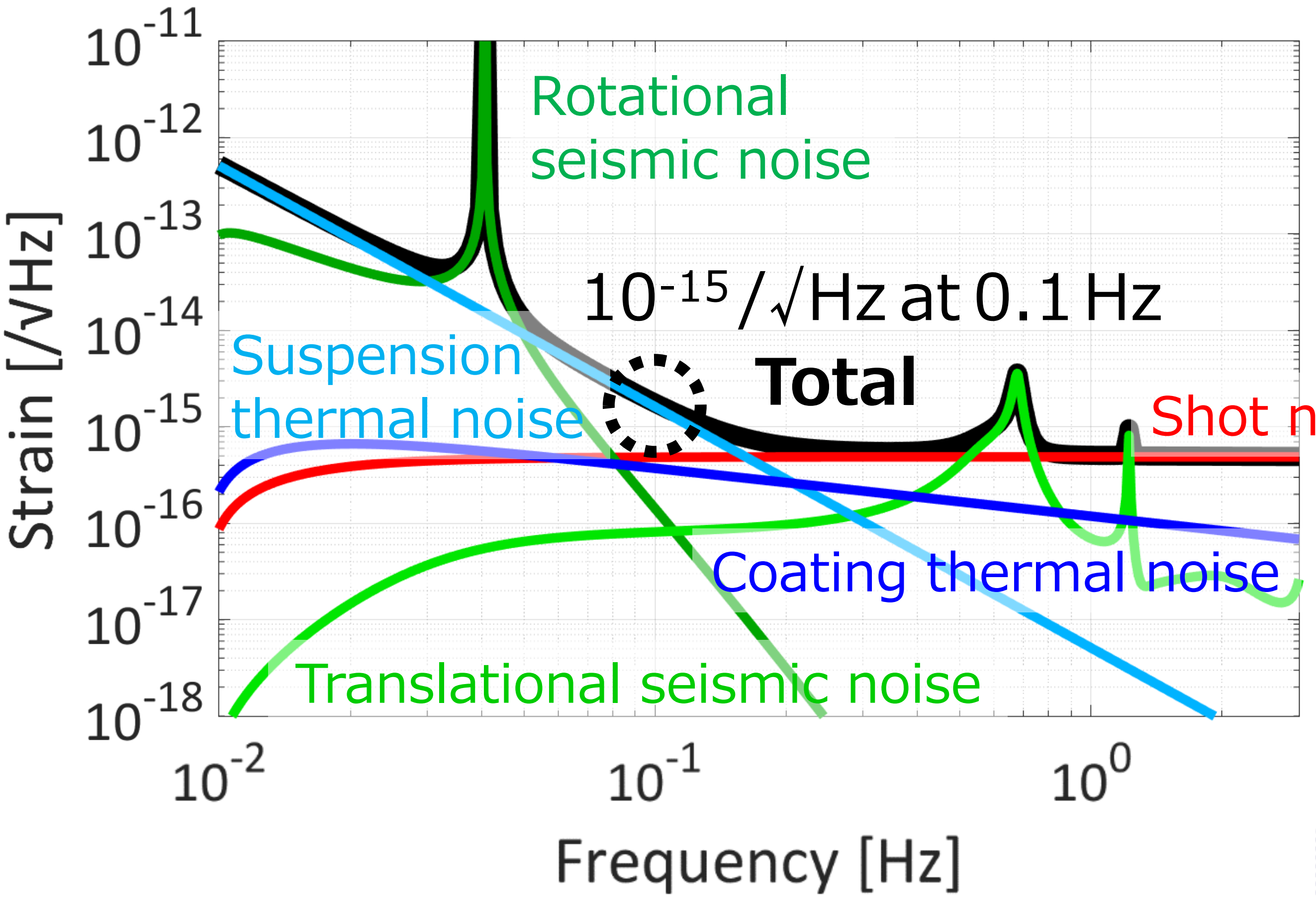
Cryogenic suspension

Torsion pendulums at 4 K

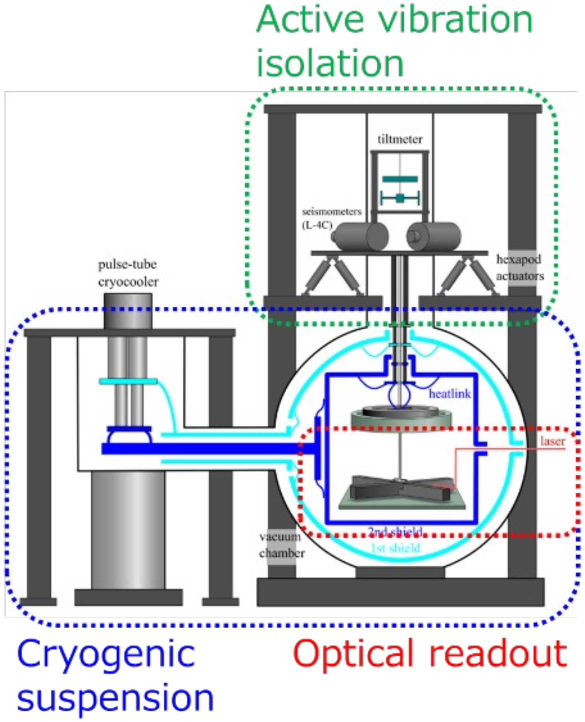
Optical readout

Detect the rotation of the pendulums

Design sensitivity of Phase-III TOBA



$10^{-15}/\sqrt{\text{Hz}}$ at 0.1 Hz

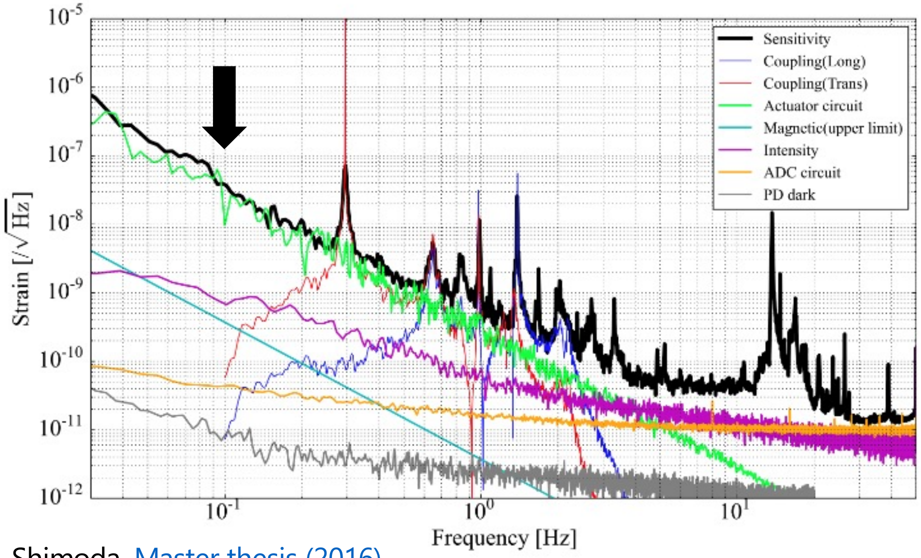


Component development of Phase-III TOBA

- Cryogenic suspension
  - Shimoda-san cooled down to 6 K and operated pendulums by an optical lever
  - Ching Pin-san is developing a sapphire wire for high Q
- Optical readout
  - Aritomi-san developed a monolithic interferometer made of fused silica and a coil-coil actuator
  - Shimoda-san demonstrated a folded WFS
  - Miyazaki-san and I demonstrated a coupled WFS
  - Takano-san developed a cryogenic monolithic interferometer made of silicon
- Vibration isolation
  - Shimoda-san reduced coupling by tuning the tilt
  - Takano-san reduced vibration by 1/1000 using AVIT
  - Mengdi-san is developing a tilt meter for AVIT

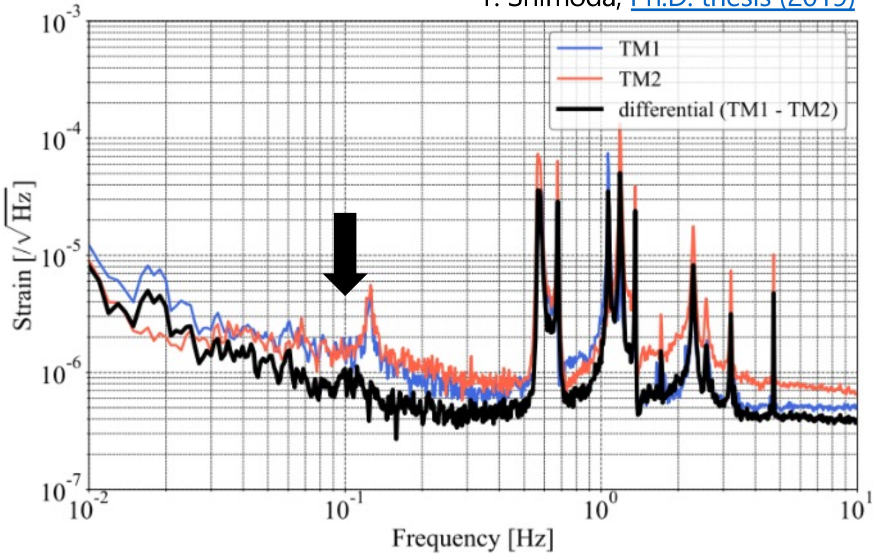
Achieved sensitivity of Phase-III TOBA

- Sensitivity at room temp.: 4×10^{-8} /√Hz @ 0.1 Hz
  - Reduced seismic coupling noise by tuning the tilt
  - Michelson interferometer
  - Actuator noise and seismic coupling noise limited sensitivity
- Sensitivity at cryo. temp.: 7×10^{-7} /√Hz @ 0.1 Hz
  - Cooled down to 6 K successfully
  - Optical lever
  - Beam jitter noise limited sensitivity



T. Shimoda, Master thesis (2016)

T. Shimoda, Ph.D. thesis (2019)



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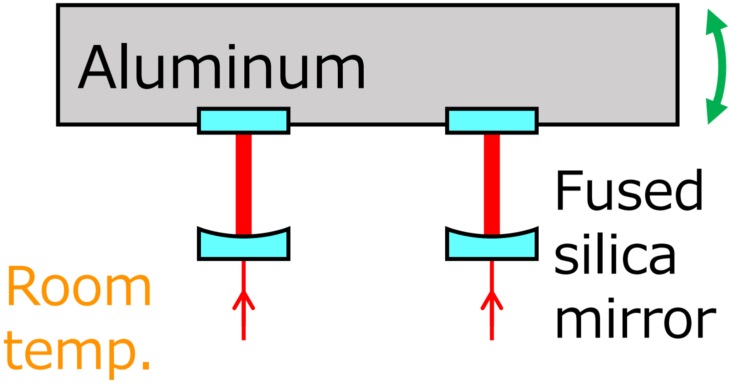
Goal of my experiment

- Target
  - To achieve the best sensitivity limited by suspension thermal noise possible in the current situation (w/o high Q wire)
  - To demonstrate a differential Fabry–Pérot cavity to detect the rotation of test masses
  - To demonstrate torsion pendulums made of silicon

First step

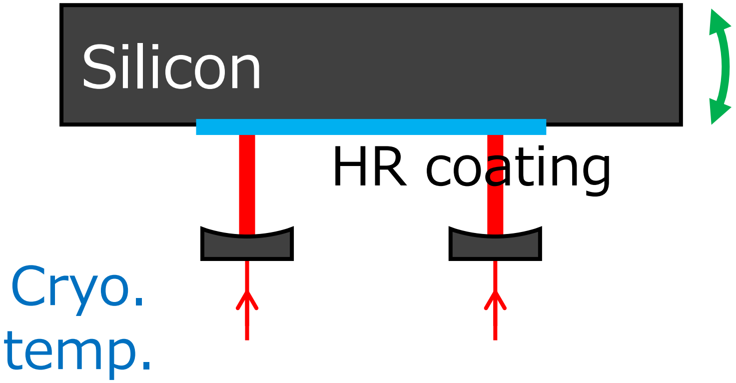
Now

Top view of pendulum



- To identify design issues
- To demonstrate cavity locking

Second step

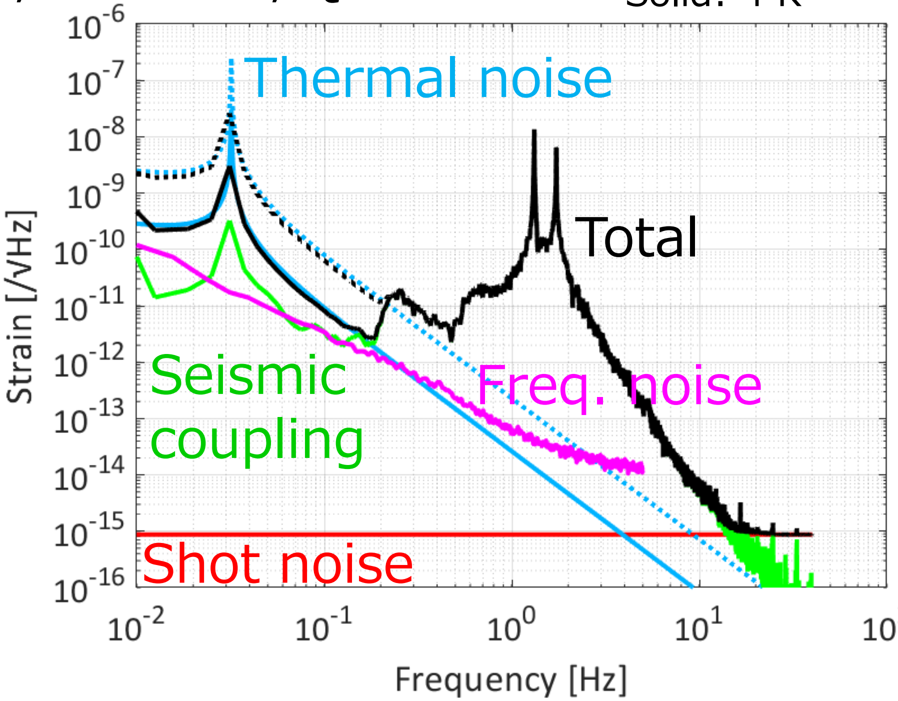


- To achieve the design sensitivity

Design sensitivity and requirement

- Target sensitivity: 8×10^{-12} /√Hz @ 0.1 Hz
  - Limited by suspension thermal noise
  - Sensitivity improvement at room temp. to cryo. temp.
- Requirement
  - Resonant freq. <0.1 Hz
    → Test mass with I=0.0083 kg m^2,
    CuBe wire with Φ=0.3 mm, l=12 cm, Q=3000
    → f_{Yaw}=32 mHz
  - Seismic coupling noise
    < thermal noise
    → Tilt of test mass <10^{-5} rad
  - Shot noise < thermal noise
    → FP cavity
    with F=400, P_{in}=1 mW
  - Freq. noise < thermal noise
    → C_{CMRR} <1/50

Doted: 300 K
Solid: 4 K

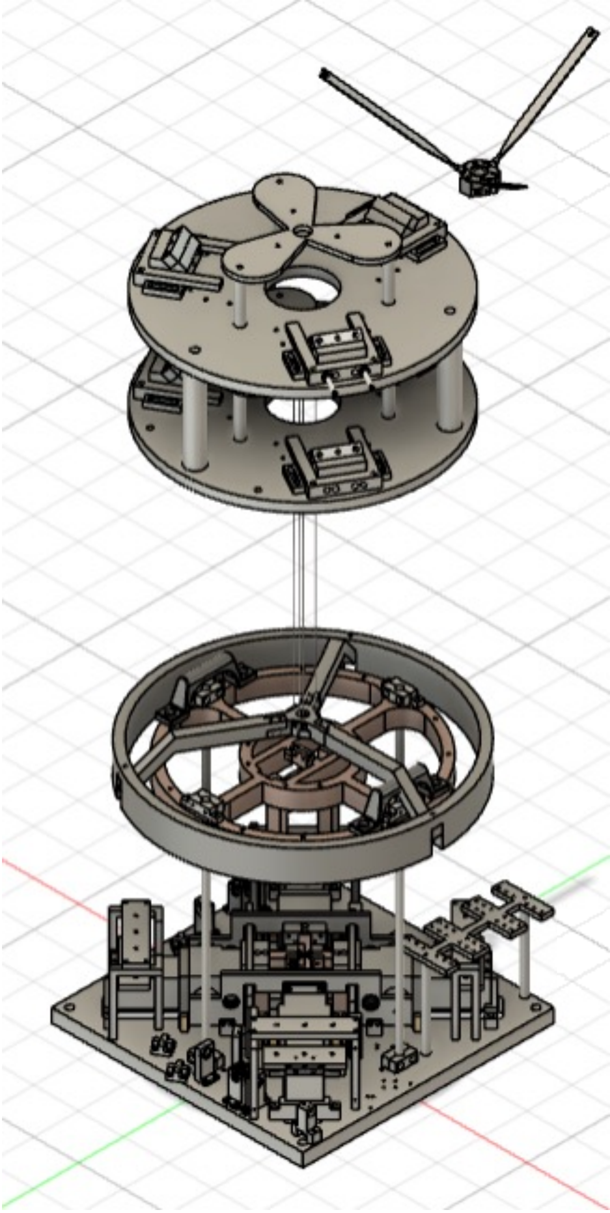


Whole suspension

- Suspension system consists of the following elements
  - Vertical spring
  - Intermediate mass
  - Two test masses
  - Optical bench

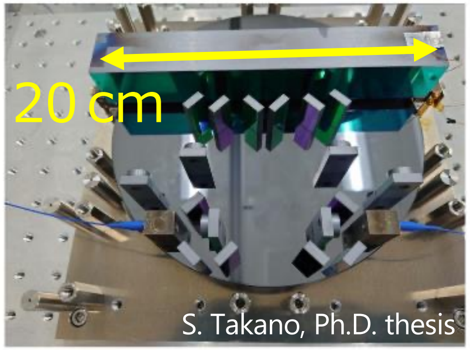
} Including optics

- I will explain one by one

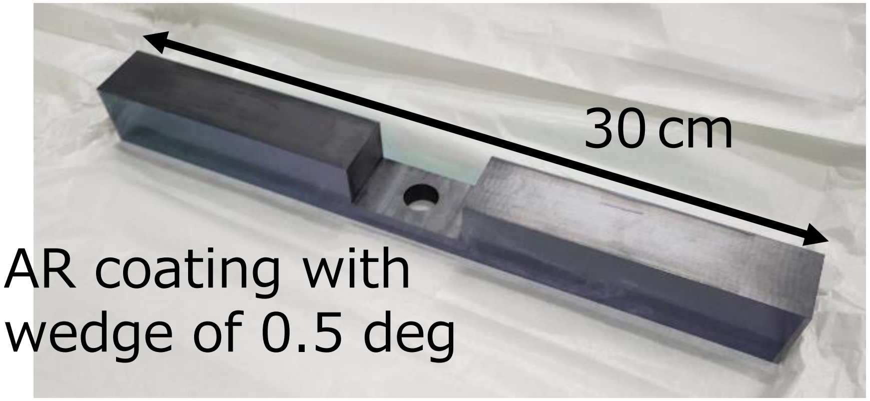


Silicon test masses and cavity mirrors

- Purchased from Sigmakoki
  (delivery time: 4 months, total cost: 3,600,000 yen)
- Difference from Takano-san’s mass
  - Longer by 10 cm
  - Counterbore for orthogonal assembly
  - Hole for suspension wire
  - Wedge to reduce reflections from the back surface

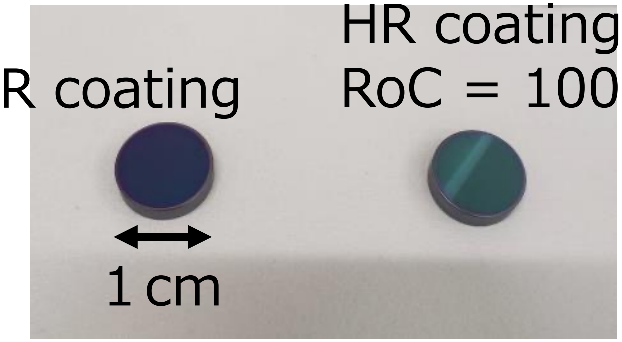


S. Takano, Ph.D. thesis



AR coating with
wedge of 0.5 deg

HR coating (99.5% @ 1550 nm),
Roughness: λ/4 (λ = 632.8 nm)

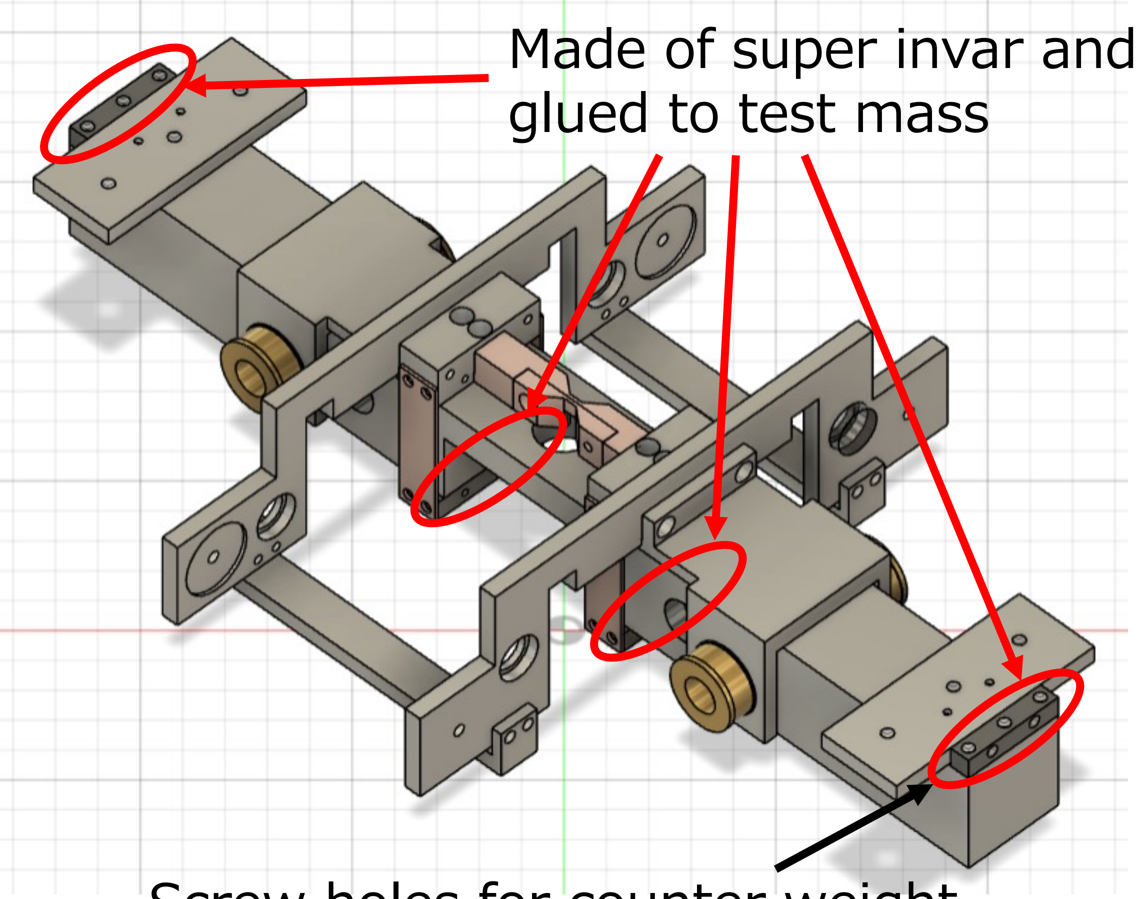


AR coating

HR coating (99%),
RoC = 100 mm

Parts for silicon test mass

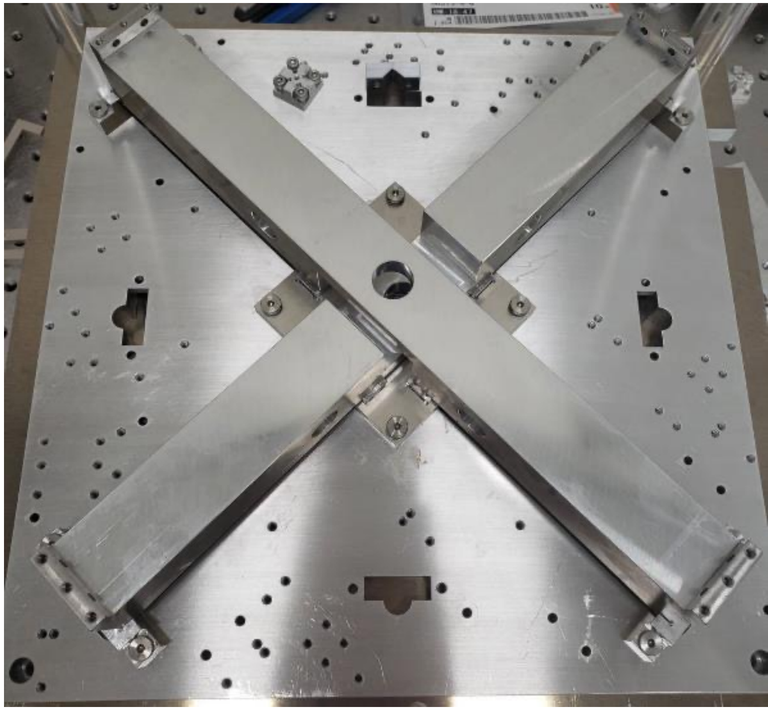
- Designed clamps to prevent silicon from cracking during cooling
    - Parts made of super invar are glued to silicon mass
    - Other parts don’t touch silicon masses



Made of super invar and glued to test mass

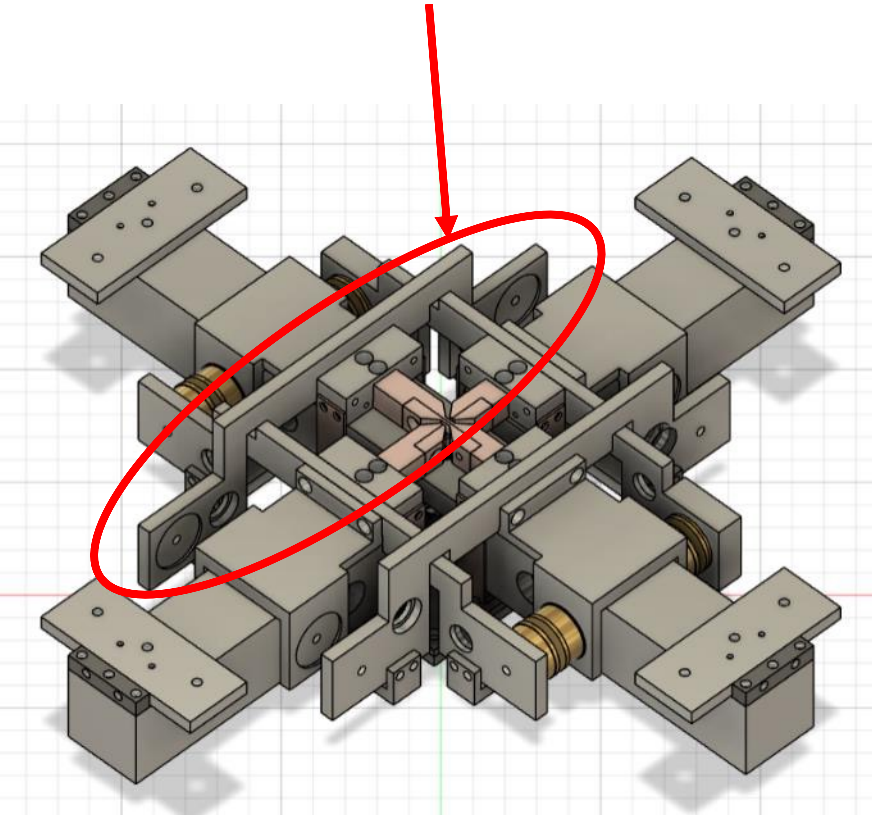
Screw holes for counter weight

Glued parts with optical bench and jigs

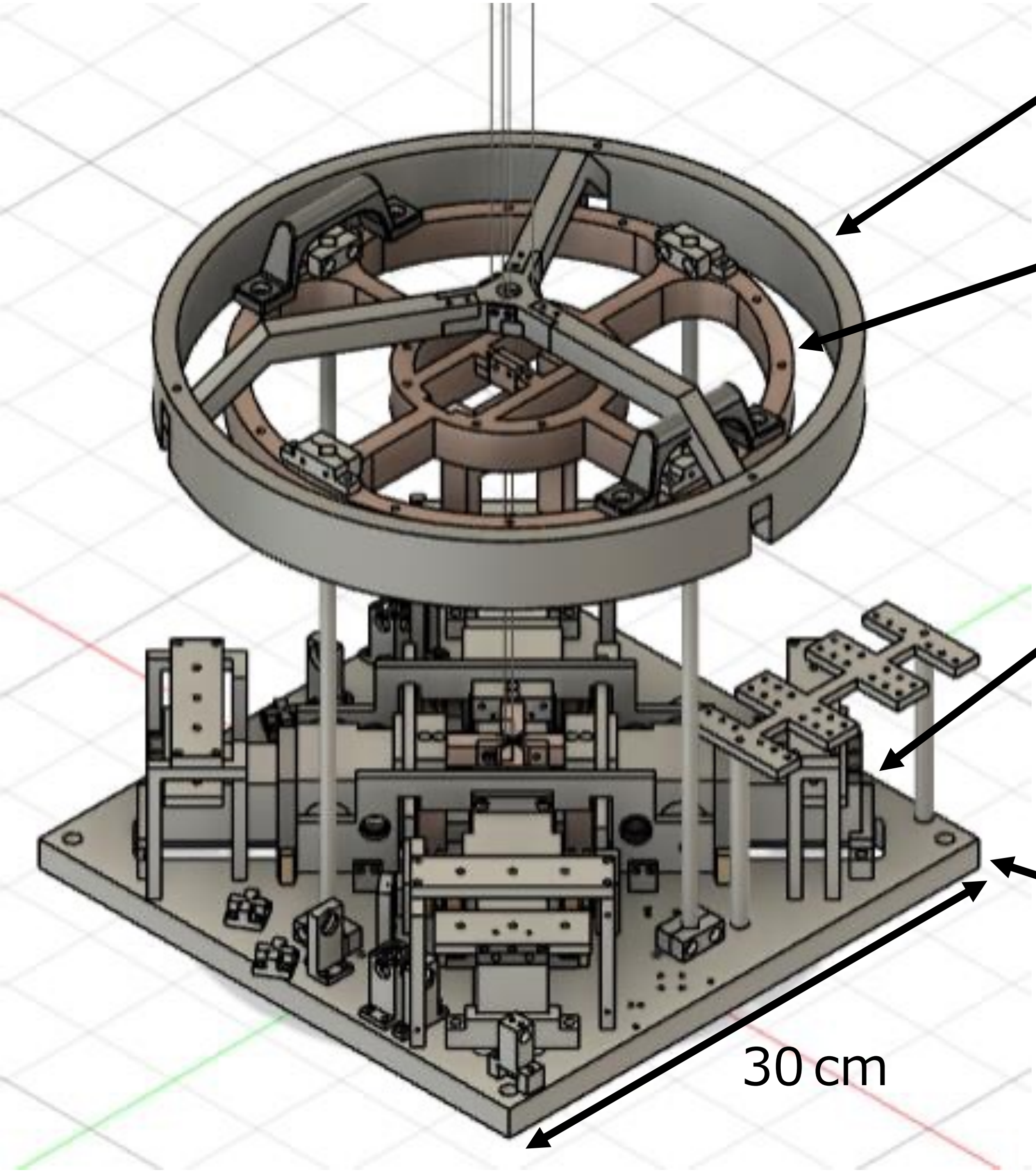


Two orthogonal test masses

- Combine the two test masses and each clamp orthogonally like “組み木細工” so that they are at the same height
- Attach two wing-shaped parts in each test mass to attach mirrors and coils
  - Wings also combine like “組み木細工”



Suspension below intermediate mass



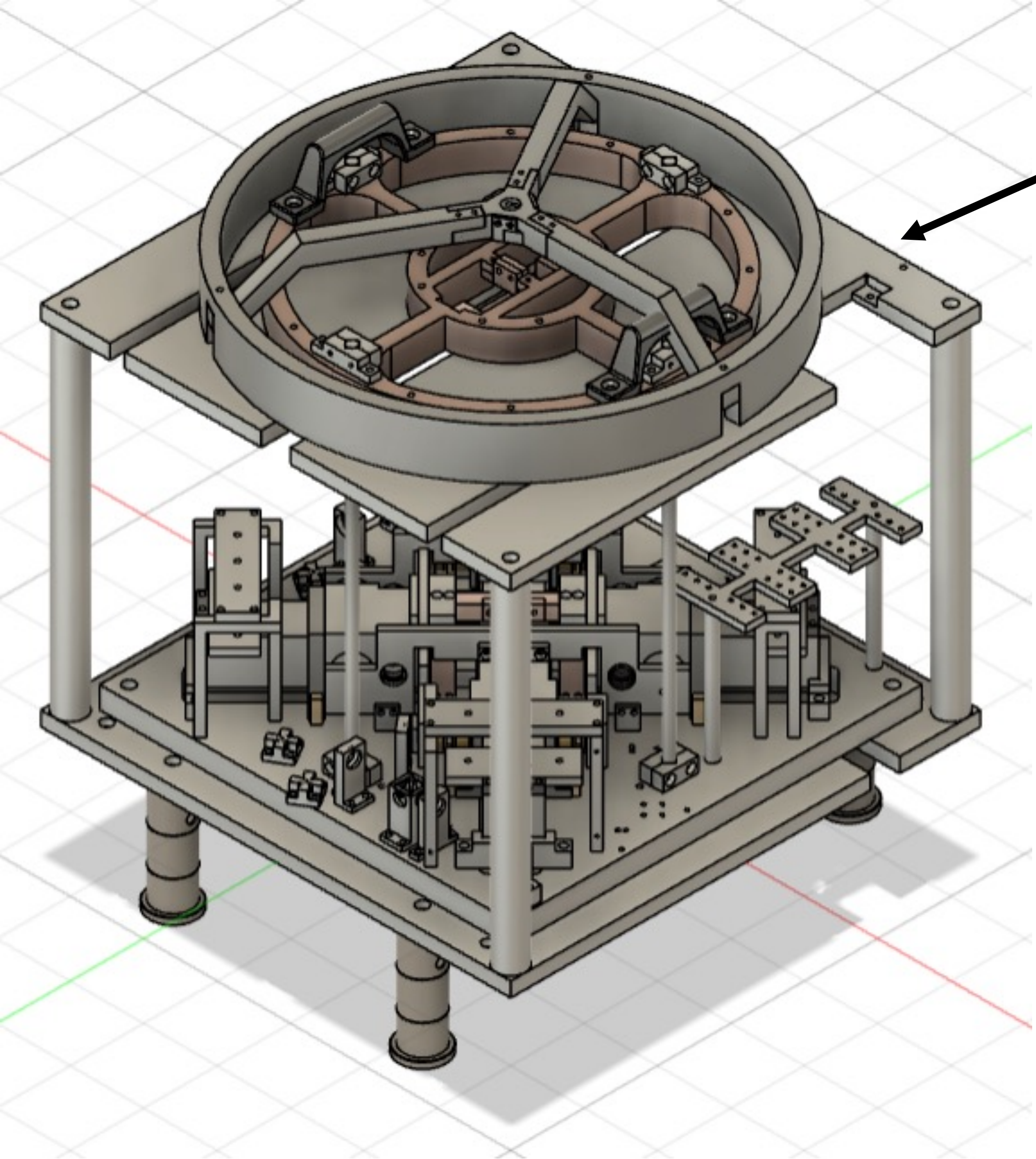
Damping magnet support
- Suspended by 3 wires
- SUS 2.9 kg

Intermediate mass
- Suspended by one wire
- Copper 2.5 kg
- With rotation stage (later)

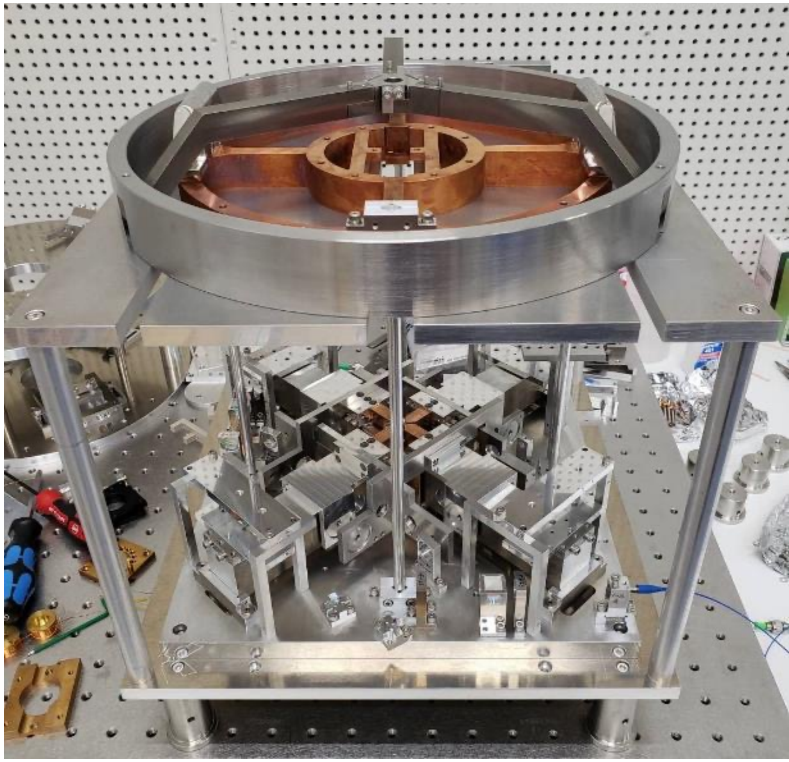
Two test masses
- Suspended by one wire
- Aluminum 0.6 kg / silicon 0.5 kg
- Other parts 0.6 kg

Optical bench
- Suspended by 4 rods with the thickness of 7 mm (same as Ono-kun’s)
- Aluminum 2.4 kg

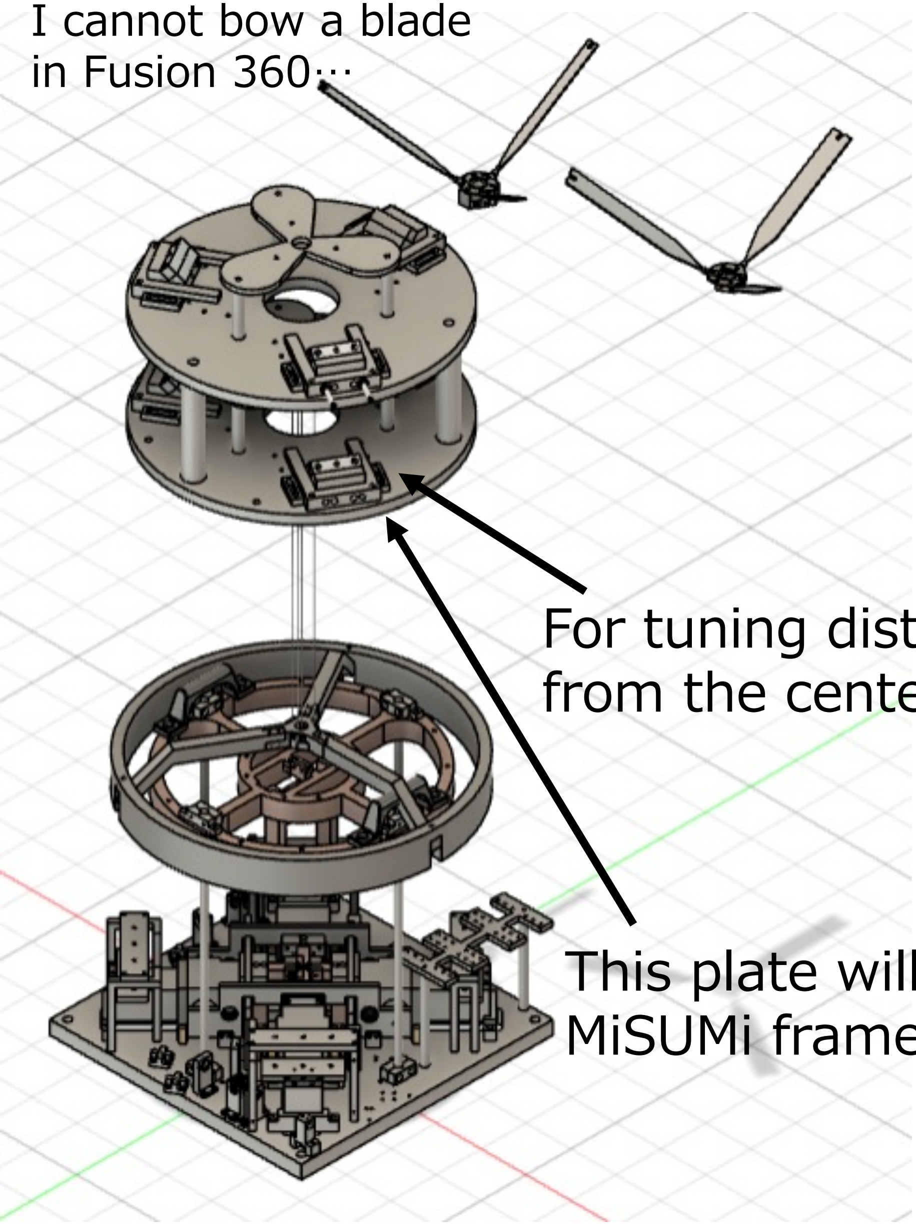
Suspension jigs



This house is just to suspend test masses and optical bench and to install them in the chamber



Vertical spring

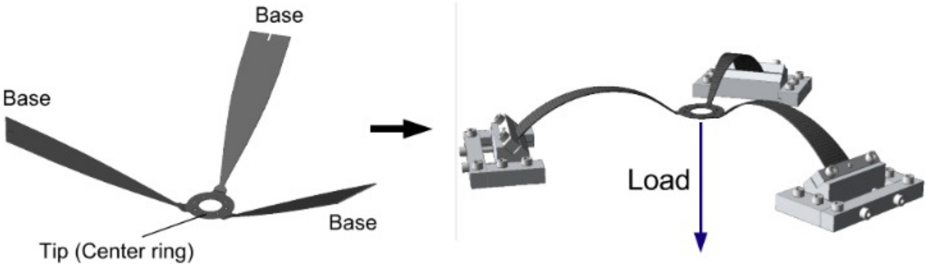


I cannot bow a blade in Fusion 360…

For tuning distance from the center

This plate will be on MiSUMi frames / AVIT

- I will introduce vertical spring for the first time for TOBA
- Referred Aso-san’s Ph.D. thesis
- Target resonant freq.: around 0.1-0.2 Hz
    - The size of the setup is much smaller than Aso-san’s
    - Used SUS304 spring material instead of Maraging

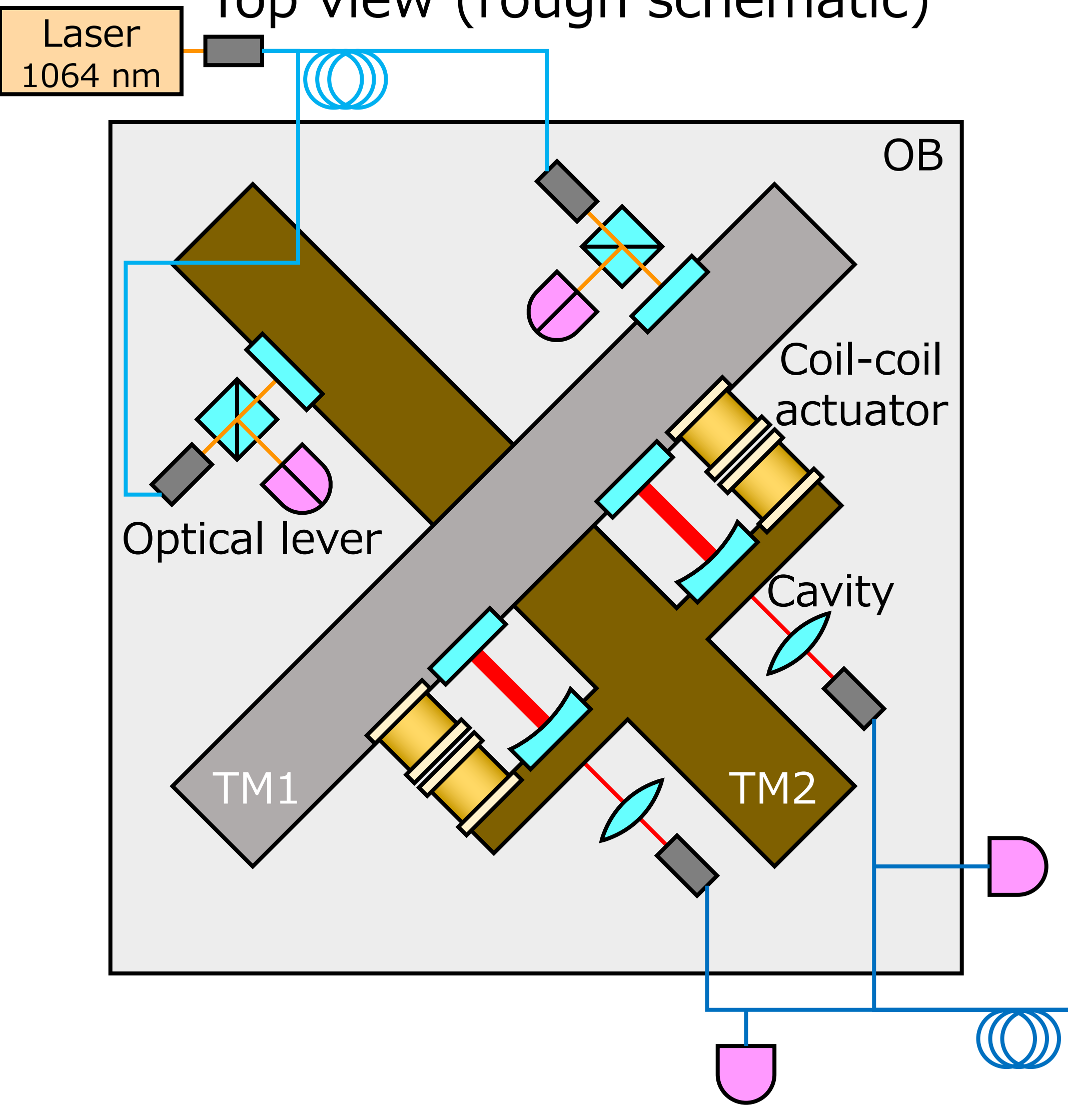


Y. Aso, Ph.D. thesis (2005)

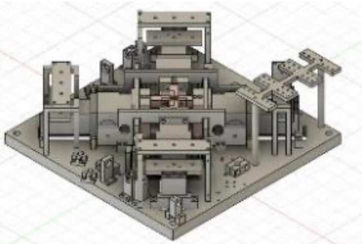
Optics

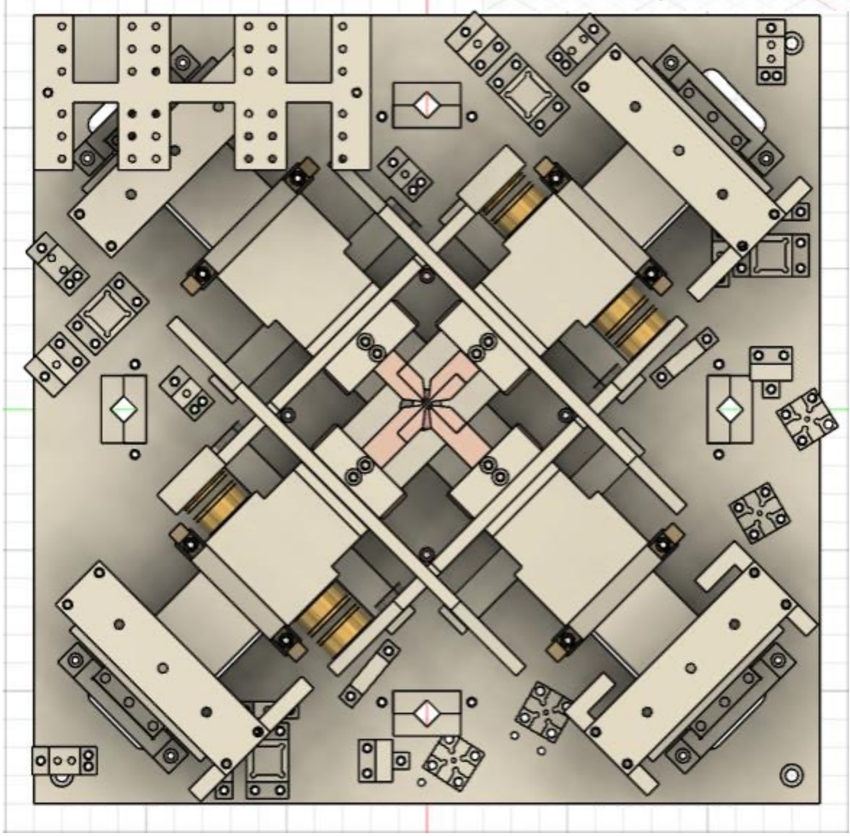
- I will explain one by one

Top view (rough schematic)



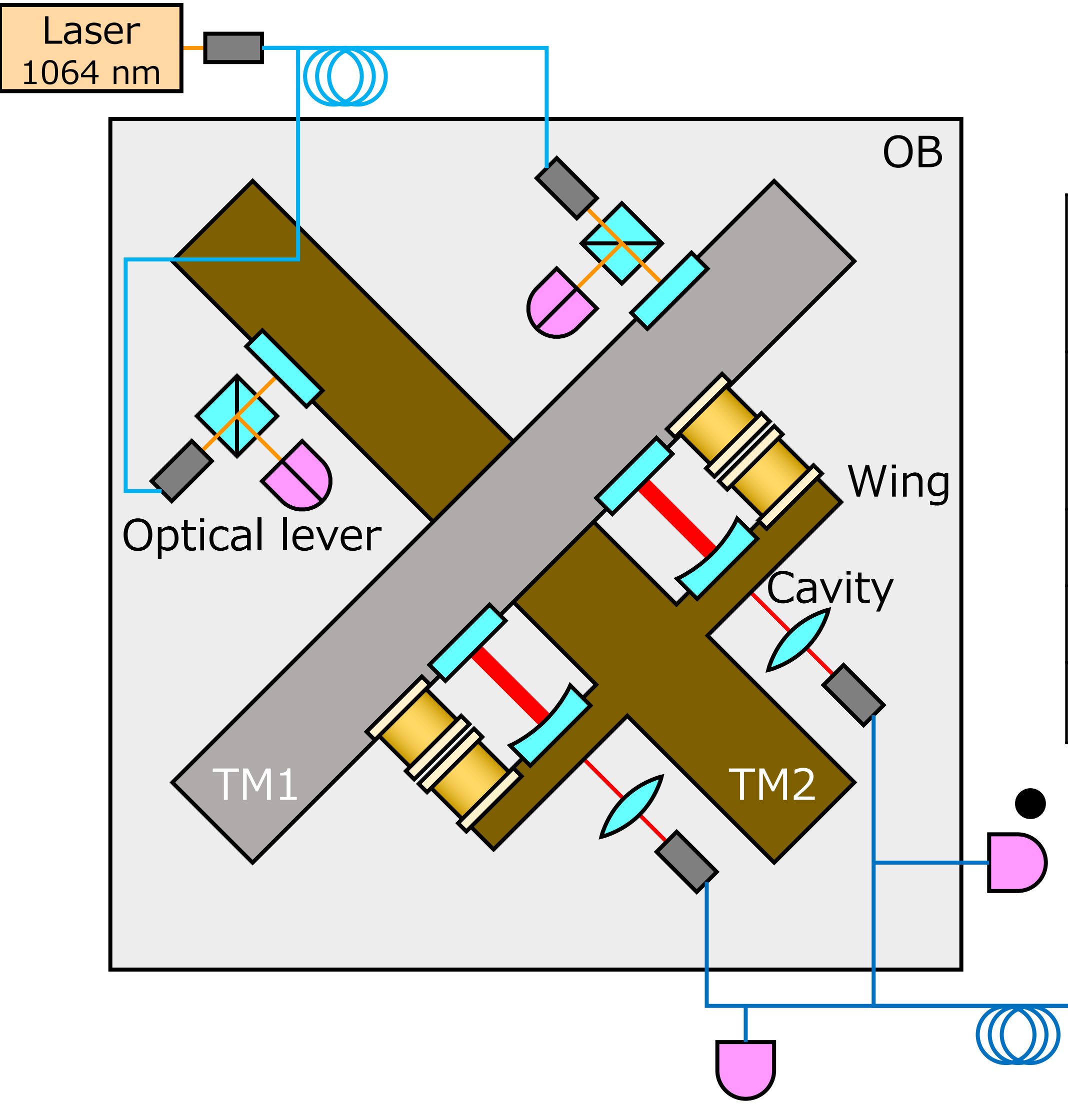
Top view (CAD)





Cavity

Top view (rough schematic)



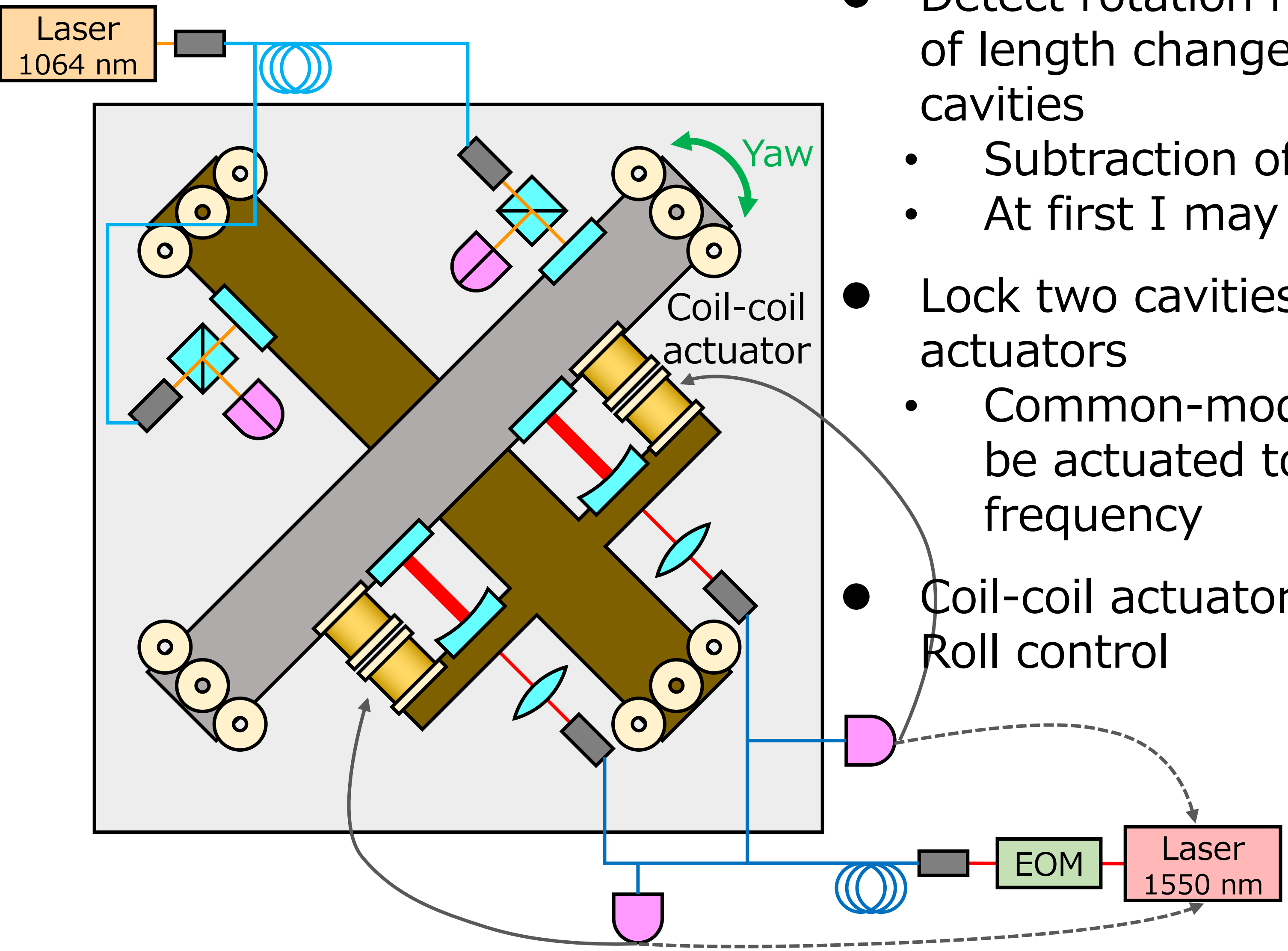
- Build cavities between two test masses
  ← Vibration of optical bench will not be noise

Input mirror	RoC	100 mm
	Reflectance	99%
End mirror	RoC	Flat
	Reflectance	99.5%
Finesse		417
Length		23 mm
Distance of two cavities		110 mm

- Optical lever as auxiliary sensor

Cavity locking and actuator

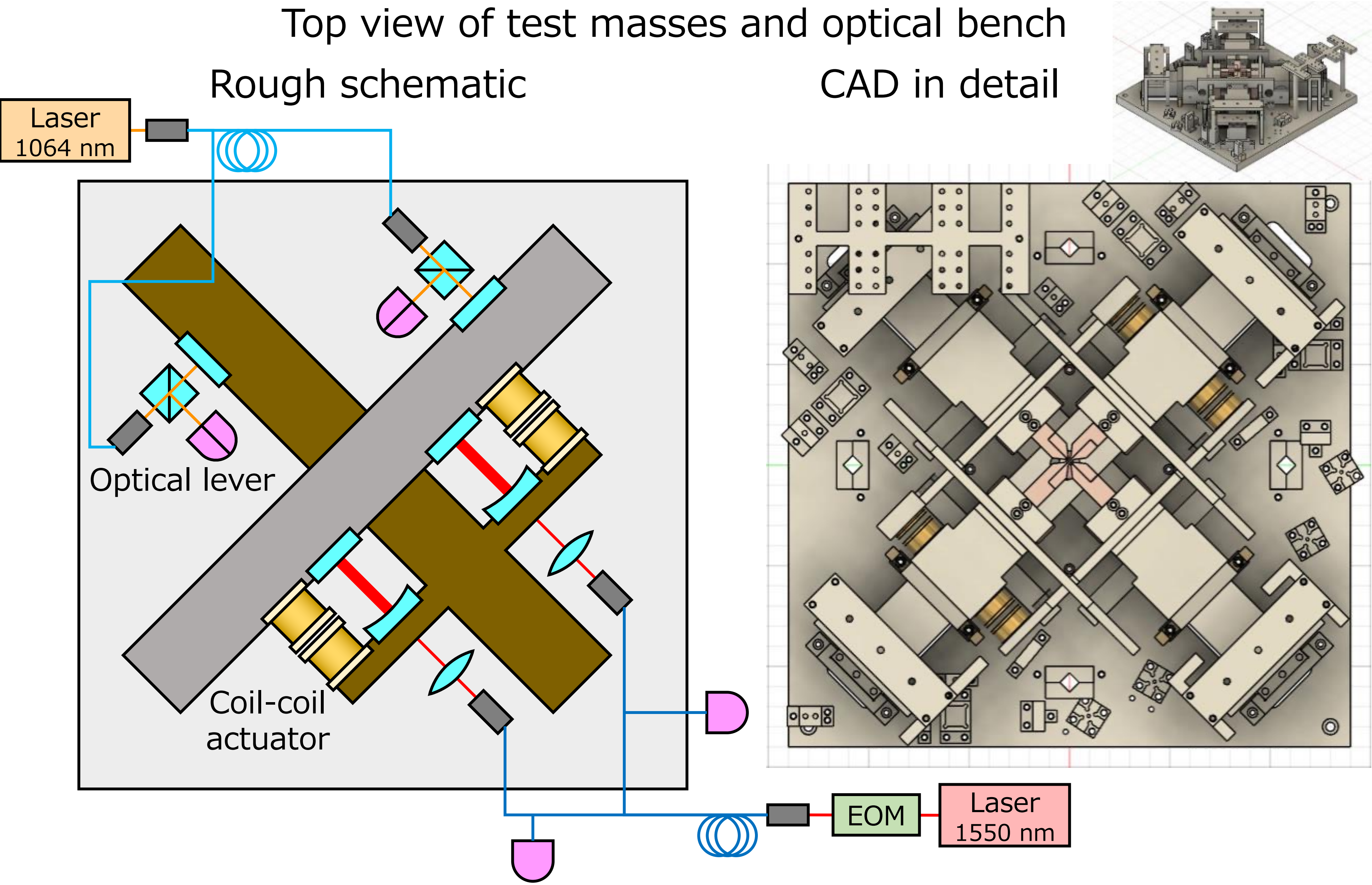
Top view (rough schematic)



- Detect rotation from difference of length change of two cavities
  - Subtraction of PDH signals
  - At first I may try side lock
- Lock two cavities with coil-coil actuators
  - Common-mode signal may be actuated to laser frequency
- Coil-coil actuators for Pitch and Roll control

CAD drawings

Top view of test masses and optical bench

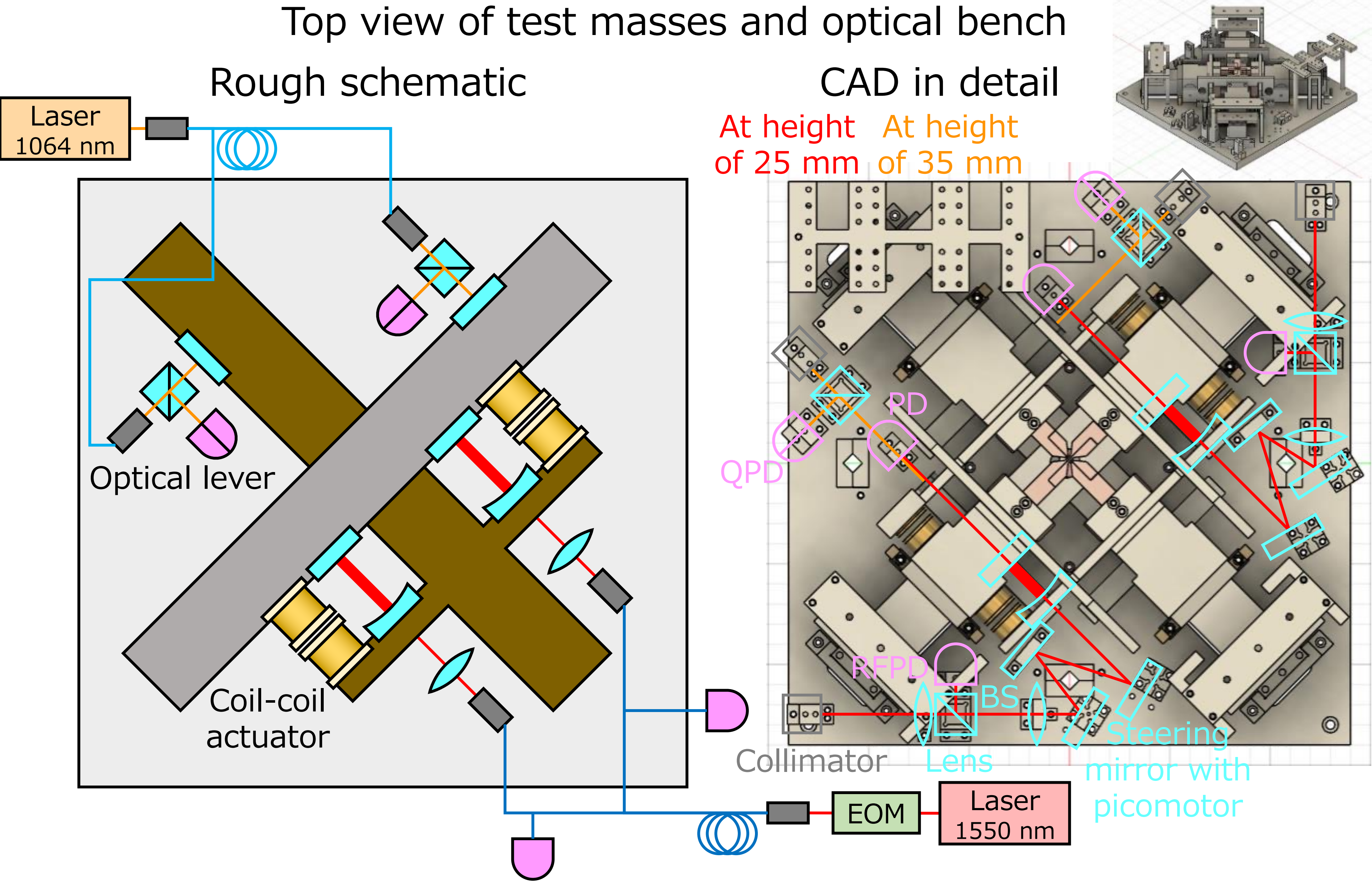


Rough schematic

CAD in detail

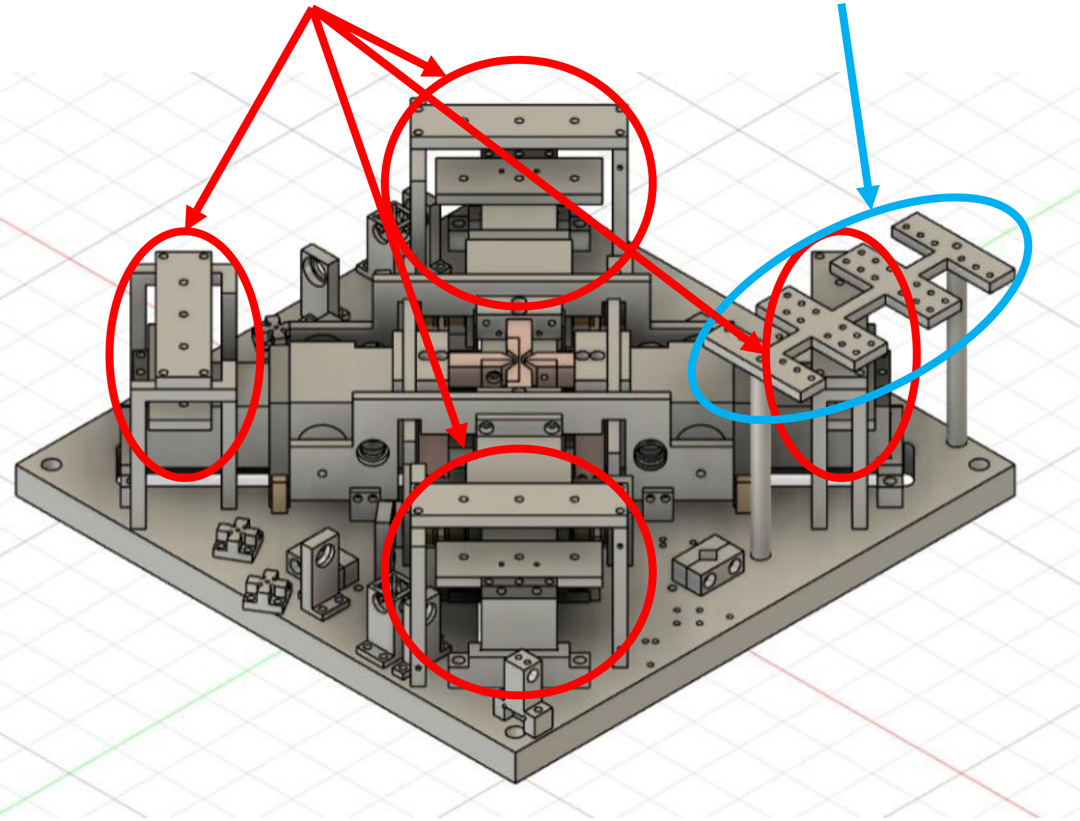
CAD drawings

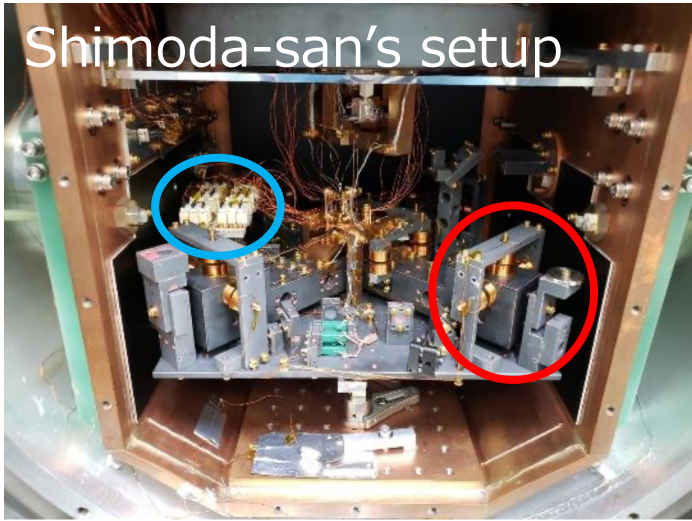
Top view of test masses and optical bench

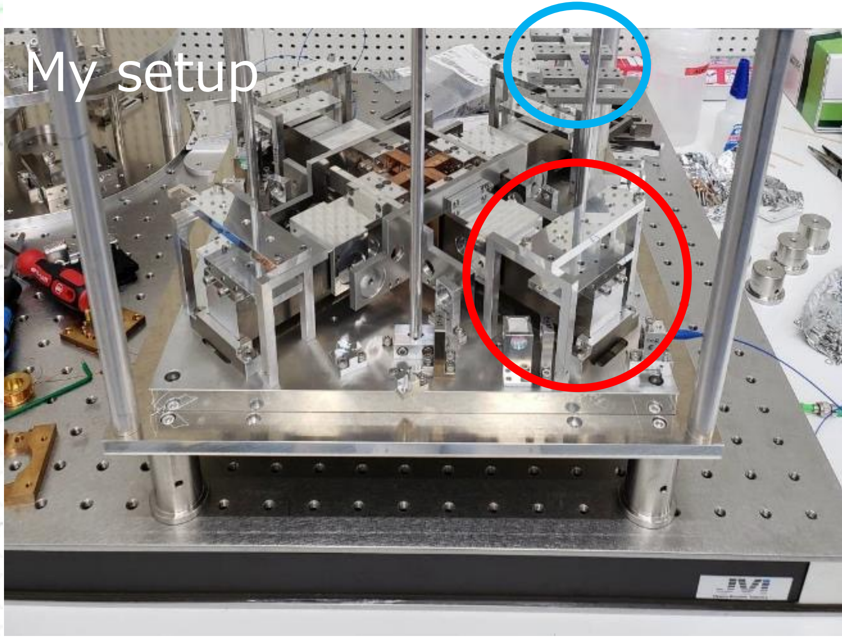


Other components

- I made coil holders and stage for electrical wires based on Shimoda-san's design

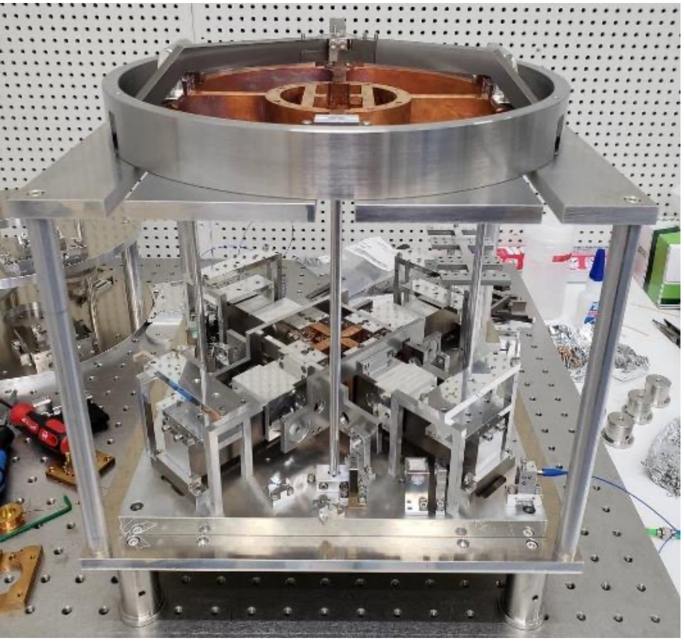


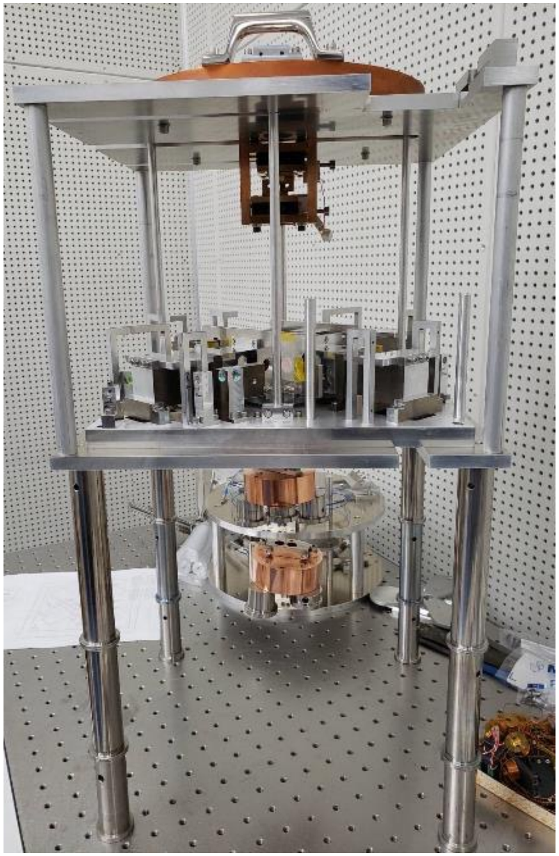


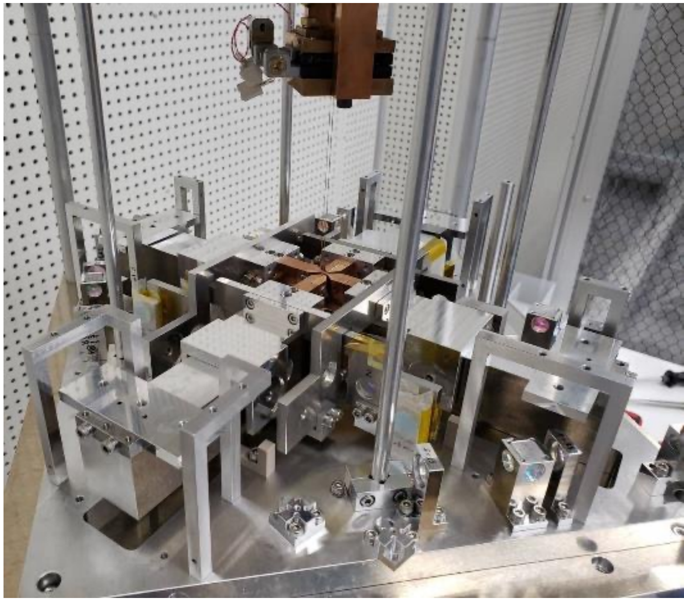


Status of experiment

- Assembled suspension jigs, magnet support, intermediate mass, test mass, and optical bench
- Put optical bench all components other than coils, PDs, mirrors with picomotors
- Suspended test masses

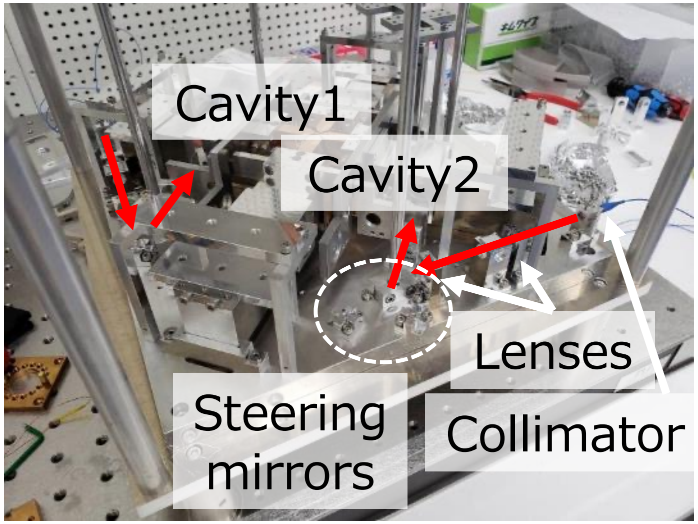


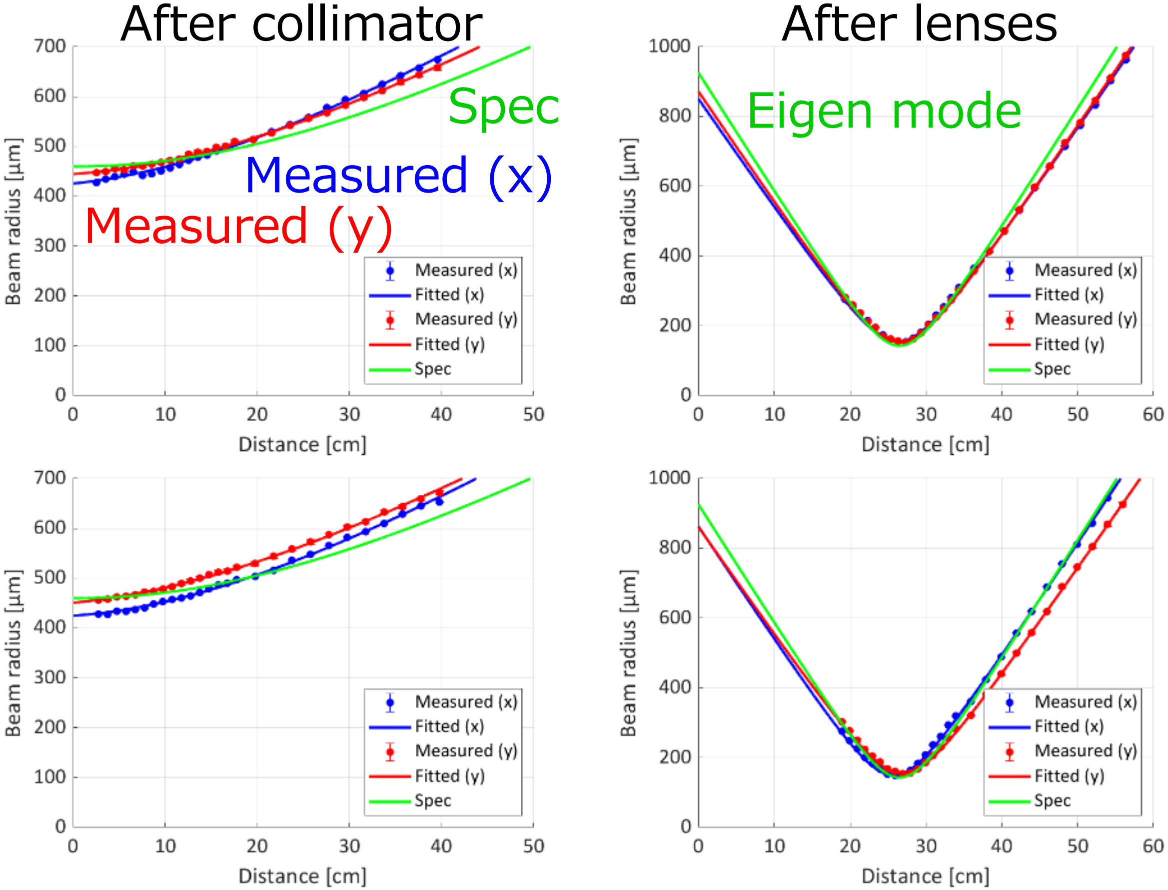




Status of optics

- Measured input beam width for cavities
- Next: to put steering mirrors with picomotors and align them to cavity




After collimator

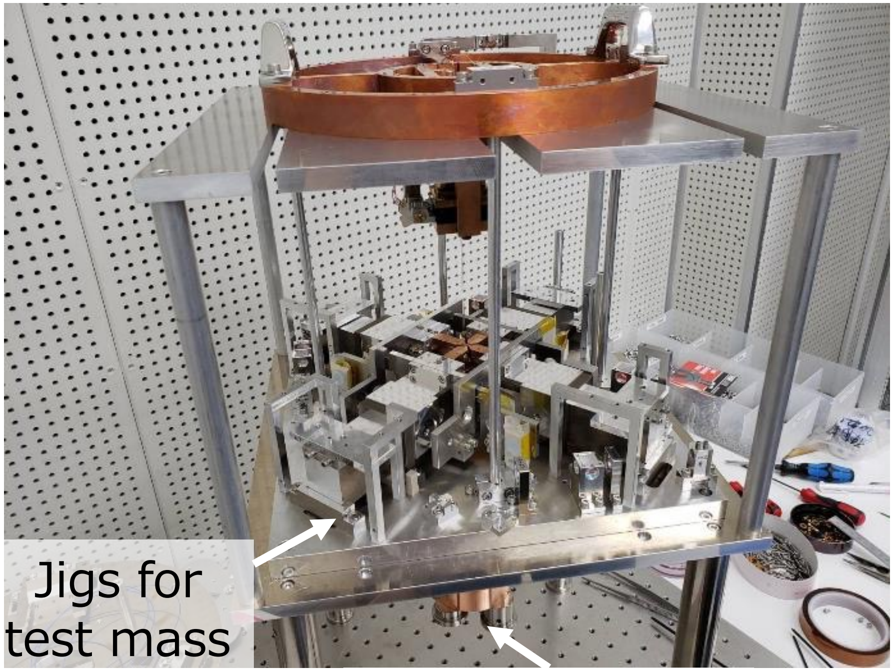
After lenses

Cavity1:
mode matching ratio 99.4%

Cavity2:
mode matching ratio 99.0%

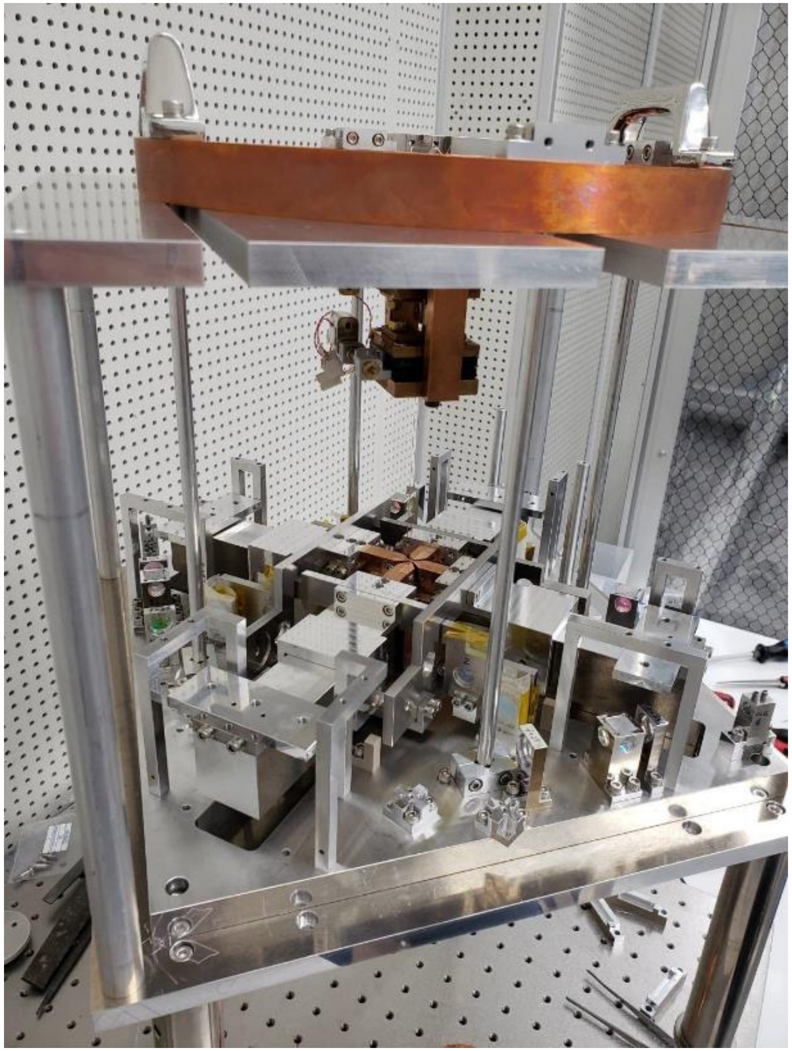
Status of suspension

- Suspended and released test masses



Jigs for test mass

Dummy mass of 1.1 kg

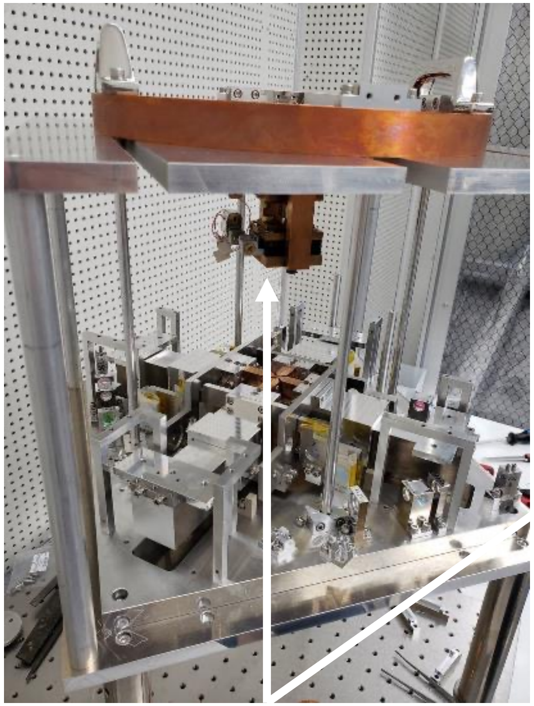


Status of suspension

- Yaw drift due to wire stiffness
  - Rotates by 4 mm on the edge = ~0.03 rad (~1.5 deg)
  - One mass hits coil holder, and the other nearly hits

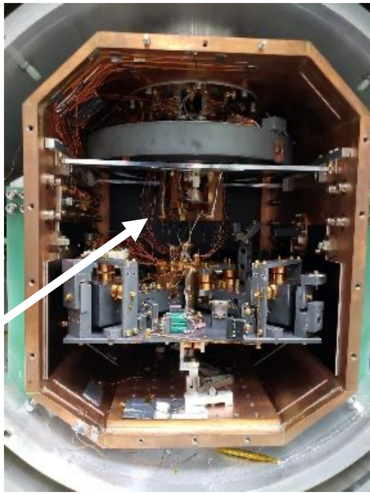
- Next: to compensate Yaw drift by rotation stage

Rotates by 4 mm on the edge
and nearly hits



Rotation stage with picomotor
(Shimoda-san used)

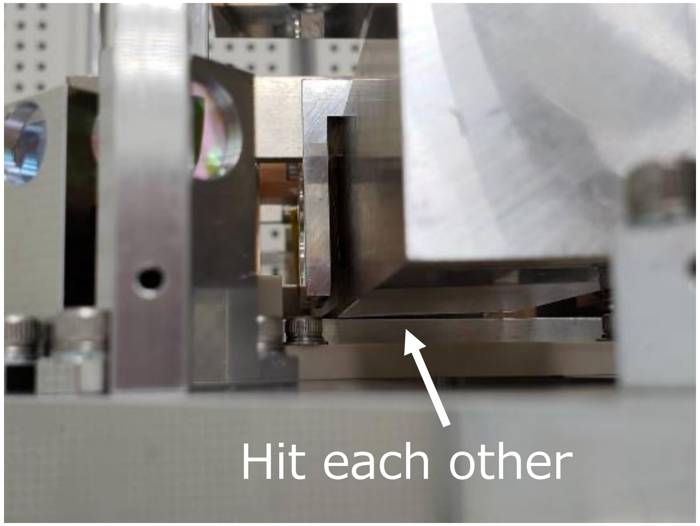
Shimoda-san’s
setup



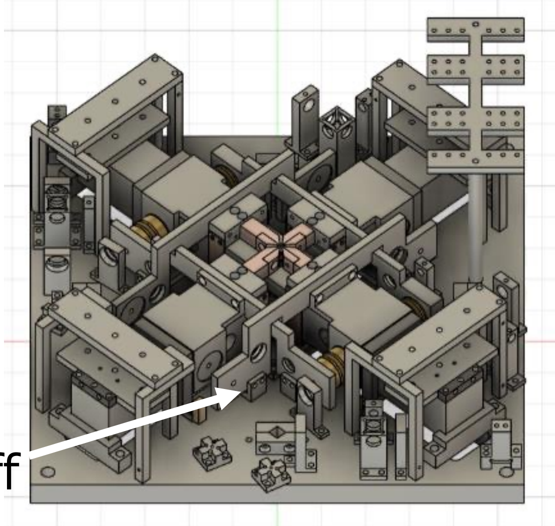
Status of suspension

- Pitch drift due to mass asymmetry
  - Height difference of ~1 mm on the edge = ~7×10^{-3} rad
  - Masses hit each other

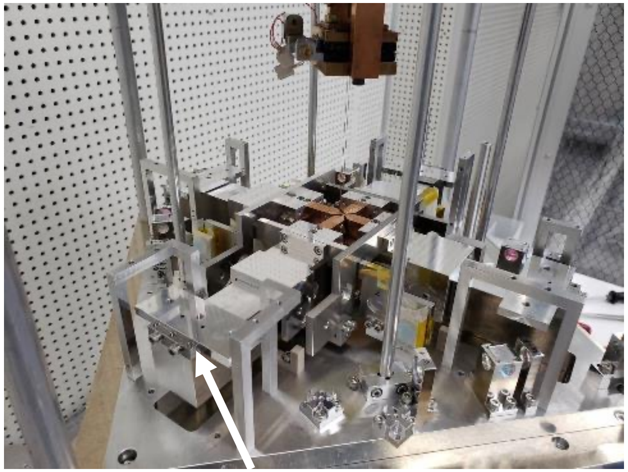
- Next: to reduce Pitch by counter weight to ~0.1 mm (7×10^{-4} rad) (requirement: 10^{-5} rad)



Hit each other



Wing support to make resonance stiff

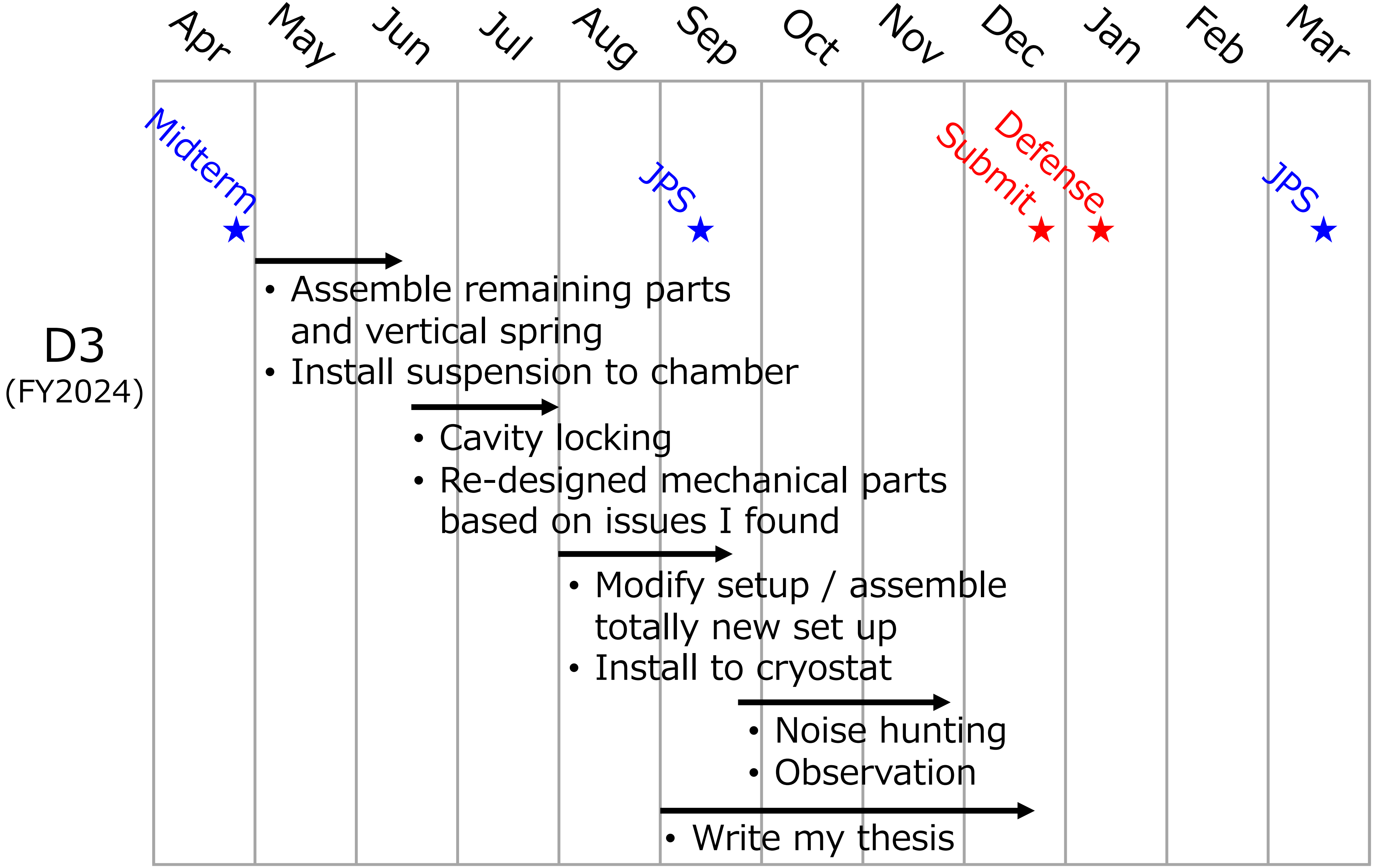


Screw holes for counter weight

Contents

- Introduction of TOBA for new members
- Design and previous studies of Phase-III TOBA
- Current status of my experiment
- Plans of my experiment

Plans toward my Ph.D. thesis



D3
(FY2024)

- Assemble remaining parts and vertical spring
- Install suspension to chamber

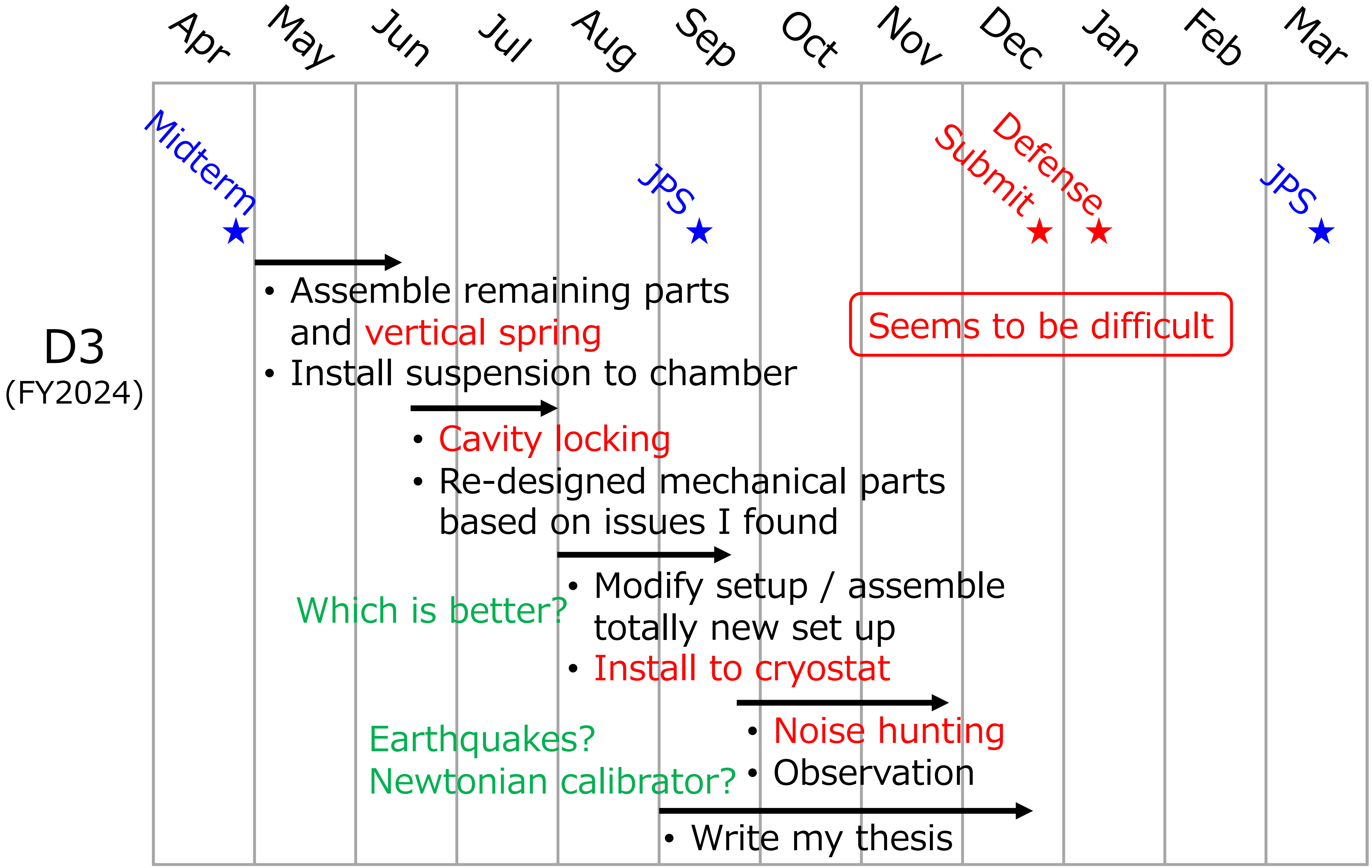
- Cavity locking
- Re-designed mechanical parts based on issues I found

- Modify setup / assemble totally new set up
- Install to cryostat

- Noise hunting
- Observation

- Write my thesis

Plans toward my Ph.D. thesis



D3
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- Assemble remaining parts and vertical spring
- Install suspension to chamber

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- Re-designed mechanical parts based on issues I found

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- Noise hunting
- Observation

- Write my thesis

Seems to be difficult

Which is better?

Earthquakes?
Newtonian calibrator?

Summary

- TOBA is a ground-based GW detector for low freq. using torsion pendulums
- Currently Phase-III TOBA is developed in Ando Lab
- I am developing the suspension and optics for the best sensitivity
- I have many things to do, but do the best for good sensitivity and my Ph.D. thesis