Future Prospects for Torsion Pendulums

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Ando Lab Mid-term Seminar 2020

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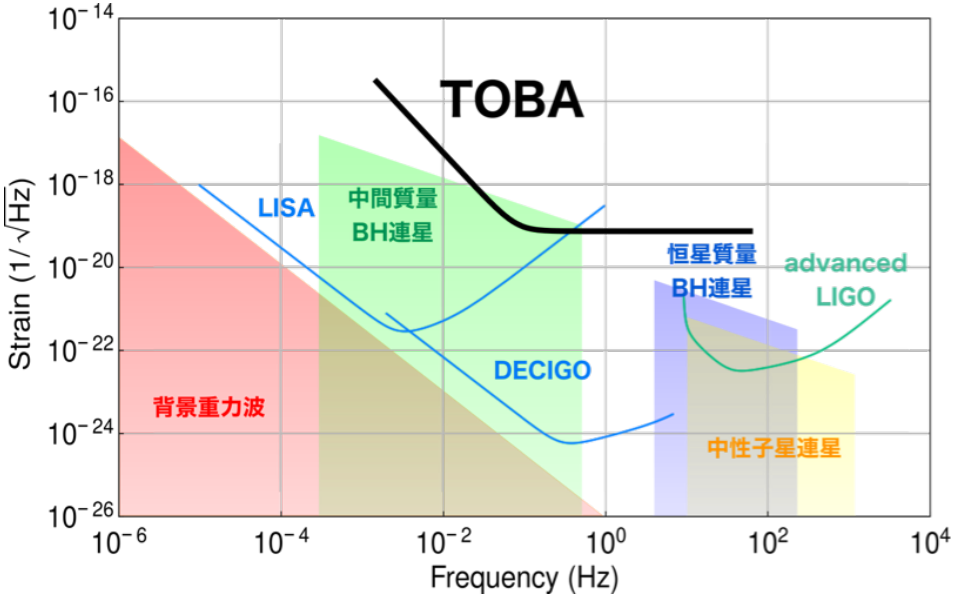
Contents

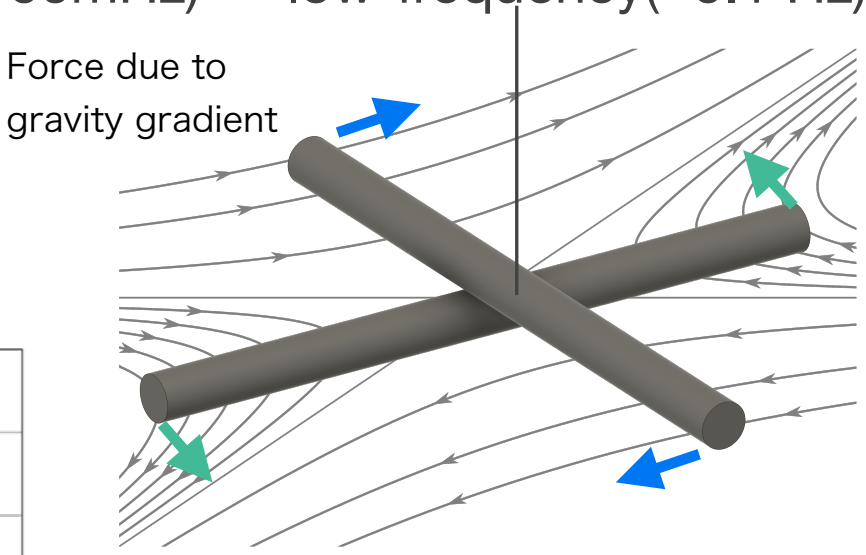
- Overview of TOBA
- Phase-III TOBA
- Current situation
- Future Plan
- Others

Overview of TOBA

TOBA

- (Introduction for newcomers)
- TOrsion Bar Antenna: suspended torsion pendulum(s)
  - Low resonant frequency (<100mHz) → low-frequency(~0.1 Hz) detector
  - Detect gravity gradient
    - GWs (CBC, SGWB, etc.)
    - Local potential (NN, EEW)

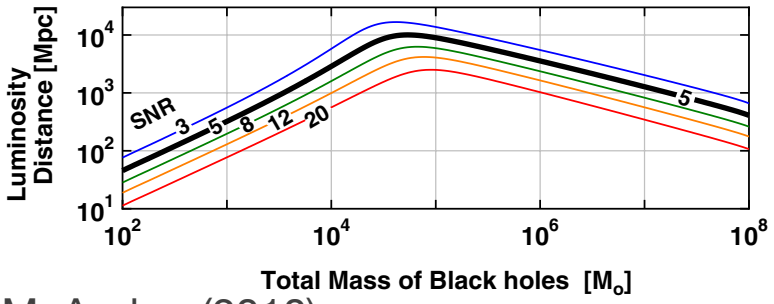




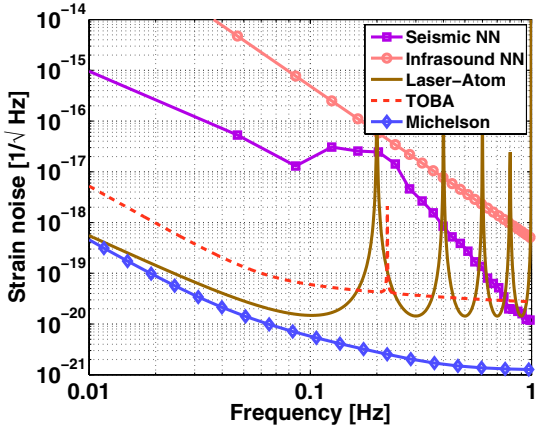
- Target Sensitivity @ 0.1Hz
  - GWs: 10^{-19} /√Hz
  - Local: 10^{-15} /√Hz

Science of TOBA

- TOBA
  - Astrophysics
    - IMBH Binary Merger
    - Stochastic GW Background
  - Geophysics
    - Newtonian Noise
    - Earthquake Alert



M. Ando+ (2010)

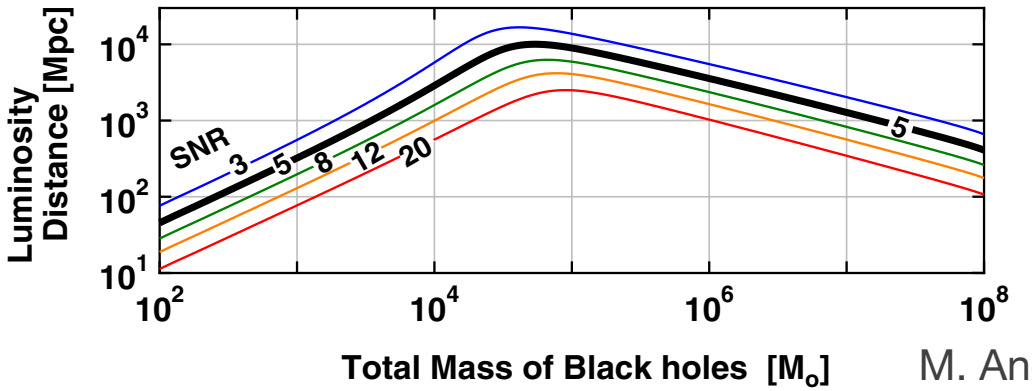


J. Harms+ (2012)

Astronomical Target

With sensitivity **$10^{-19}/\sqrt{Hz}$** …

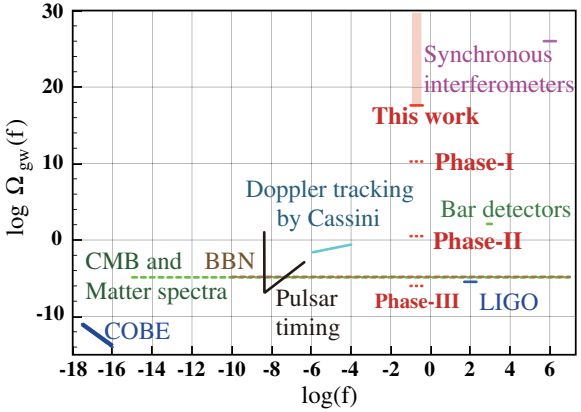
- Intermediate mass blackhole (IMBH) merger



M. Ando+ (2010)

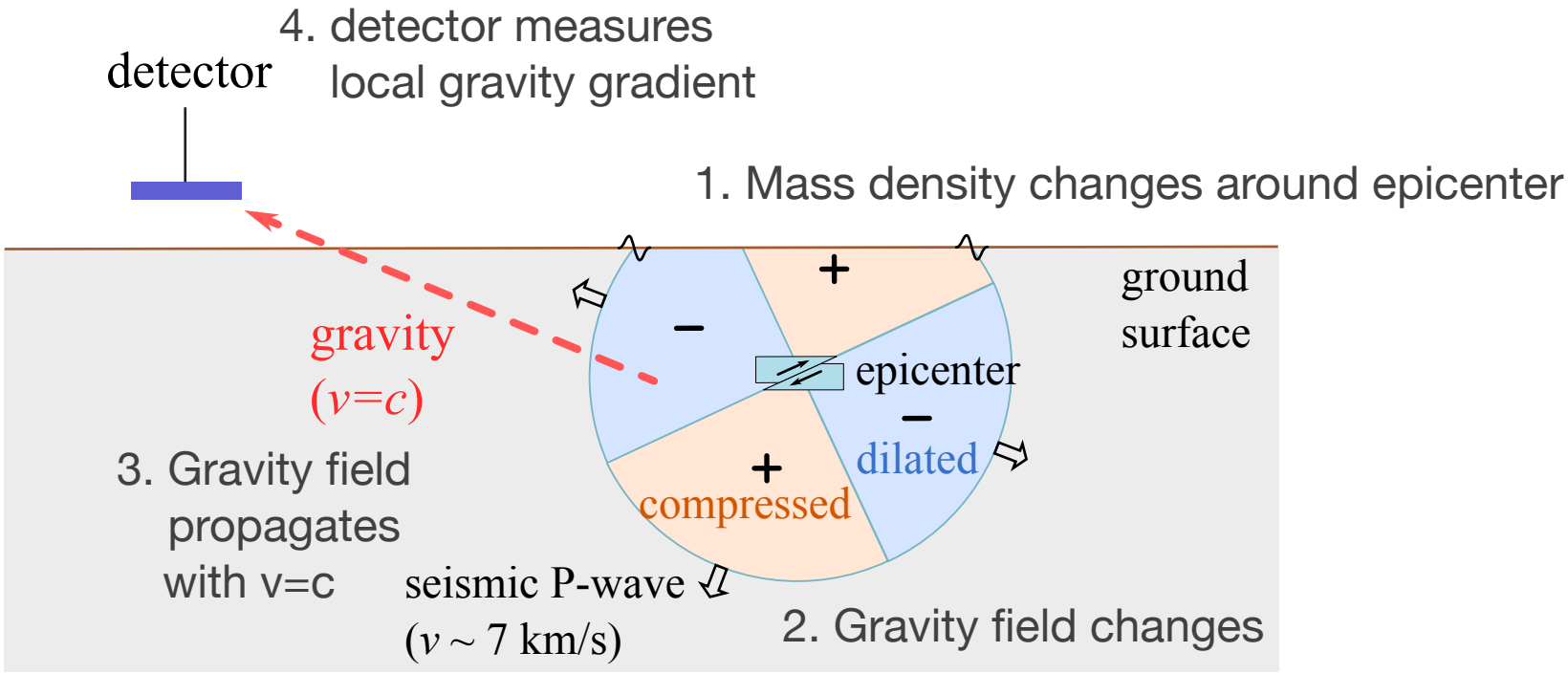
- 10^5 $M_\odot$ in 10 Gpc
- Hint for SMBH generation

- Stochastic GW background (SGWB)



- $\Omega_{GW} \sim 10^{-7}$ → Exceed BBN limit
- Insight for early universe

Earthquake Early Warning

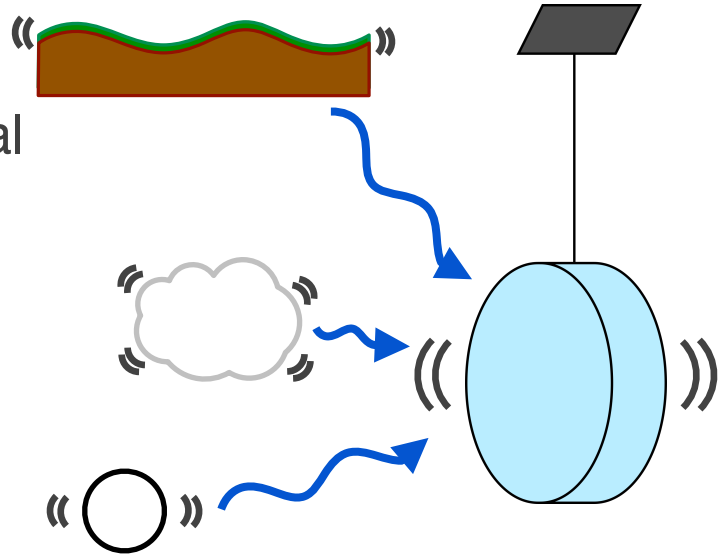


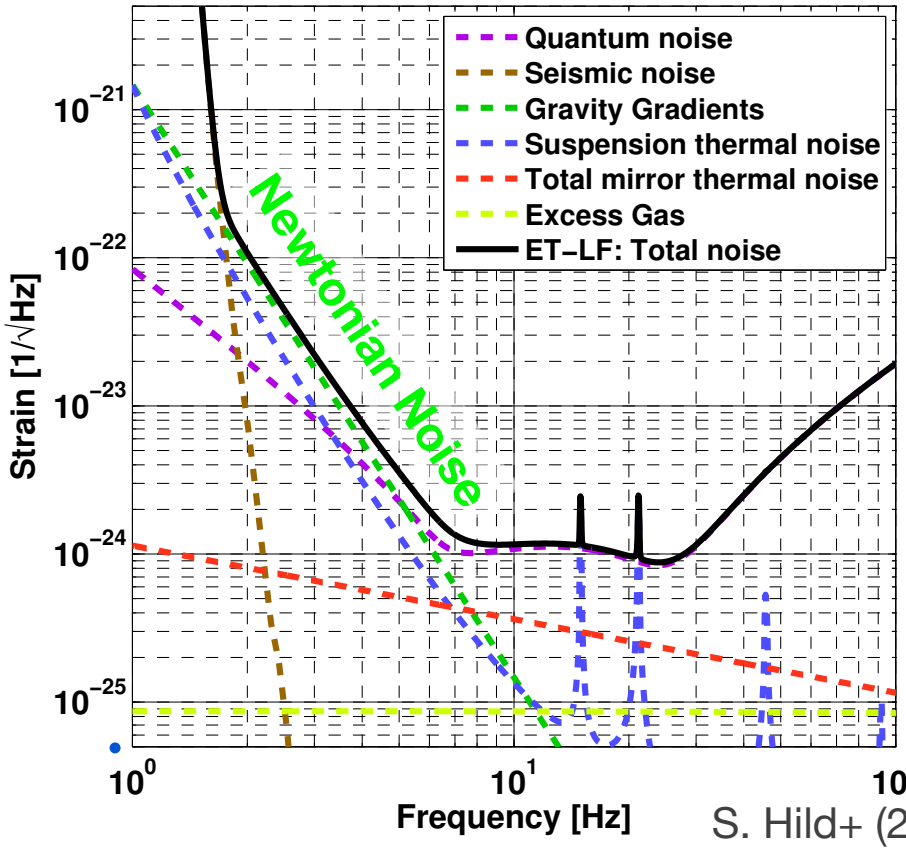
- Current warning: detect EQ by P-wave
  - Gravity field propagation is much faster than P-wave!
- With sensitivity 10-15/√Hz, TOBA can detect an M7 EQ 100 km away in 10 sec

Newtonian Noise

Newtonian Noise (Gravity Gradient Noise)

- Gravity gradient induce by local potential
  - Fundamental noise for GW detectors





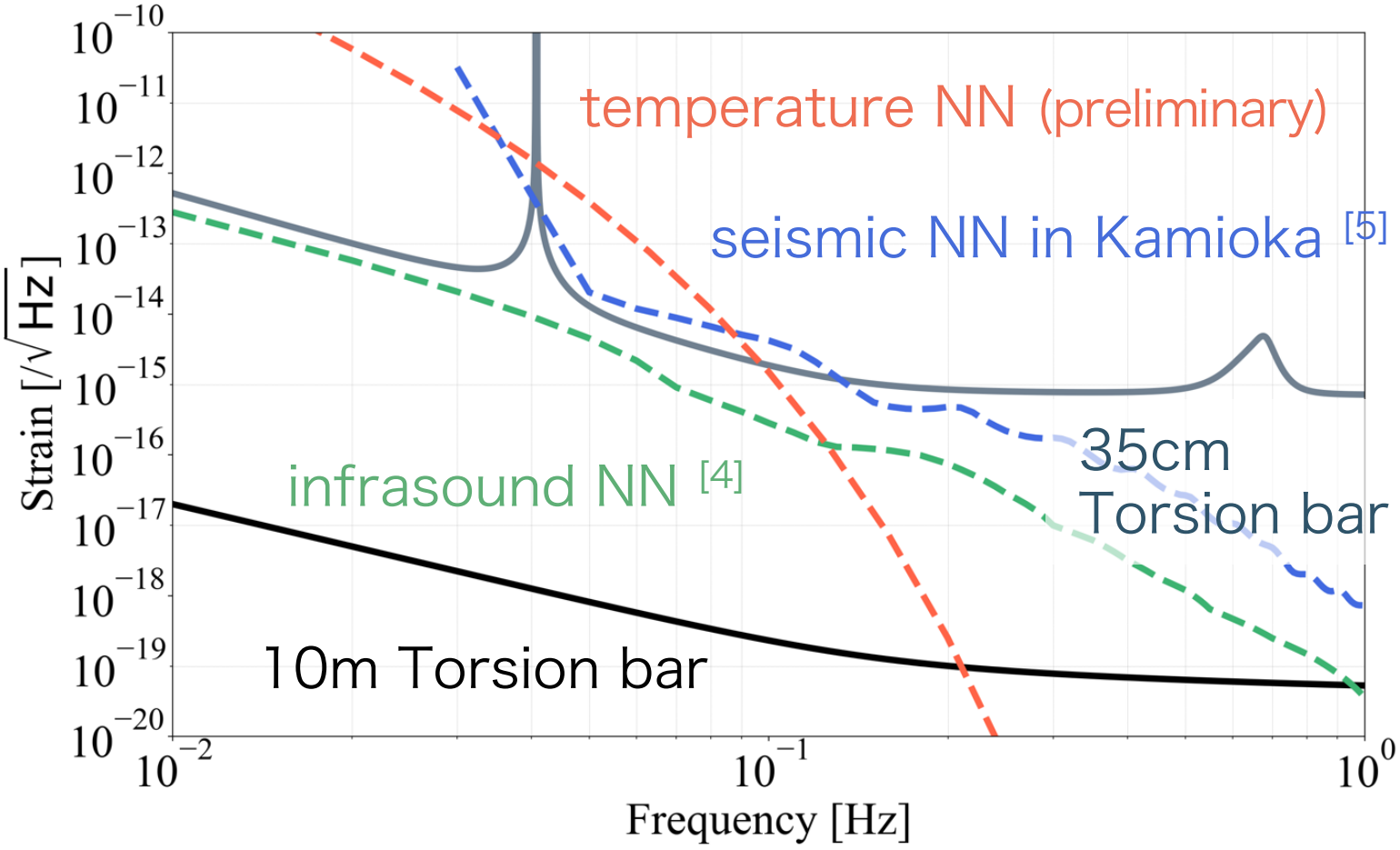
S. Hild+ (2011)

Sources

- Seismic motion
- Pressure fluctuation
- Temperature fluctuation
- Moving object

Newtonian Noise Measurement

- TOBA has potential for measurement of some types of NN
  - Test models, establish mitigation scheme, …



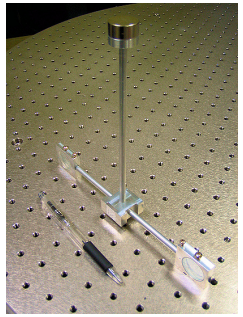
Development Plan

Phase-I (2009) → Phase-II (2015) → **Phase-III (Now)** → Final (Target)

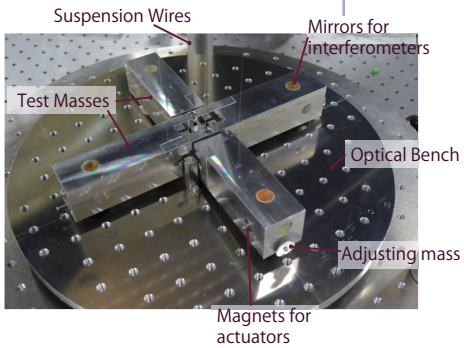
Principle Test

$10^{-8}/\sqrt{Hz}$ @ 0.1 Hz
(Established)

- Room Temp.
- 25cm TM(s)



M. Okada
Master Thesis

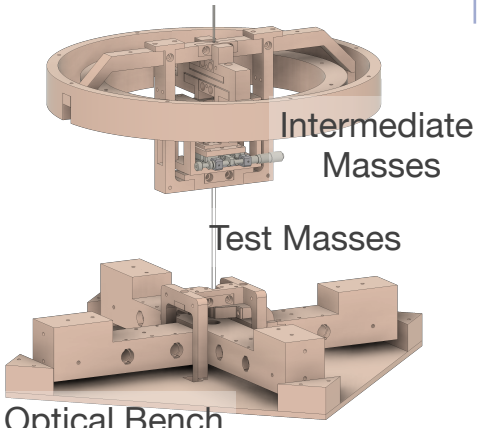


A. Shoda
Ph.D Thesis

Cryogenic Test

$10^{-15}/\sqrt{Hz}$ @ 0.1 Hz
(Design)

- **Cryo. Temp. (4K)**
- 35cm TMs

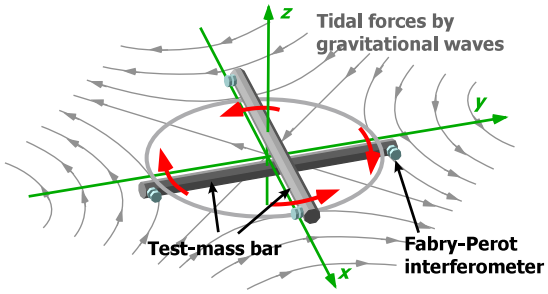


Optical Bench

Goal

$10^{-19}/\sqrt{Hz}$ @ 0.1 Hz
(Target)

- **Cryo. Temp. (4K)**
- **10m** TMs

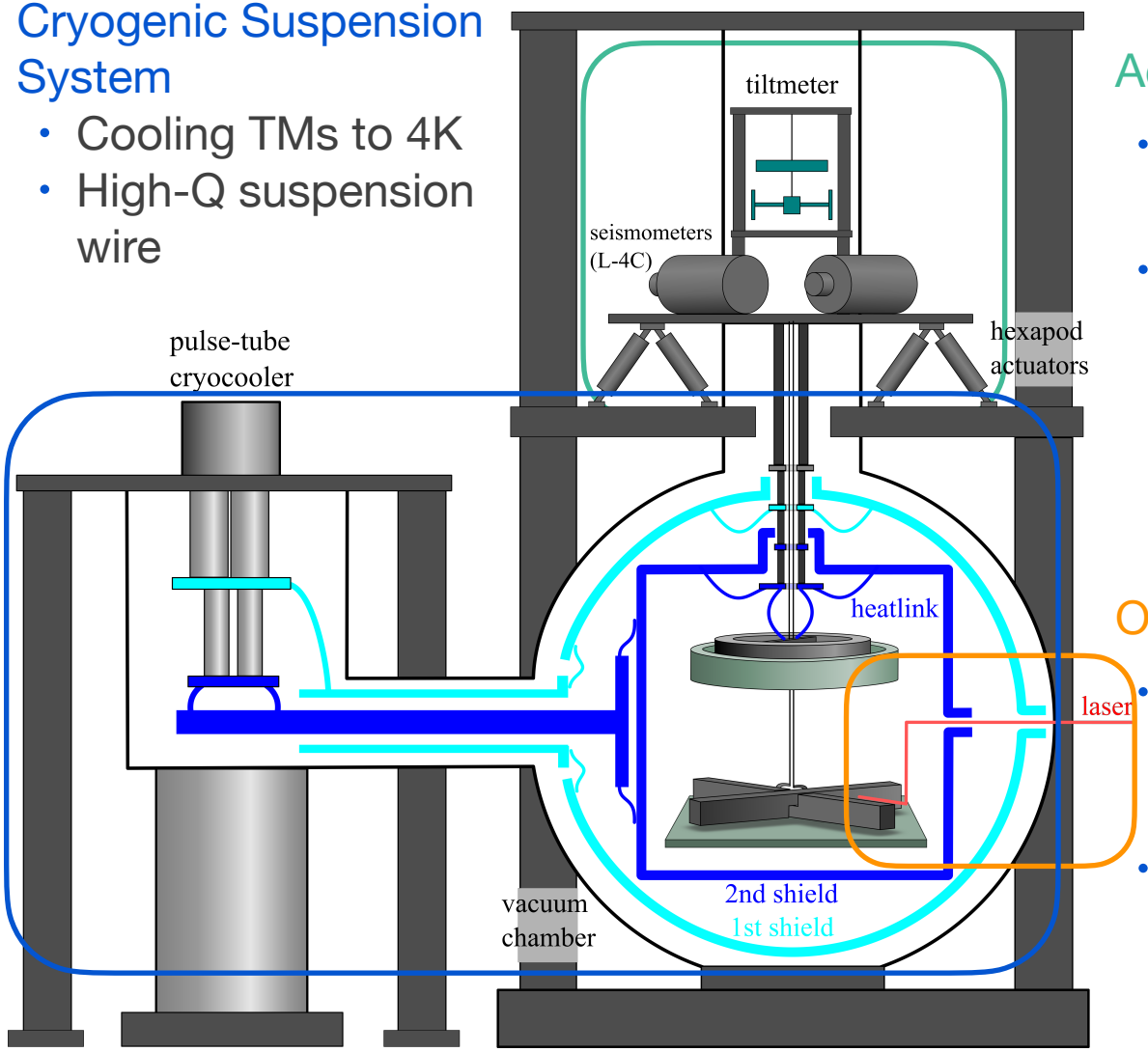


Phase-III TOBA

Setup of Phase-III TOBA

Cryogenic Suspension System

- Cooling TMs to 4K
- High-Q suspension wire



Active Vibration Isolation System

- Reduction of vibration at the suspension point
- Reduction of vibration induced cryocooler

Optical System

- Rotation measurement by high-sensitive wave front sensor
- Beam jitter control in order to follow the incident beam to the optical bench

Cryogenic Suspension System

Cryogenic Cooler

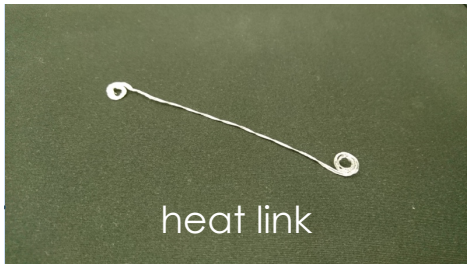
- Cool down TMs to 4 K
- Two radiation shields (50 K & 4 K)

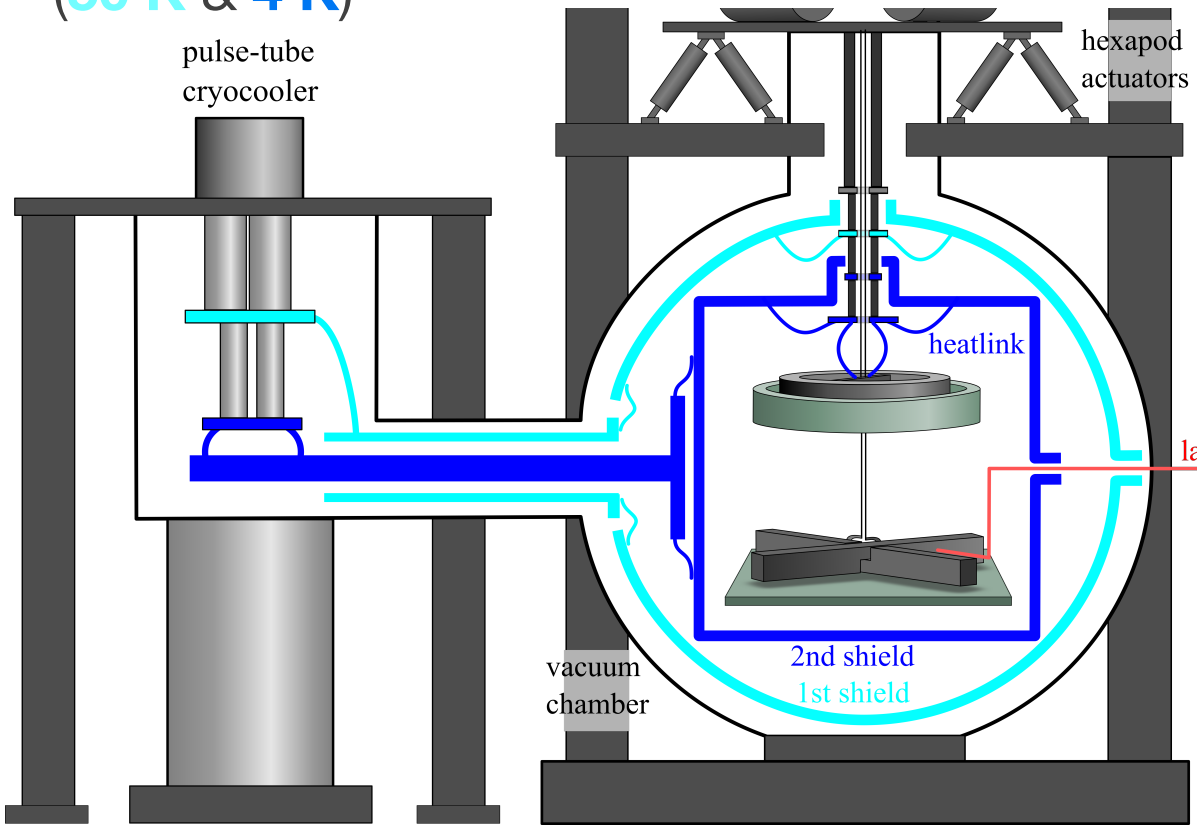
Suspension wire

- Si wire
- High Q value (>10^8)

Heat Links

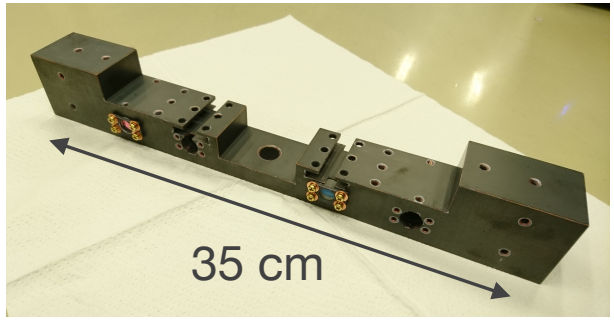
- High-purity aluminum
  - Conductive cooling





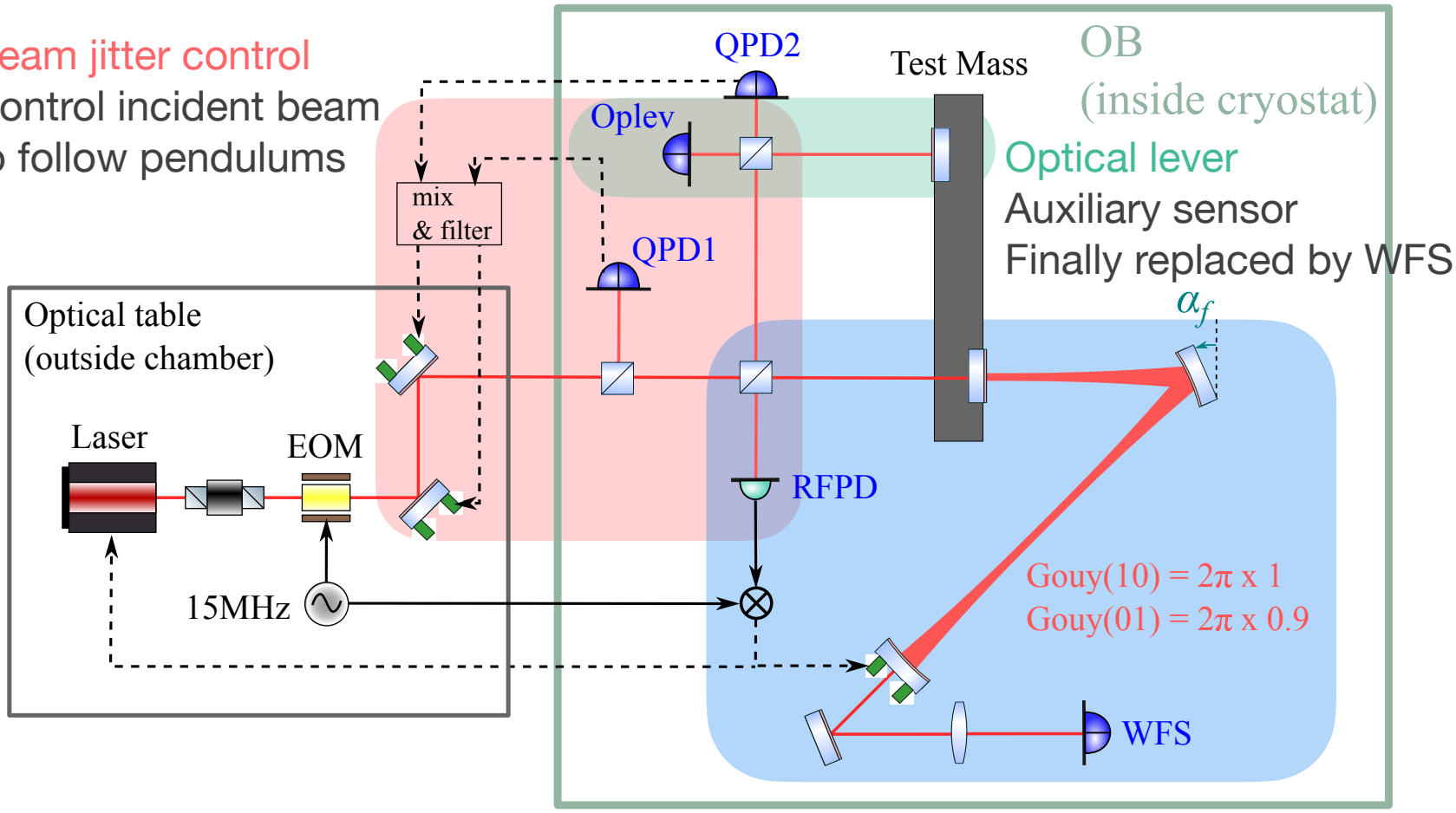
TMs

- Copper
- Surface is oxidized



Optical System

Beam jitter control
Control incident beam
to follow pendulums



Wave Front Sensor (WFS)
Measure HG10 mode induced
by rotational motion

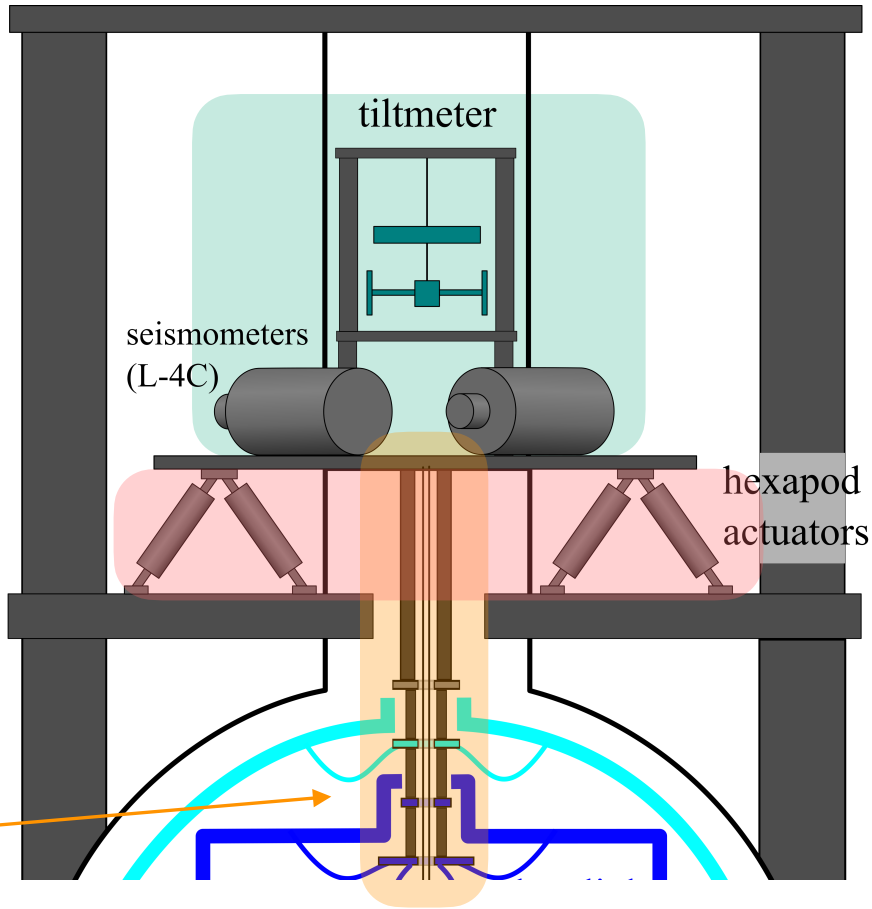
Active Vibration Isolation System

- Reduction of seismic vibration
  - Coupling from horizontal vibration
    - 10^{-7} m/√Hz @ 0.1 Hz
  - Nonlinear coupling
    - 10^{-10} m/√Hz @ 1 Hz

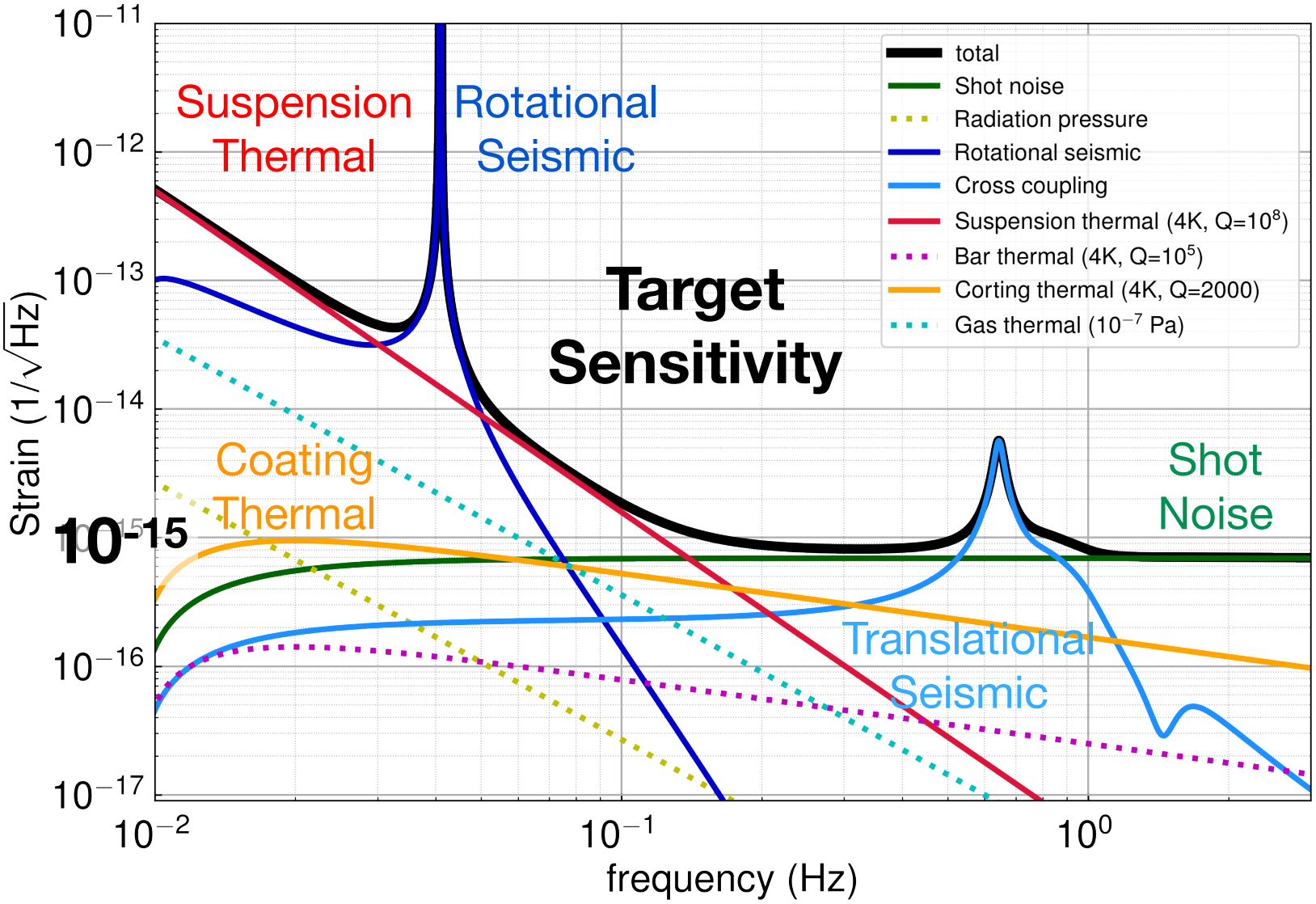
Measure motion at the suspension point by seismometer & tilt meter

Feedback the signal to actuators to cancel out the motion

- Reduction of vibration induced by cooler



Design Sensitivity



Development Items

- Cryogenic Suspension System
  - Cooling System → Shimoda
  - High-Q suspension wire → Ching Pin
- Optical System
  - New WFS with higher sensitivity → Shimoda, Miyazaki
- Active Vibration Isolation
  - Reduction of translational seismic noise → Takano
  - Reduction of vibration induced by cooler

Development Items

- Cryogenic Suspension System
  - Cooling System → Shimoda
  - High-Q suspension wire → Ching Pin

- Optical System
  - New WFS with higher sensitivity → Shimoda, Miyazaki

- Active Vibration Isolation
  - Reduction of translational seismic noise → Takano
  - Reduction of vibration induced by cooler

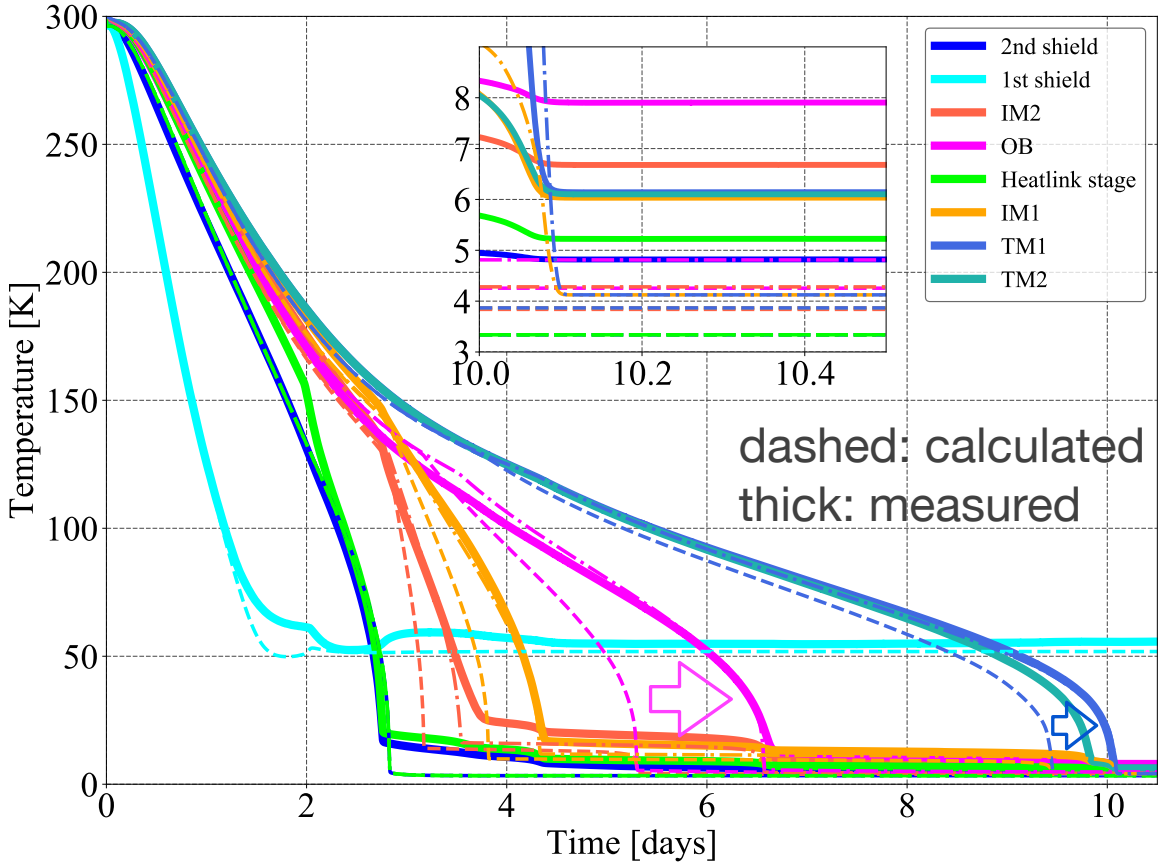
Current Situation

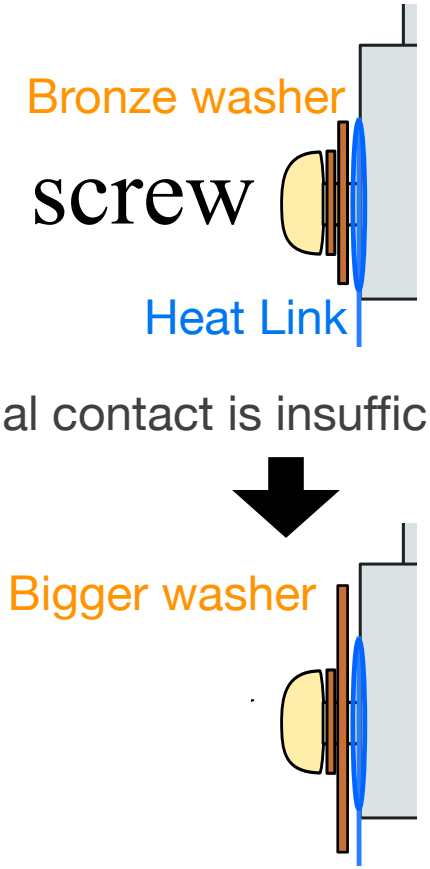
Current Status

- Cryogenic Suspension System
  - ○ Cooling down TMs at 6.1 K
  - × Achieved temperature is higher (design: 4 K)
  - × Cooling speed is smaller than expected
- Optical System
  - × Measured by optical lever, cavities are not locked
  - × Residual jitter noise (0.01 - 1 Hz)
  - × Interference of stray light (floor level)
- Active Vibration Isolation System
  - ○ Controlling 3-axis translation simultaneously
  - × Tilt-horizontal coupling
  - × Resonance of the structure

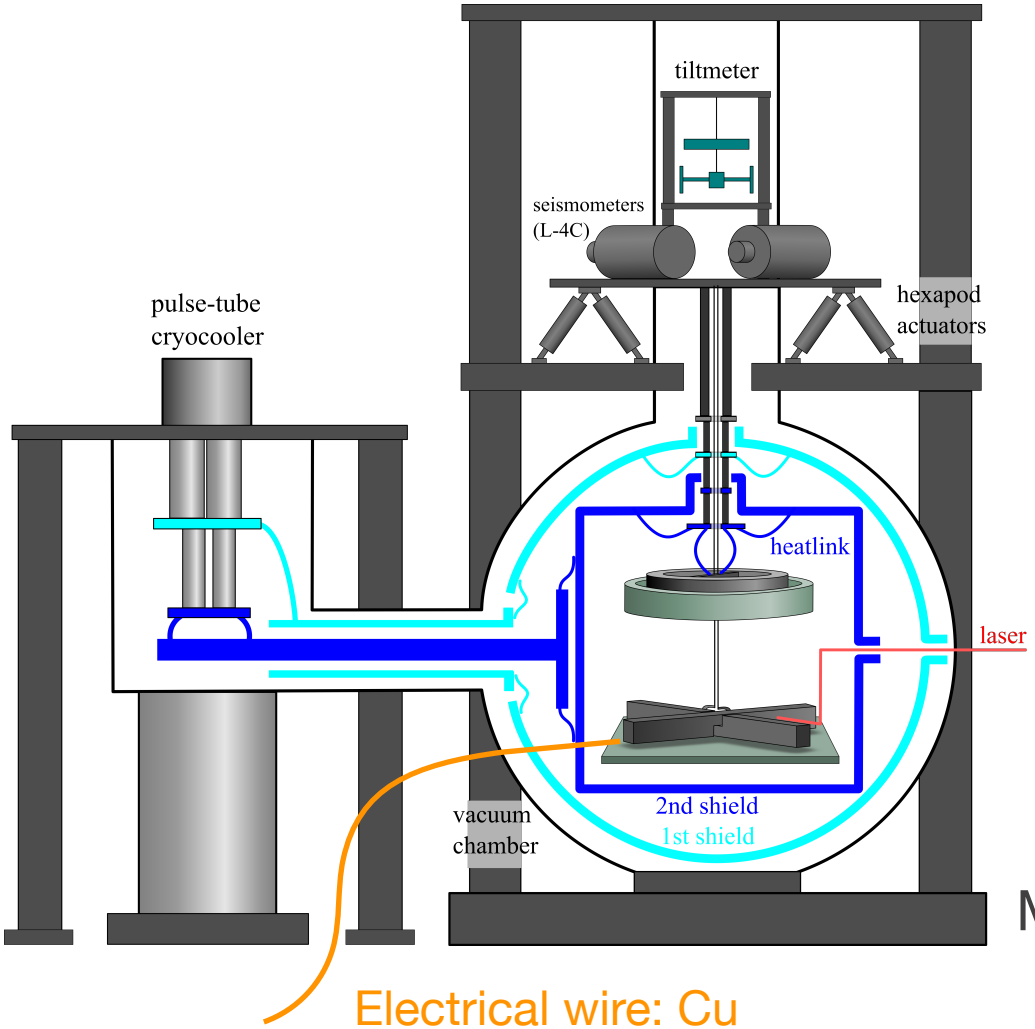
Cryogenic Performance

- Slower cooling speed → smaller thermal conductivity of heat links
- Can be explained by supposing smaller value by 30 - 50 %
  - Good contact procedure is necessary





Higher Achieved Temperature



2nd shield: 4.8 K (+1.5 K)
- Heat inflow via electrical wires
- Worse performance of cooler

Heat Link VIS: 5.2 K (+1.9 K)
- Heating by actuator coils

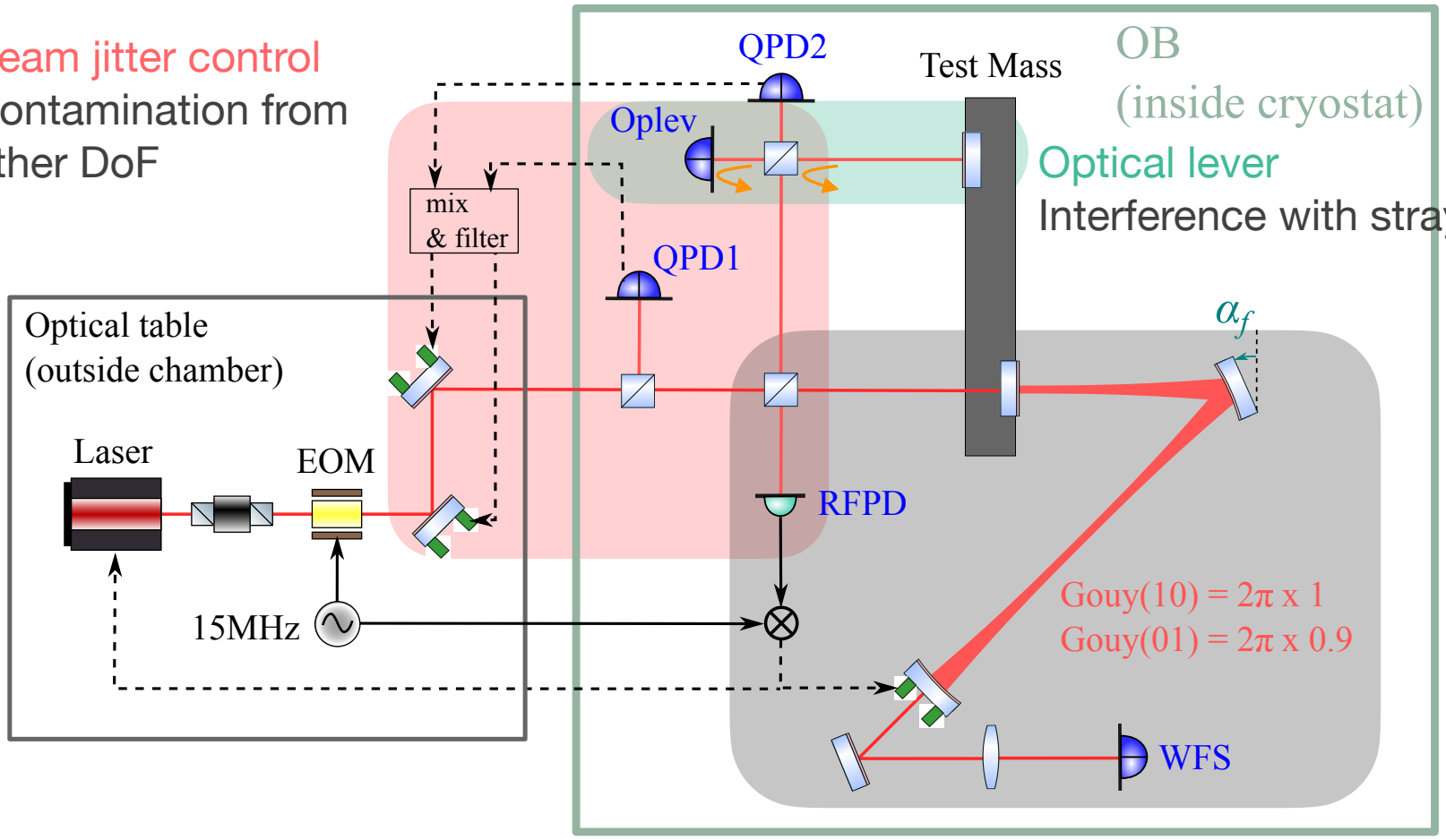
Test Mass: 6.1 K (+2.0 K)
- Heating by actuator coils

Electrical wire: Cu
- Haet generation?

Main sources: Heat generation of
- Actuator coils on TMs and OB
- Electrical wire

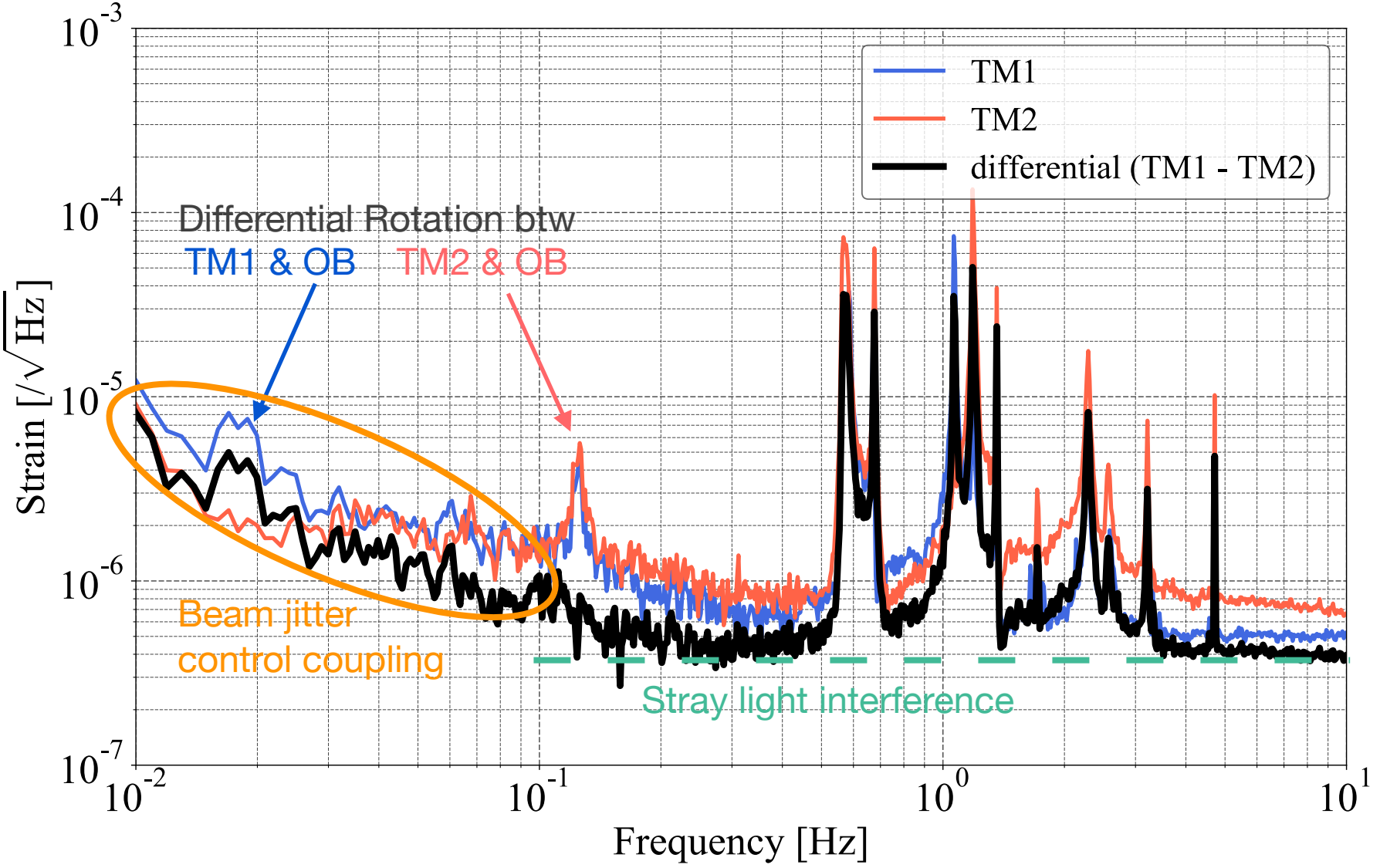
Optical System

Beam jitter control
Contamination from other DoF



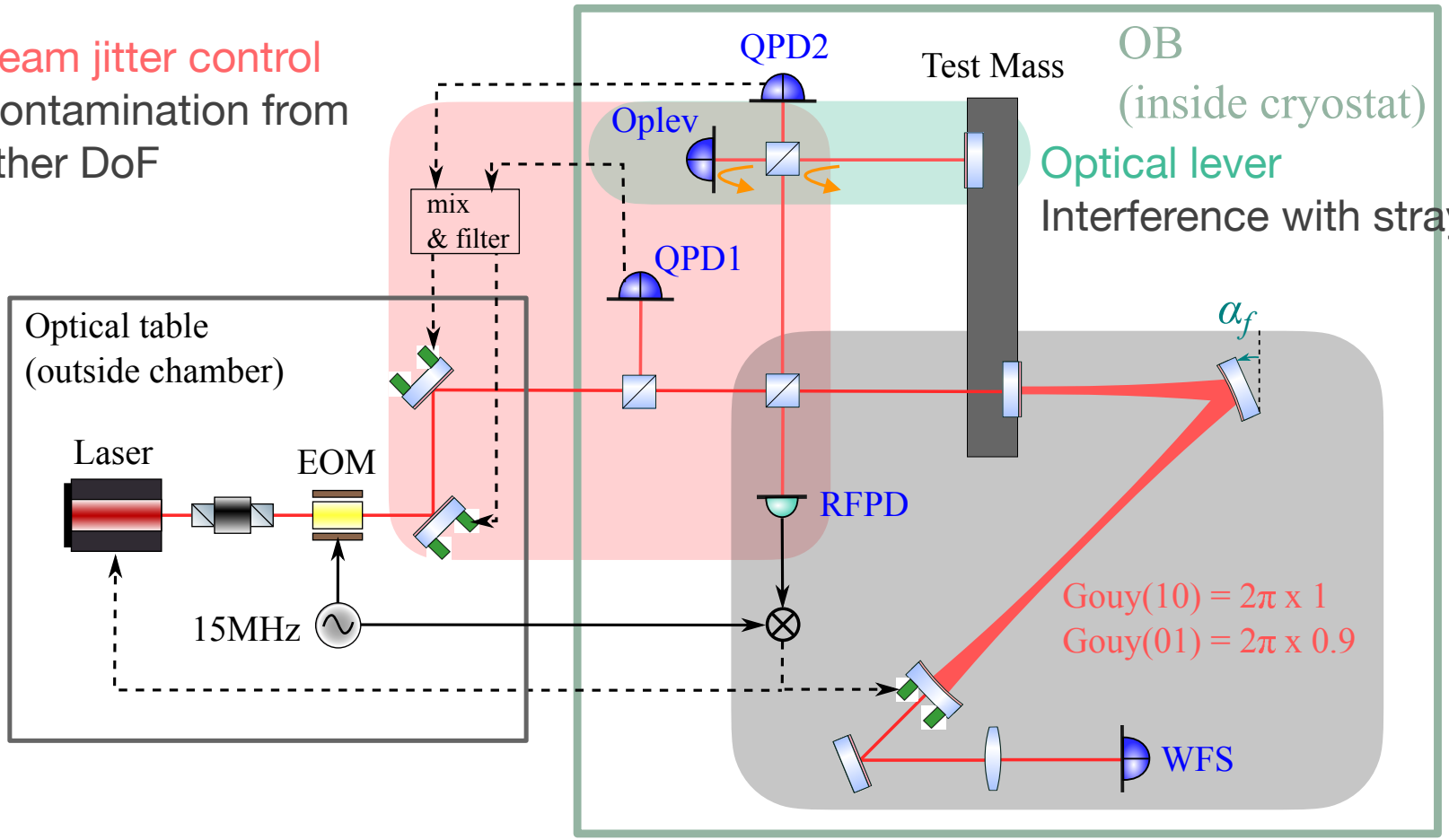
Wave Front Sensor (WFS)
Not locked

Current Sensitivity



Optical System

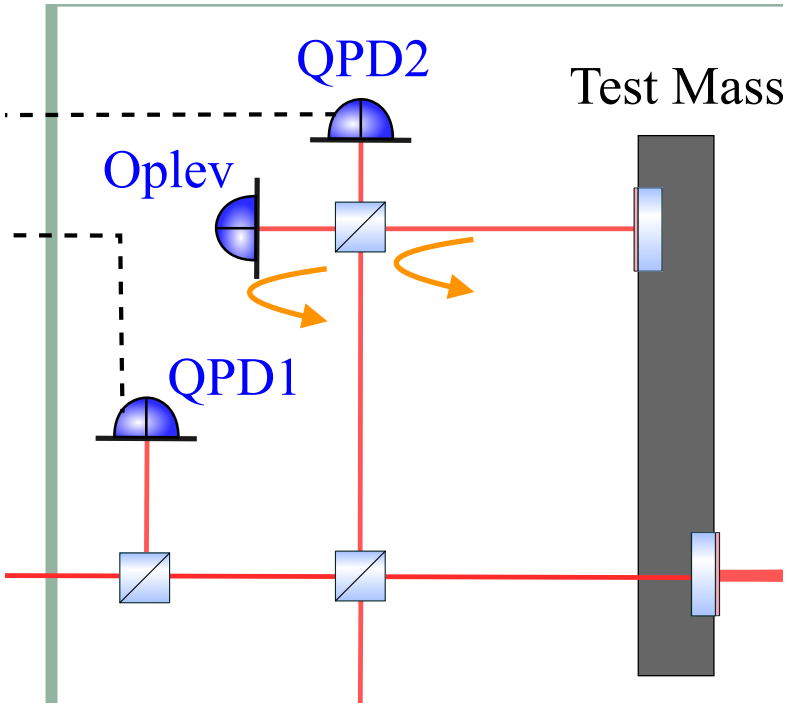
Beam jitter control
Contamination from other DoF



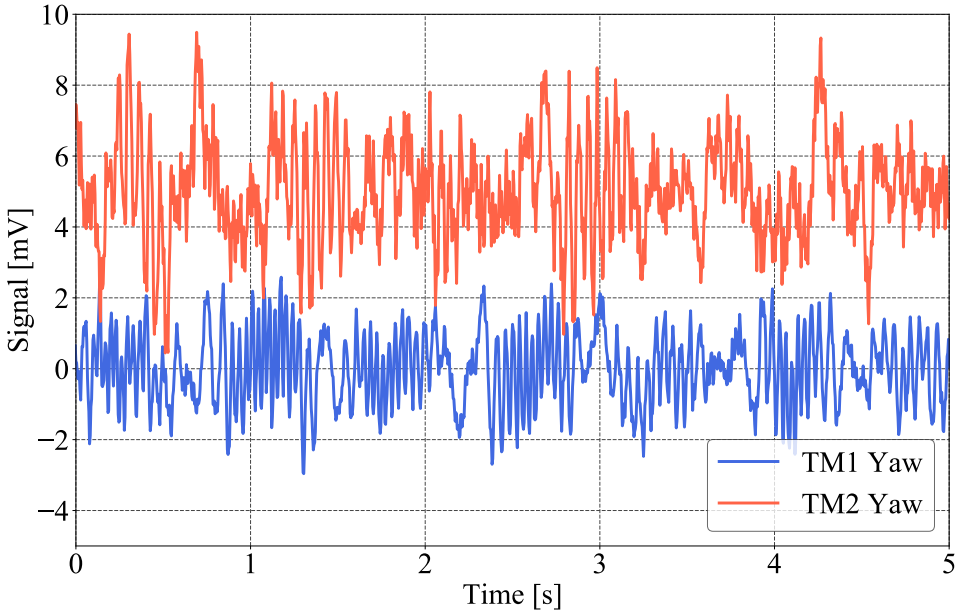
Wave Front Sensor (WFS)
Not locked

Stray Light Problem

Front reflection at
- Cube BS
- QPD surface
  - Stray light



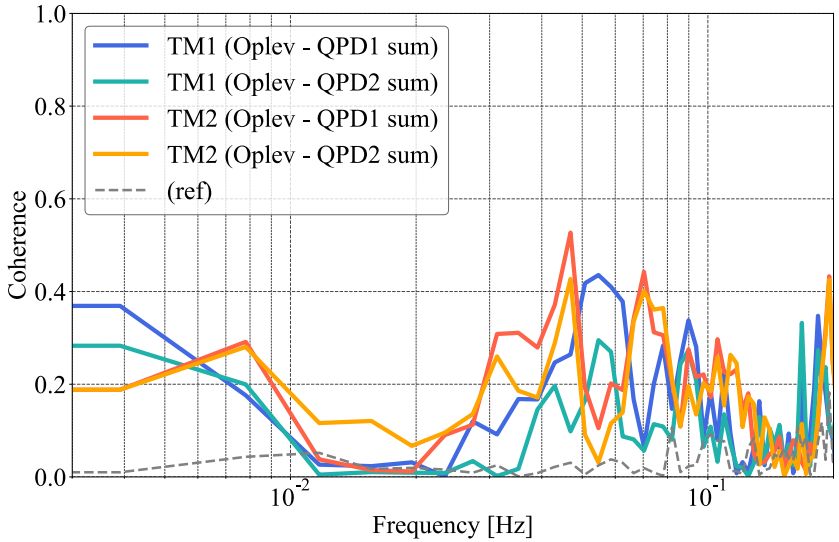
Interference with stray light contaminates oplev signal

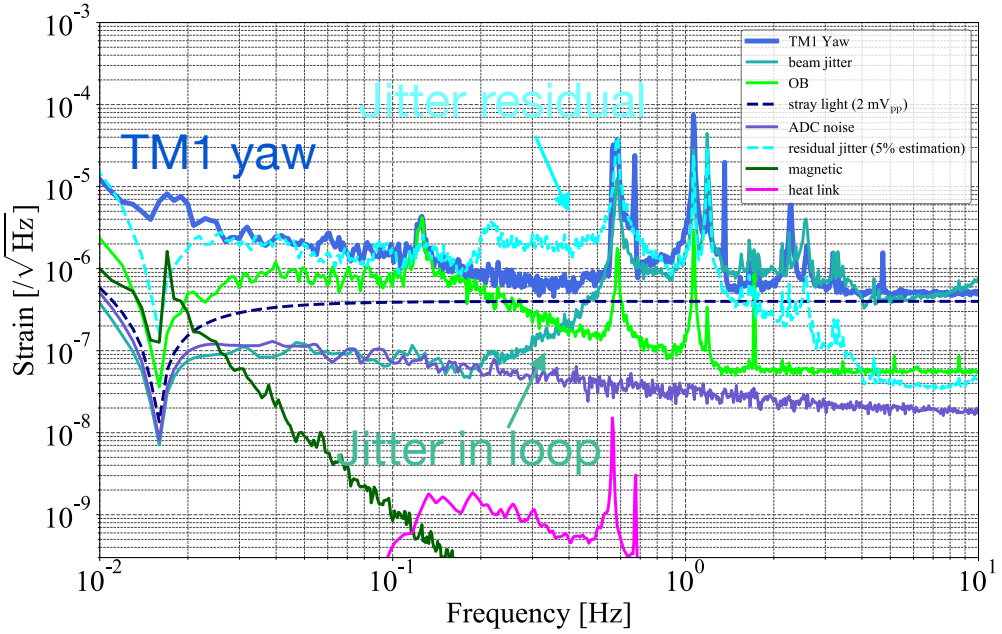


Beam Jitter Control Noise

- Some coherence btw TM oplev yaw & Jitter QPD sum
  - Beam jitter control signal shakes beam additionally
  - Contaminates oplev signal

Coherence btw
TM oplev yaw & QPD sums

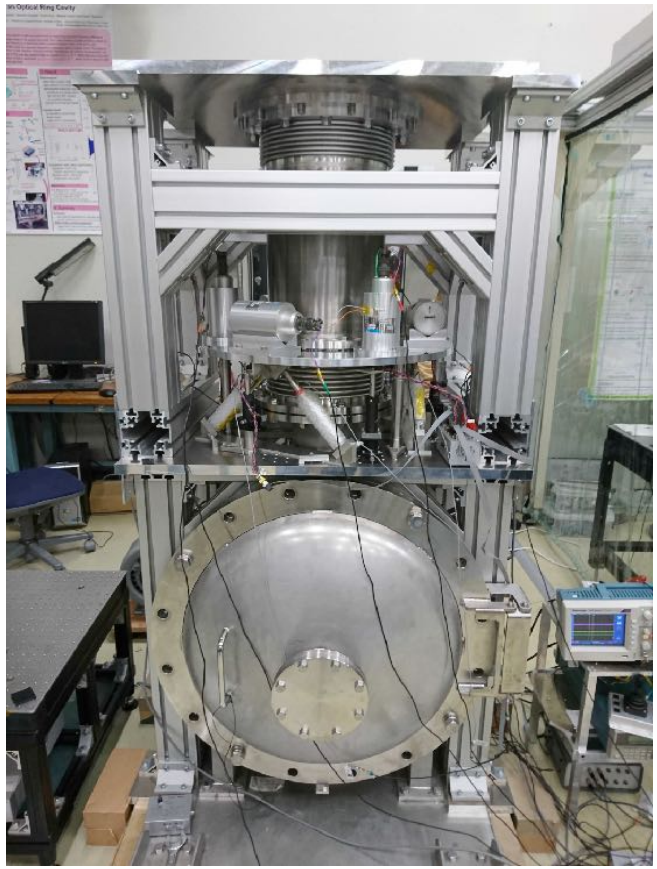




5% residual assumption
- can be explained the noise budget well

Active Vibration Isolation System

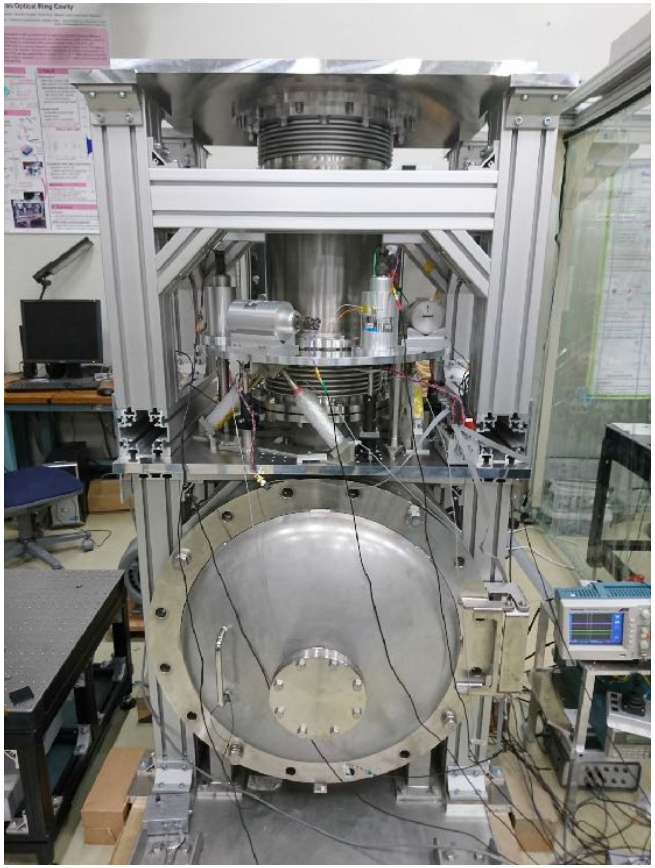
- 2019 April: Frame exchange, servo modification

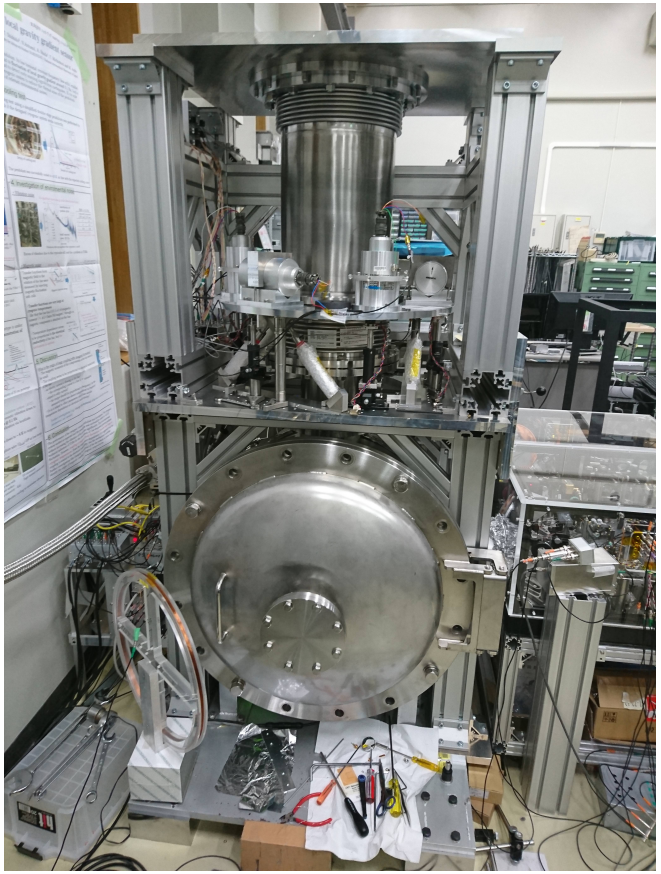


- 2019 June: Succeeded in controlling 3 axis simultaneously

Active Vibration Isolation System

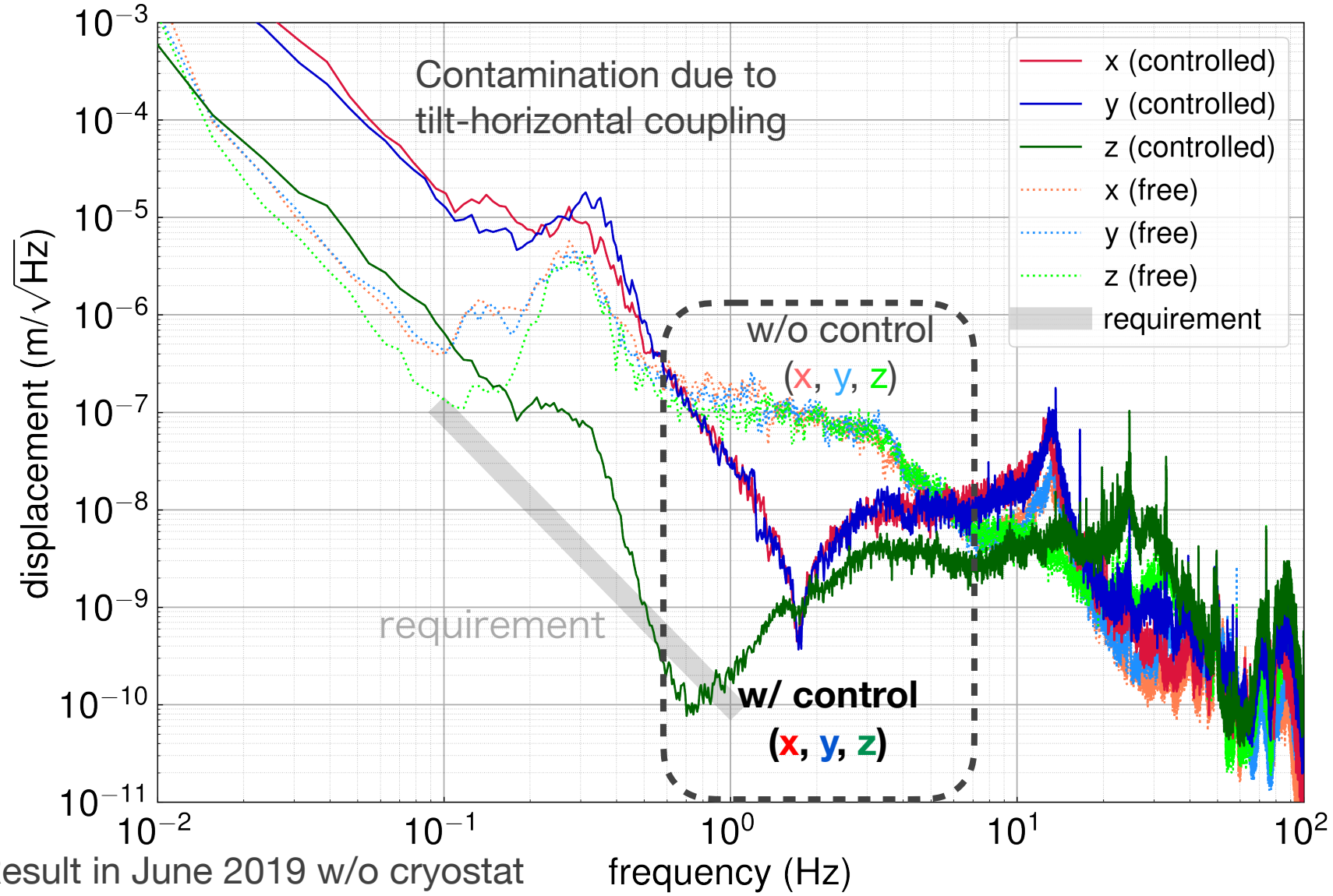
- 2019 July: Installation to the TOBA chamber





- 2020 Feb: Test run with cryogenic temp.

Active Vibration Isolation Performance



Result in June 2019 w/o cryostat

After Installation

Some difference in characteristics of actuators

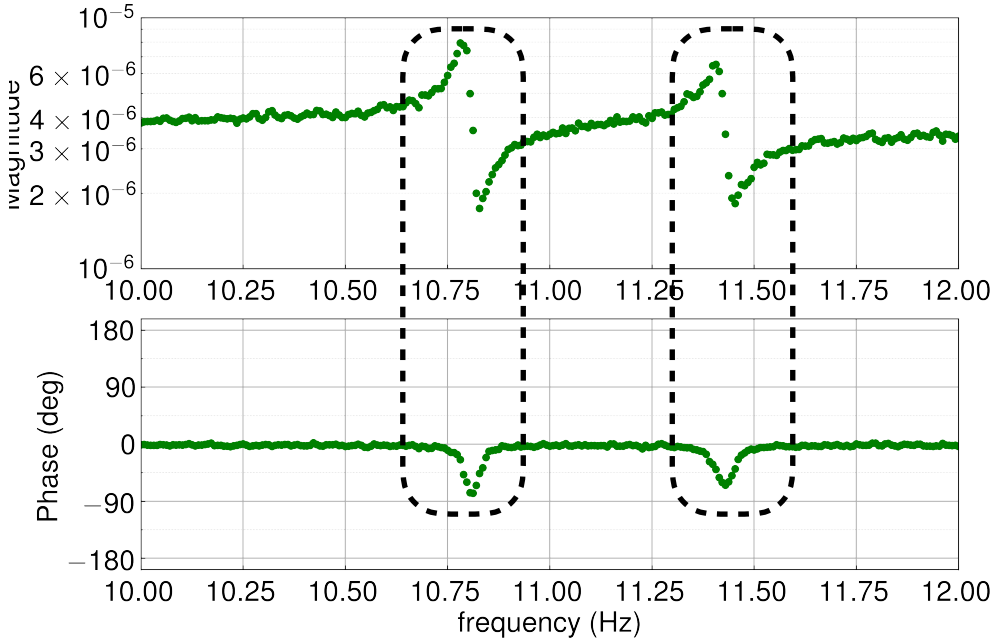
- High-Q parasitic resonance

	x	y
f1 (Hz)	13.5	13.8
Q1	9	13
f2 (Hz)	15.1	15.2
Q2	10	16

	x	y
f1 (Hz)	15.4	18.4
Q1	67	101
f2 (Hz)	16.7	19.1
Q2	182	2000

Hard to compensate to the resonance!

- Low frequency resonance in z axis



No such resonances before installation!

Future Plans

Update Plans

Cryogenic system

- Test better way to attach heat links
- Replace electrical wires to ones with less thermal conductivity

Optical system

- Cube BS → Plate BS to avoid stray light interference
- Introduce MC to suppress beam jitter

Active Vibration Isolation

- Damp resonance mode of the structure by adding damper
- Install tiltmeter to reduce tilt-horizontal coupling
- Introduce sensor correction servo

Others

- Introduce magnetic shield

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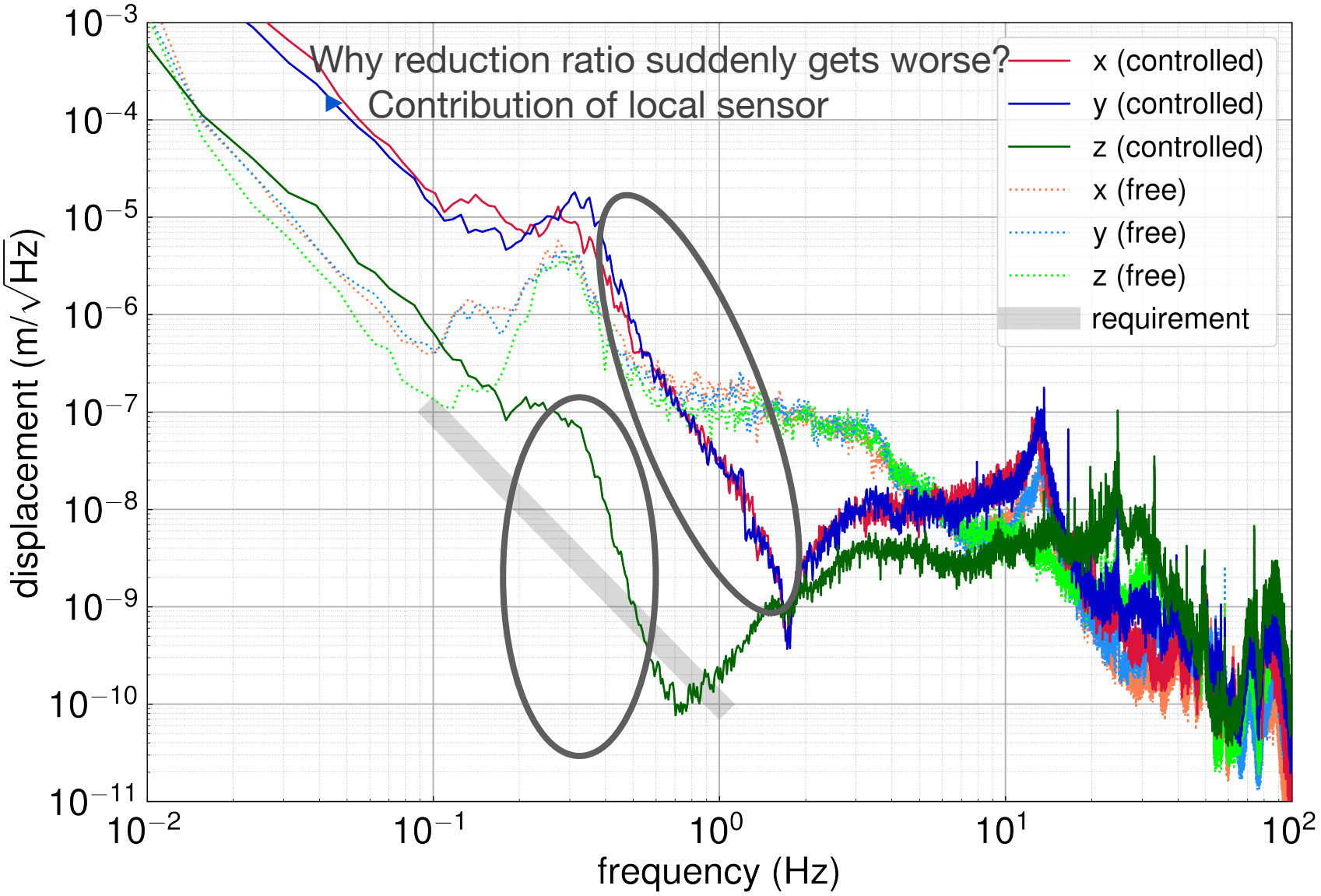
AVIT upgrade

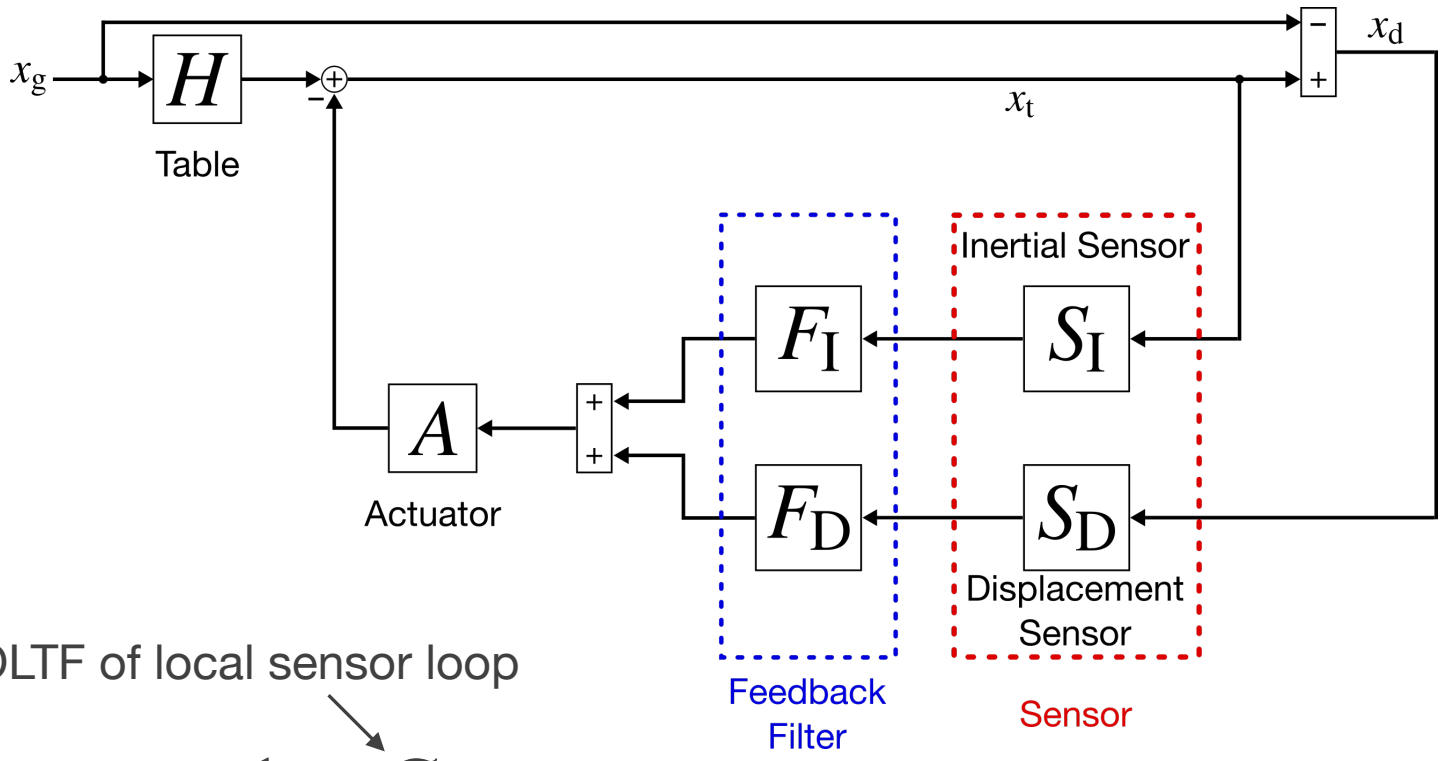
How to avoid the effects of parasitic resonance?

- Make resonant frequency higher
  - Need to exchange the structure
- Damp the resonance
  - Let's use shock absorbers
  - Easy to install

Sensor Correction



Control Servo



OLTF of local sensor loop

$$x_t = \frac{1 + G_D}{1 + G_I + G_D} x_g$$

$$|G_I| \ll |G_D|$$

$$\simeq x_g$$

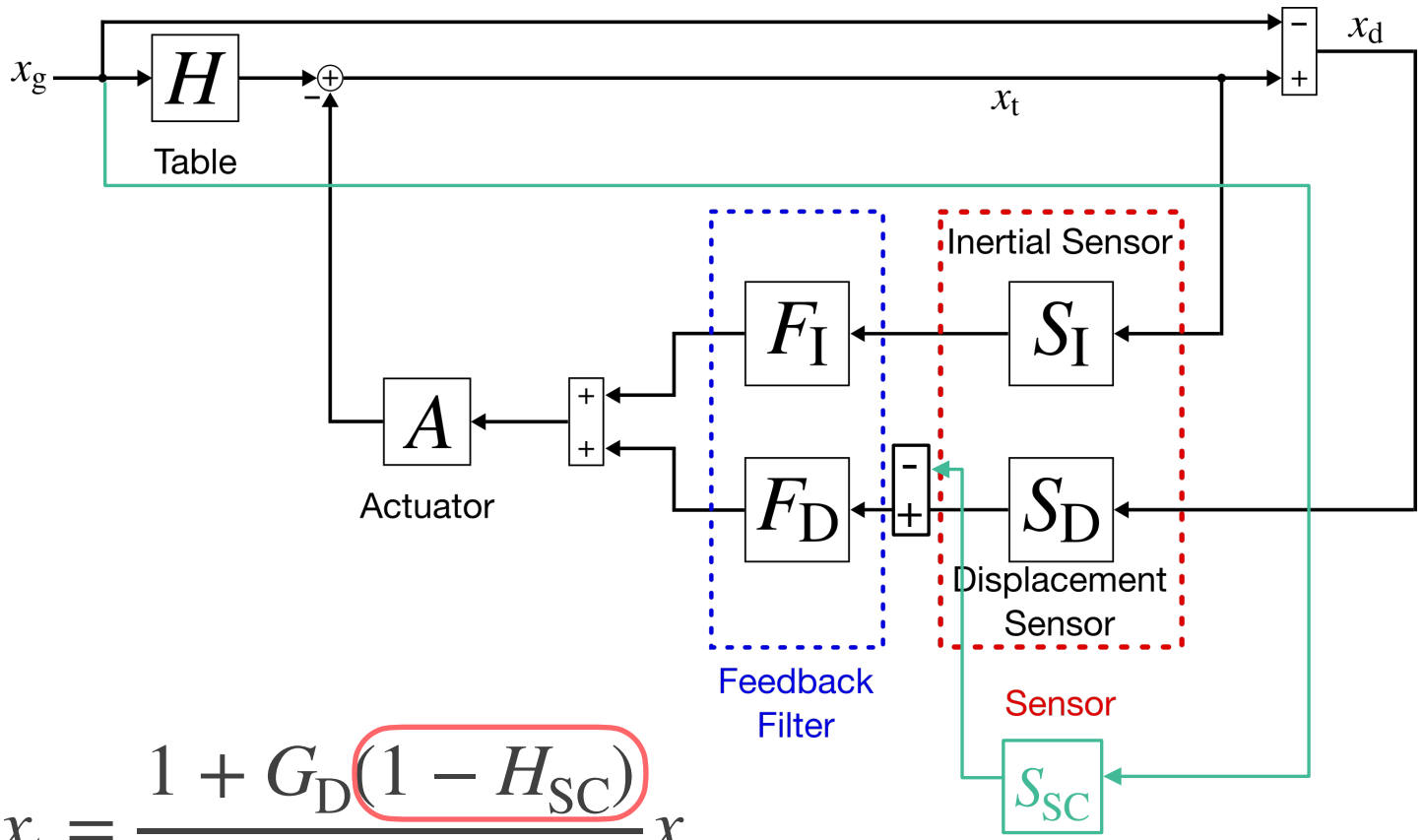
OLTF of inertial sensor loop

Displacement sensor signal degrades reduction ratio where $|G_I| << |G_D|$

Optical System Modification

- Problems so far
  - Jitter control noise
  - Stray light interference
- In both case, we need to modify optical system
-

Control Servo



$$x_t = \frac{1 + G_D(1 - H_{SC})}{1 + G_I + G_D} x_g$$

Witness sensor

Measuring vibration outside the AVIT

Witness sensor cancels the local sensor signal

- Restore reduction performance

Update Plans

Cryogenic system

- Test better way to attach heat links
- Replace electrical wires to ones with less thermal conductivity

Optical system

- Cube BS → Plate BS to avoid stray light interference
- Introduce MC to suppress beam jitter

Active Vibration Isolation

- Damp resonance mode of the structure by adding damper
- Install tiltmeter to reduce tilt-horizontal coupling
- Introduce sensor correction servo

Others

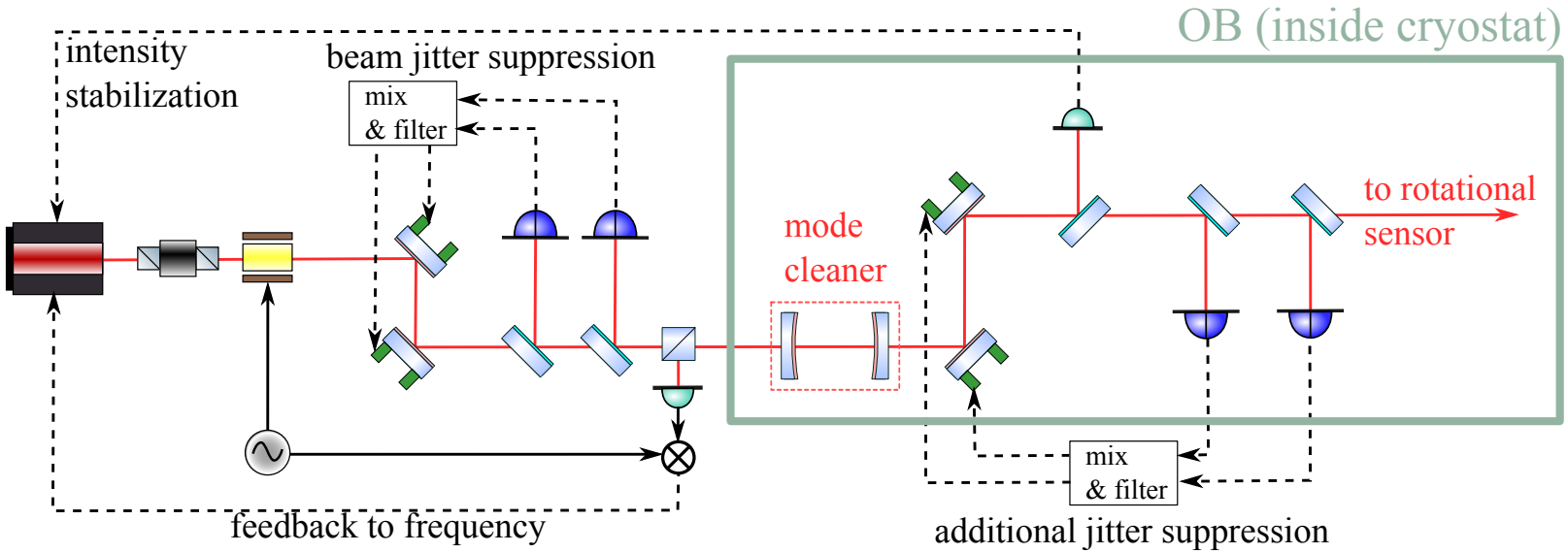
- Introduce magnetic shield

Install Mode Cleaner

- Requirement for jitter reduction: **10^{-6}**

  ← $10^{-9}/\sqrt{Hz}$ w/o control, $10^{-15}/\sqrt{Hz}$ is the target

  - Passive reduction by mode cleaner



Suppose $F=10^4$:

- 10^{-3} reduction by mode cleaner
- 10^{-1} reduction by additional suppression
- 10^{-2} reduction by WFS

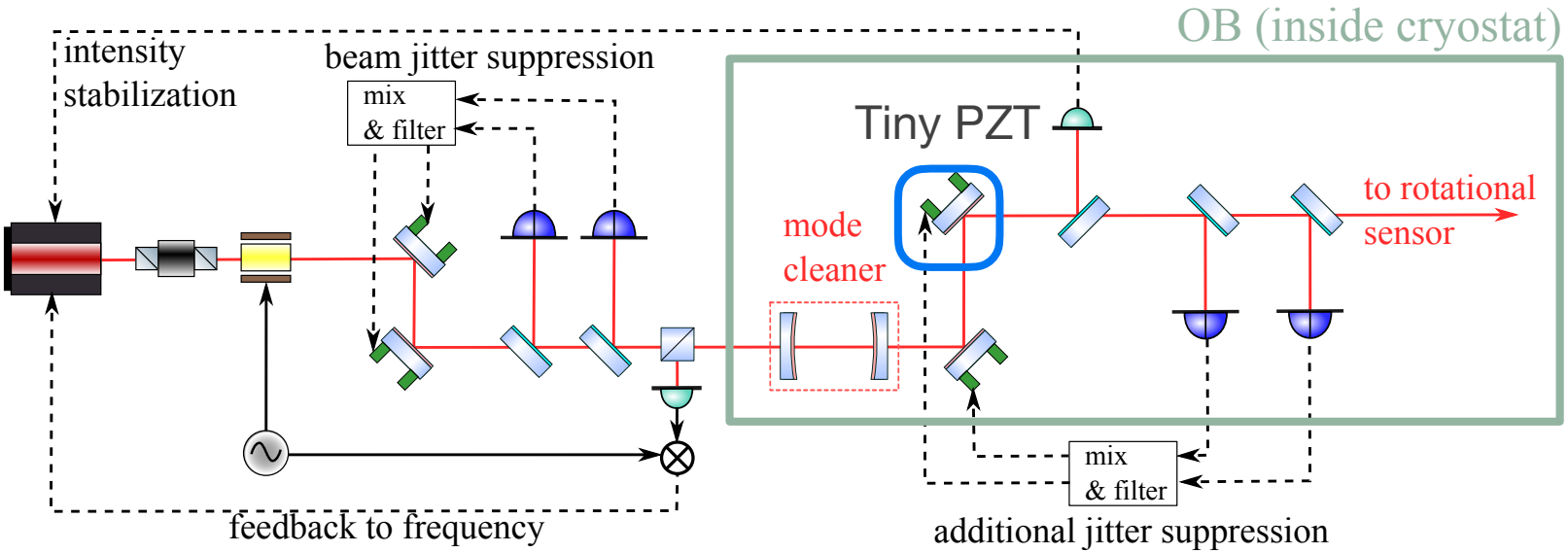
How to Control cavities?

- If we introduce a mode cleaner, sideband for control of main cavity also suppressed
  - How to control mode cleaner and cavity simultaneously?

1. Make the round trip length of MC so that sideband is on resonance next to the carrier
   - For 15 MHz sideband, round trip length = 20 m
   - Too long!
2. Between MC and the gain cavity insert a phase modulator
   - One candidate
3. Use suppressed sideband to lock the main cavity
   - Another way
4. Consider another locking way
   - I have no idea

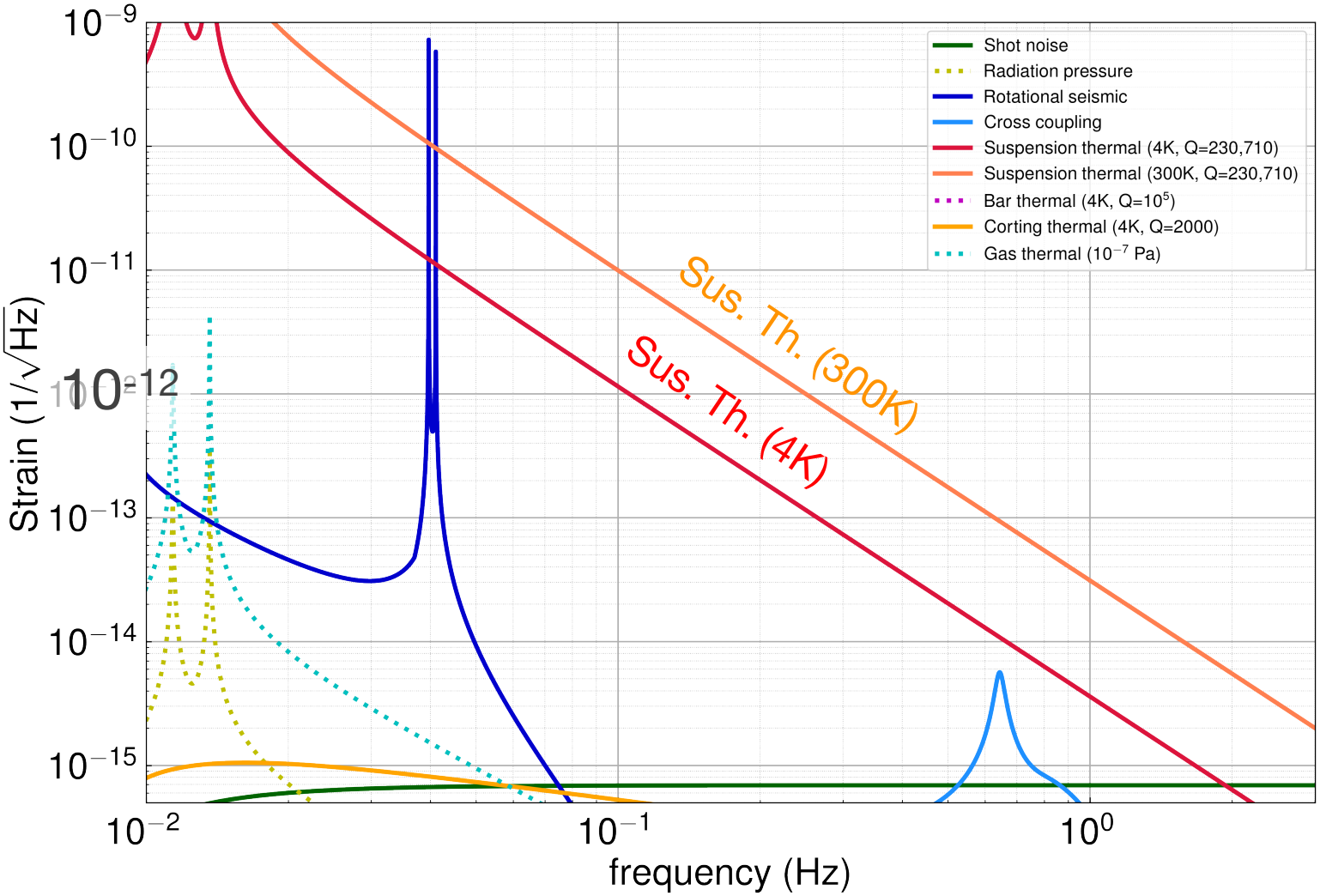
Phase Modulator

- How to modulate the laser in phase under cryogenic temperature?
  - EOM
    - I'm not sure it is work at 4 K
  - Mechanical phase modulation
    - Use tiny PZT and oscillate it in ~ MHZ



Goal (?)

With current suspension wire → limited by suspension thermal noise



Target of My Research

Achieve sensitivity $10^{-12}/\sqrt{\text{Hz}}$ @ 0.1 Hz

- Lock the cavity and demonstrate new WFS
  - First trial for pendulums
- Introduce MC and suppress beam jitter
  - 10^{-6} reduction is the target
- See suspension thermal noise @ 300 K and 4 K
  - Show the merit of cryogenic system

Science of that Sensitivity

- What can I do with this sensitivity?

- Newtonian noise injection
  - G-cal like injection (moving mass)
  - Inject temperature fluctuation

- Non-equilibrium thermal noise
  - Heat ™ to make huge heat flow
  - Test the thermal noise models

- Currently no quantitative estimation…
- Fortunately(?) I have time to estimate them

End