Axion Search, Sensitive Angular Sensor & Torsion-Bar GW Antenna

Yuka Oshima
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Self introduction

Yuka Oshima (大島 由佳)

Ph.D. student at Ando Group,
Department of Physics, University of Tokyo

I got my master's degree this March

<table>
<tr><td>Year</td><td>2016</td><td>2017</td><td>2018</td><td>2019</td><td>2020</td><td>2021</td><td>2022</td><td>2023</td><td>2024</td></tr>
<tr><td rowspan="2">My grade</td><td colspan="4" rowspan="2">Undergraduate student at Univ. of Tokyo</td><td colspan="5">Graduate student at Ando Group, Univ. of Tokyo</td></tr>
<tr><td colspan="2">Master course</td><td colspan="3">Ph.D. course</td></tr>
<tr><td>My research topic</td><td colspan="9">Axion dark matter search with a ring cavity
Wavefront sensor with a coupled cavity
Torsion-bar GW antenna</td></tr>
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1. Axion dark matter search with a ring cavity
   - Since my undergraduate student
2. Wavefront sensor with a coupled cavity
   - For my master thesis (done)
3. Torsion-bar GW antenna
   - For my Ph.D. thesis (plans)

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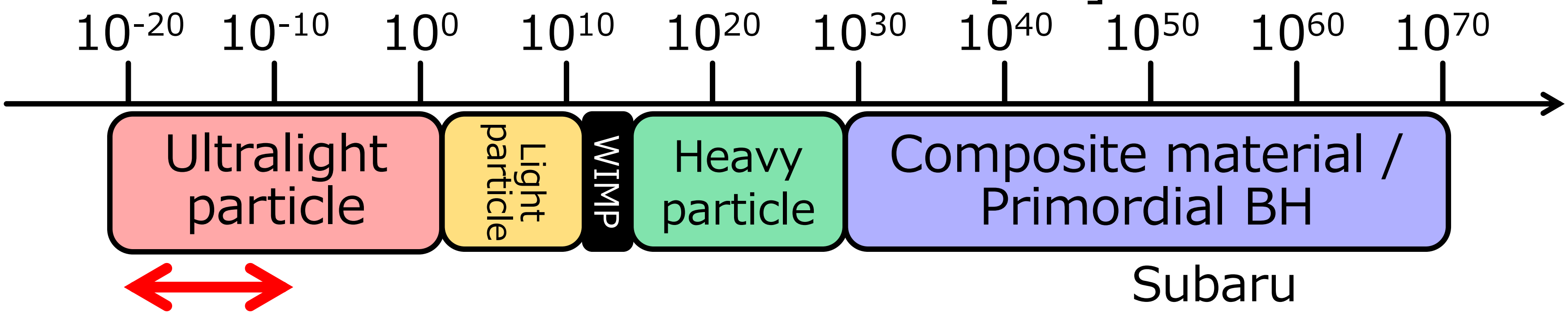
Axion search with laser interferometers

- Need to search for dark matter in a wider mass range
- Axions can be searched with laser interferometers
- Our project "DANCE":
  Dark matter Axion search with riNg Cavity Experiment

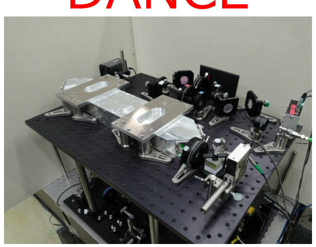
I. Obata, T. Fujita, Y. Michimura, PRL 121, 161301 (2018)

Dark matter mass [eV]



Laser interferometers

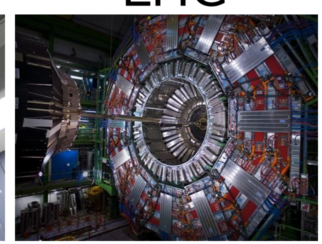
DANCE



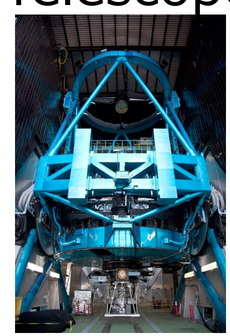
KAGRA

XENON1T

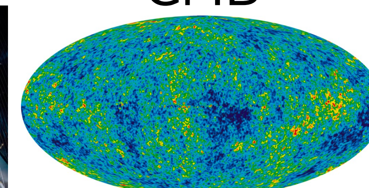
LHC



Subaru Telescope

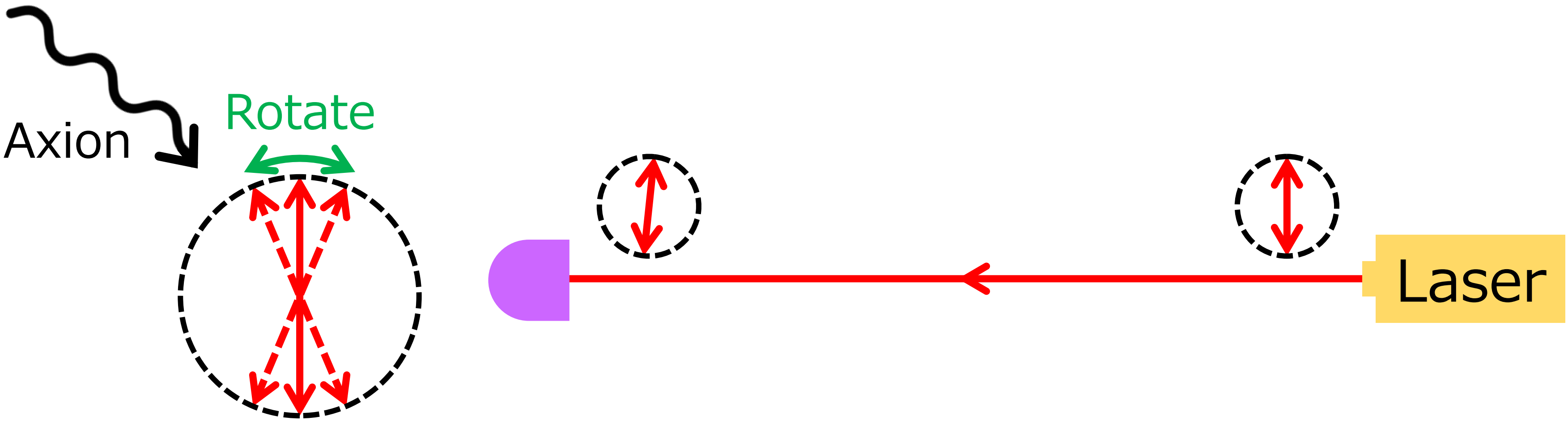


CMB

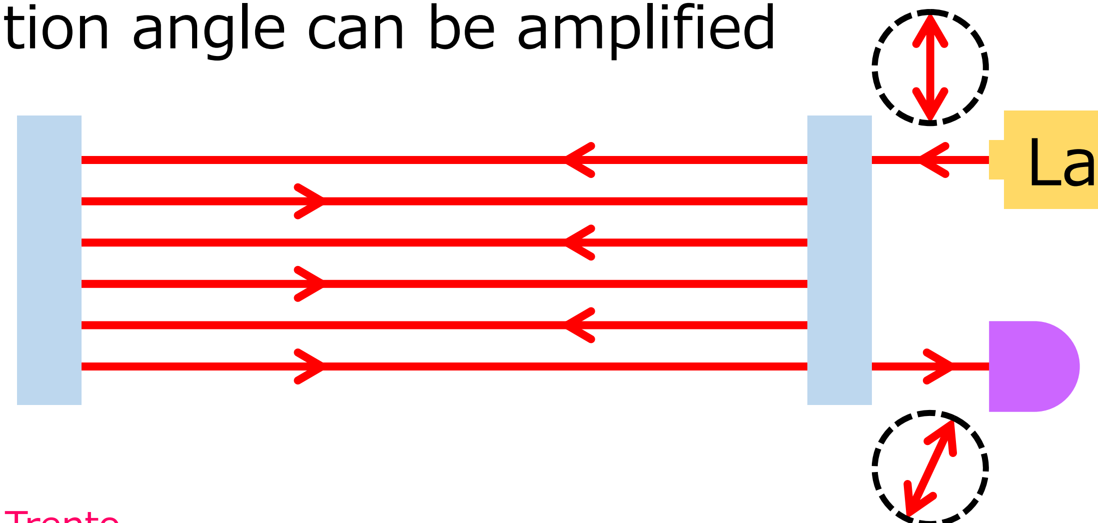


Signal amplification with cavities

- Axion-photon coupling makes linear polarization rotate
- Rotation angle is too small to be observed

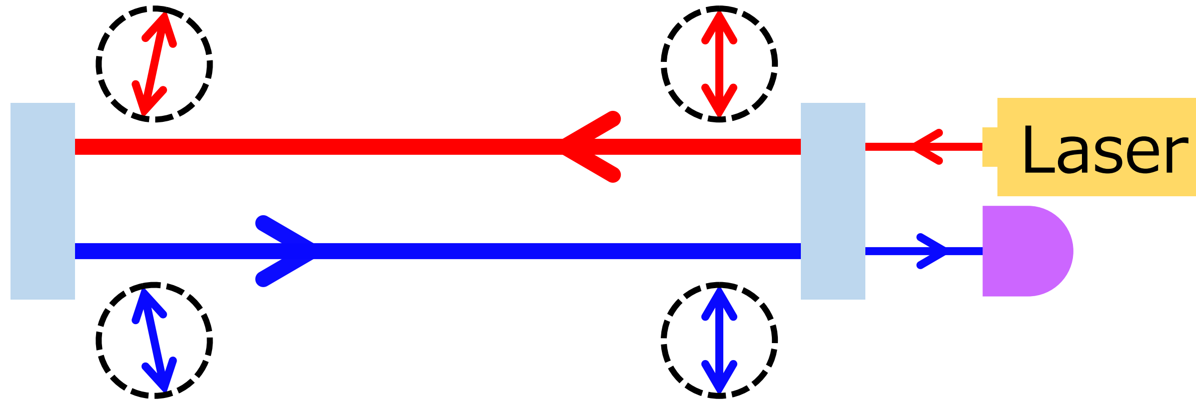


- Laser light runs between mirrors many times in a cavity
  → The rotation angle can be amplified

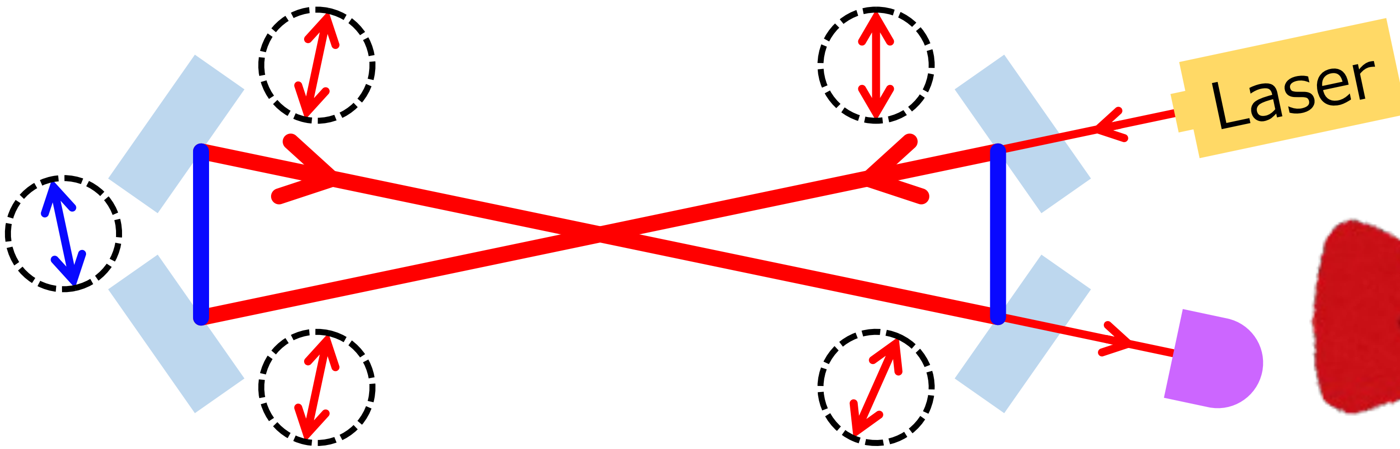


Bow-tie ring cavity

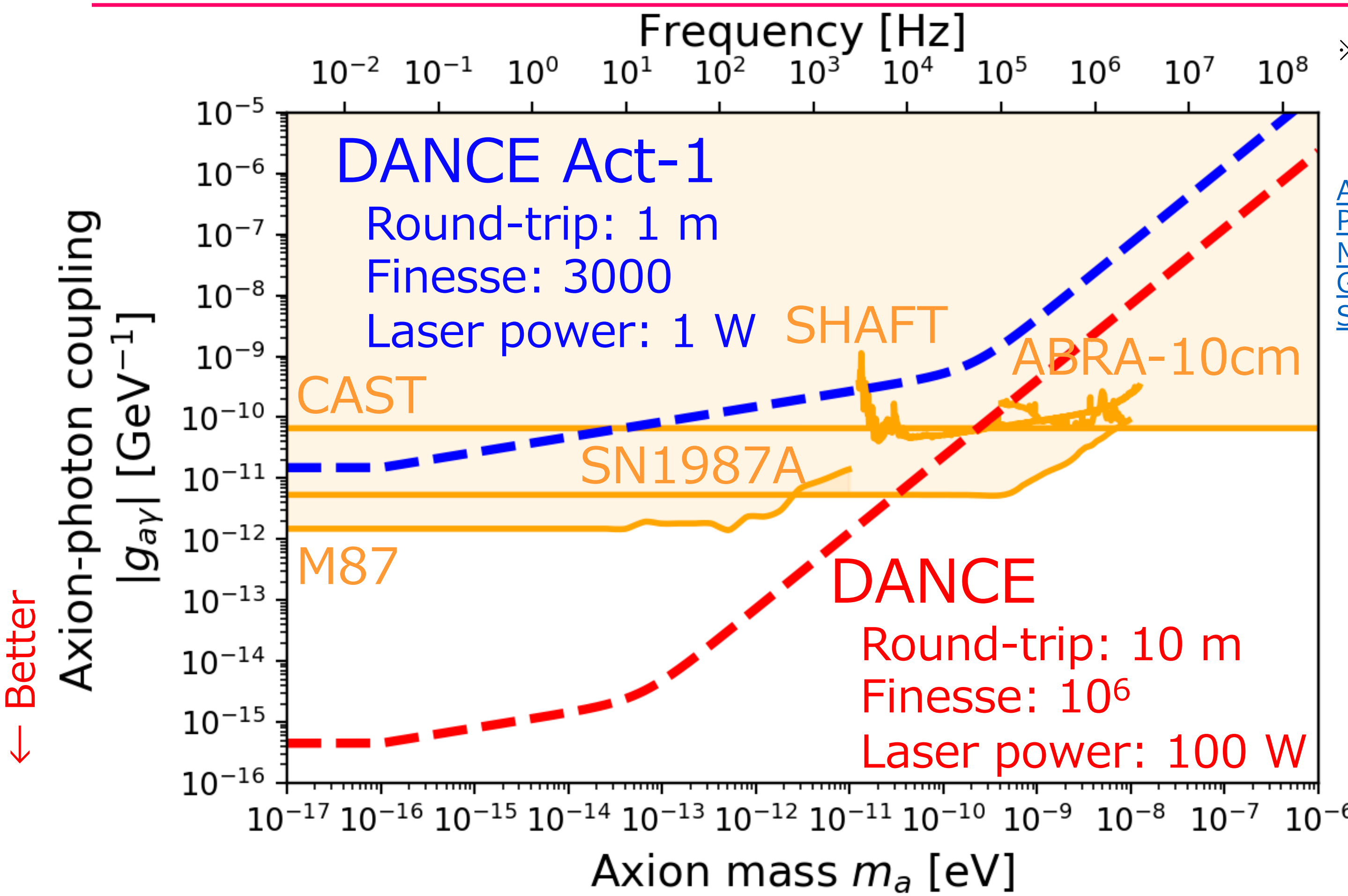
- Rotated direction is inverted in a linear cavity
  → Rotation effect is cancelled out



- A bow-tie ring cavity prevents linear polarization from inverting rotated direction



Design sensitivity of DANCE



※ If one-year observation
If only shot noise
If DM is all composed of axion

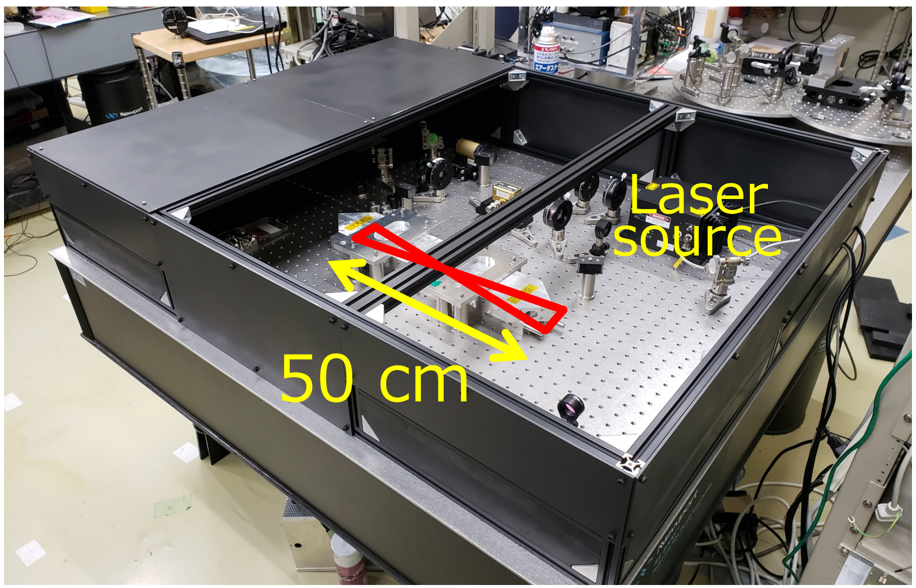
Anastassopoulos+ (2017)
Payez+ (2015)
Marsh+ (2017)
Gramolin+ (2021)
Salemi+ (2021)

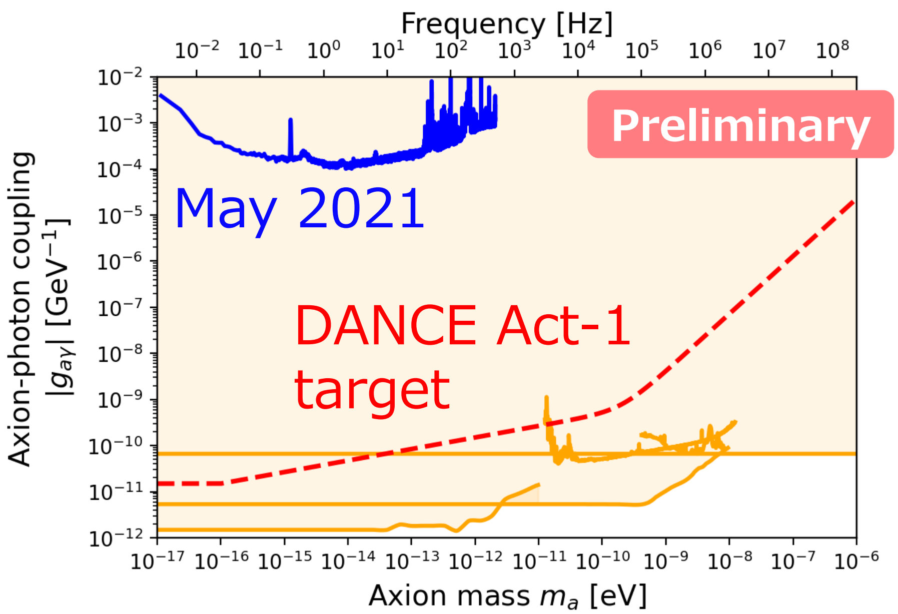
- DANCE can improve the current best upper limits by several orders of magnitude
- DANCE Act-1 has moderate parameters but can go beyond CAST limits

Current status of DANCE Act-1

- Finished assembly and evaluation of the optics
- Acquired data for two weeks in May 2021
- Data analysis is ongoing with theoretical researchers

Y. Michimura+, J. Phys.: Conf. Ser. 1468 012032 (2020)
Y. Oshima+, J. Phys.: Conf. Ser. 2156 012042 (2021)
H. Fujimoto+, J. Phys.: Conf. Ser. 2156 012182 (2021)





- Current sensitivity is much worse than target sensitivity, but the first result is expected this year

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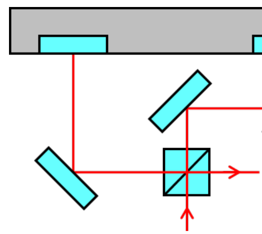
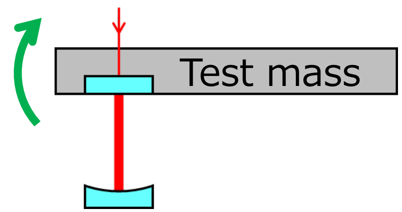
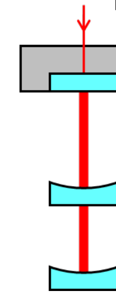
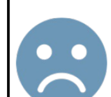
Comparison of angular sensors

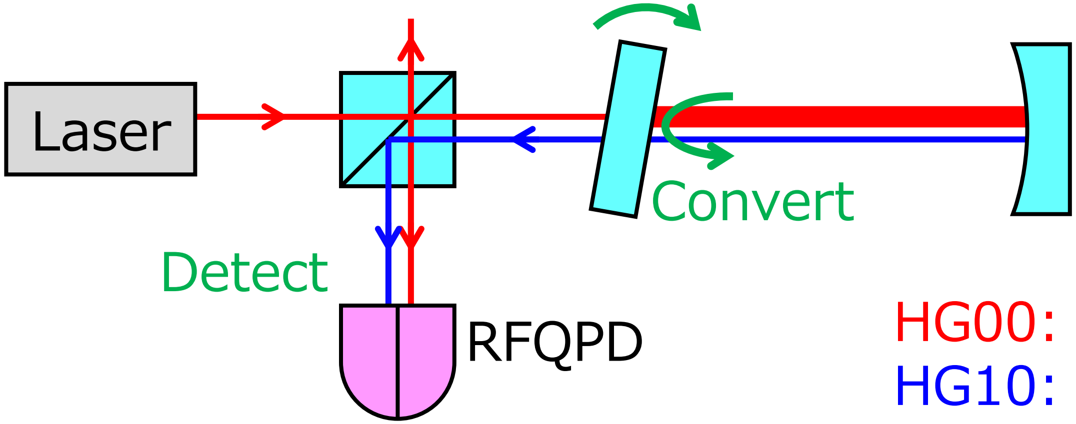
- Sensitive angular sensors are needed for GW detectors, especially for the rotation of TOBA (later)

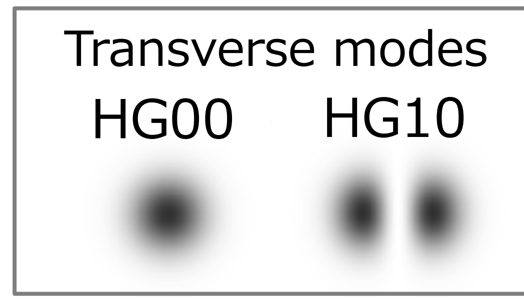
	Michelson interferometer	Wavefront sensor	Coupled WFS
			 My master thesis
Shot noise TOBA's requirement: 5×10^{-16} rad/√Hz		 No signal amplification	 Signal amplification
Freq. noise	 Non-parallel of two mirrors		
Beam jitter	 Asymmetry of two light paths		 No amplification of beam jitter
Thermal noise		 Narrow range measurement	 Narrow range measurement
Linear range			 Trade-off with signal amplification

Wavefront sensor

- WaveFront Sensor (WFS):
  angular sensor with an optical cavity

- HG10 is generated by mirror tilt
- Detect interference between HG00 and HG10
- Take the difference between left and right signals





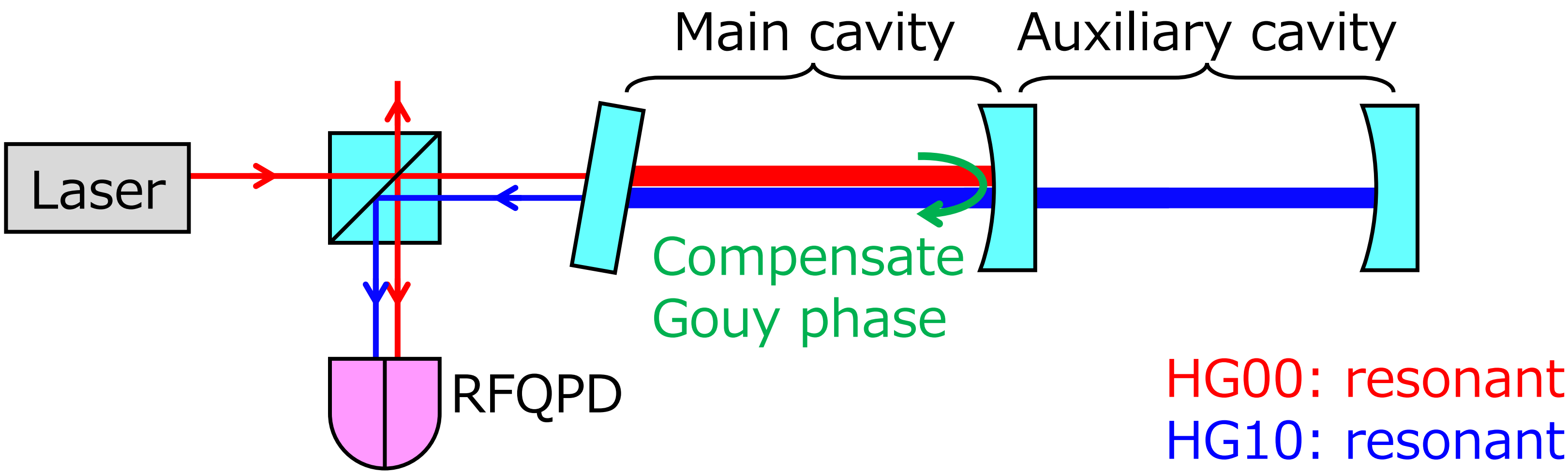
HG00: resonant
HG10: Off-resonant

- HG00 and HG10 do not resonate simultaneously due to Gouy phase

  → HG10 is not amplified in the cavity

Coupled wavefront sensor

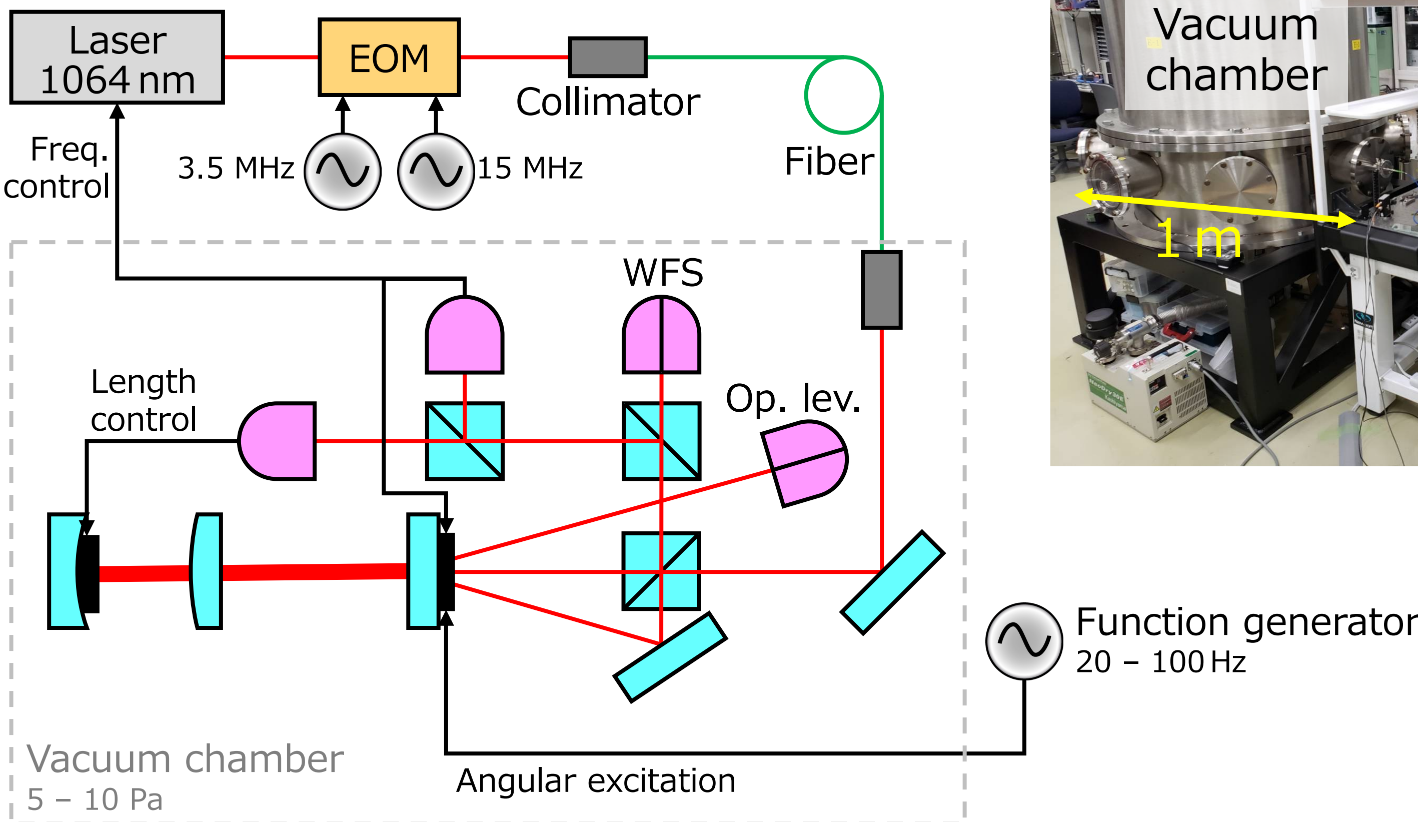
- Coupled wavefront sensor (Coupled WFS):
  wavefront sensor with a coupled cavity

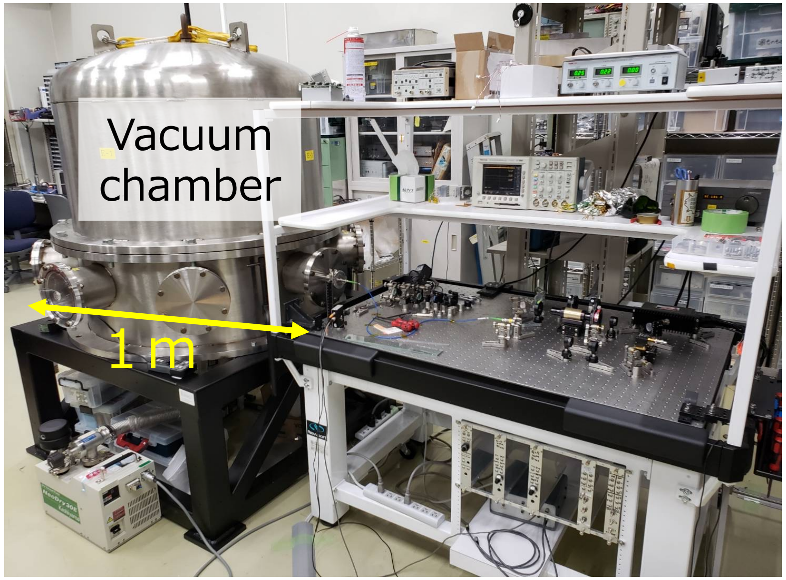


- HG00 and HG10 can resonate simultaneously
  due to Gouy phase compensation by the auxiliary cavity
  → HG10 is amplified in the main cavity
  → Coupled WFS signal is larger than WFS signal

Experimental demonstration

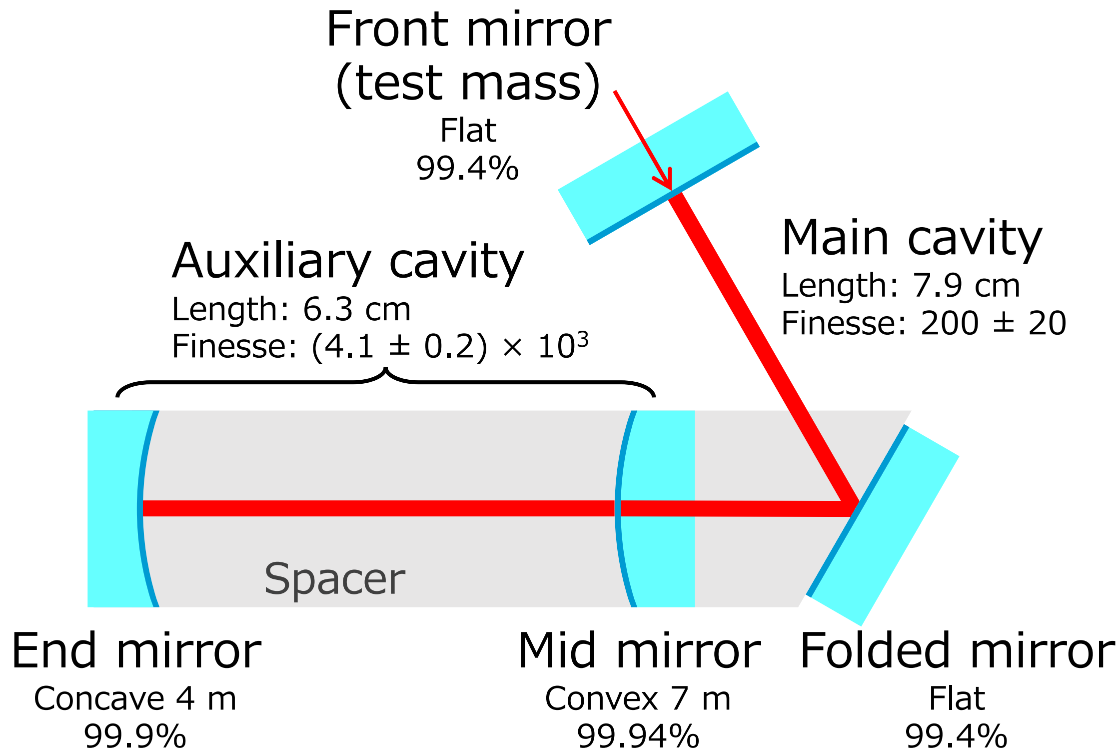
- Goal: Evaluate signal amplification
  - Compare the signal intensity of WFS and Coupled WFS

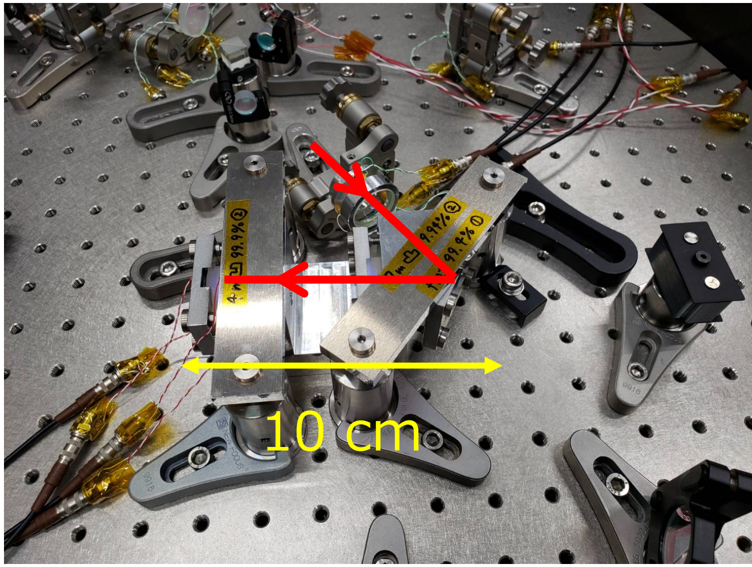




Design of coupled cavity

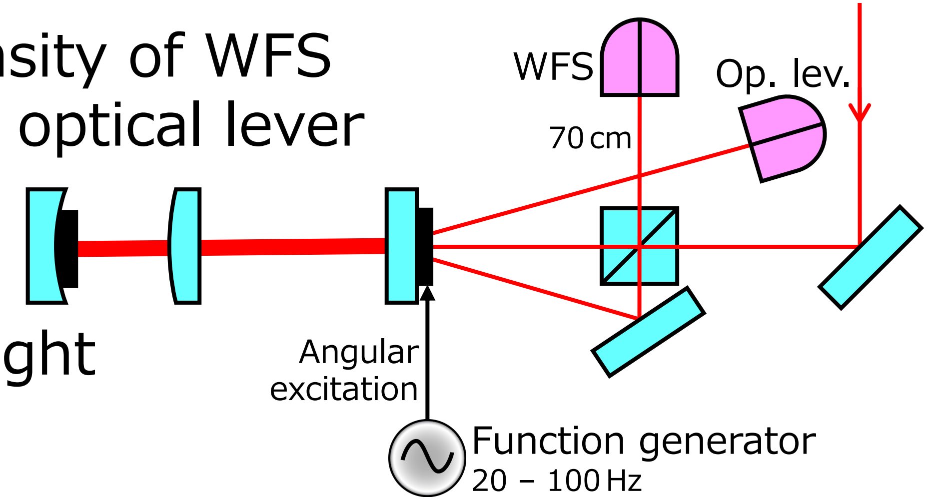
- Parameters are designed to enable phase compensation
  - Reflectivity and loss of the auxiliary cavity are important
    → HR coating is facing the auxiliary cavity
- The main cavity is folded to monitor the transmitted light
- Mirrors are fixed to a spacer to stabilize the alignment



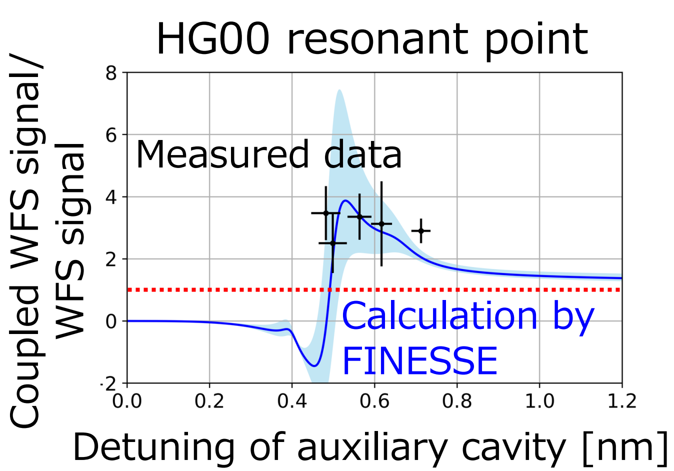


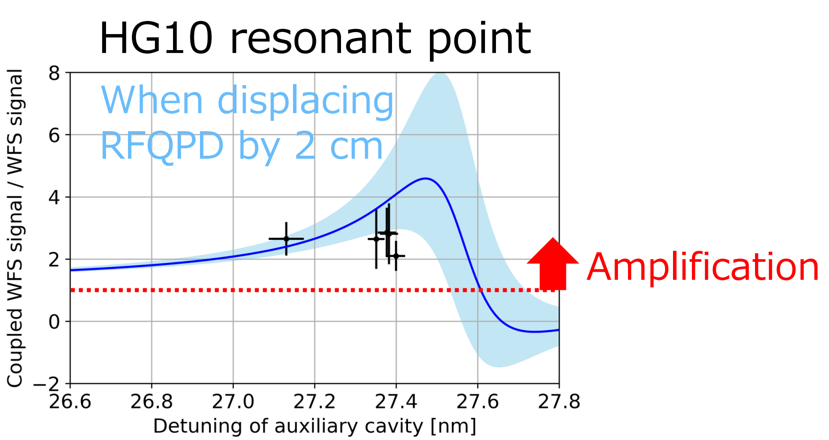
Results of signal amplification

- Calibrated the signal intensity of WFS and Coupled WFS with an optical lever
- Calibrated the lock point of the auxiliary cavity with the power of trans. light



- Angular excitation for front mirror as a test mass
  → Signal amplification





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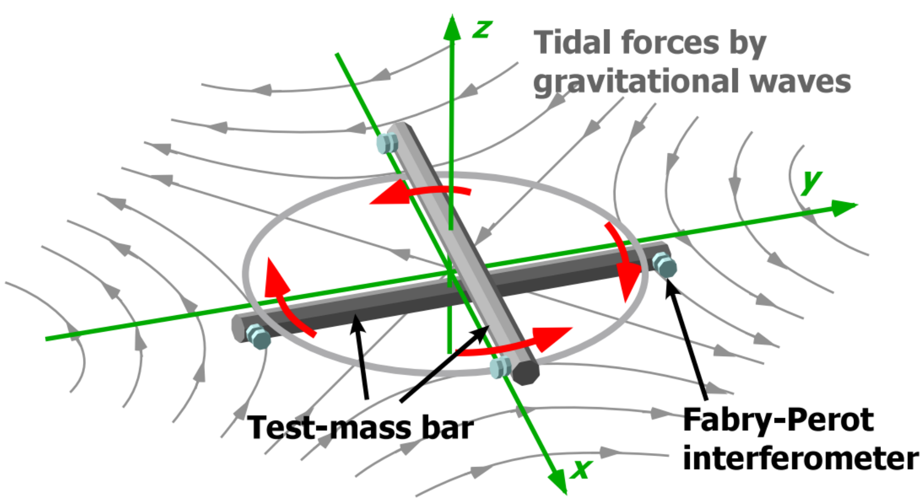
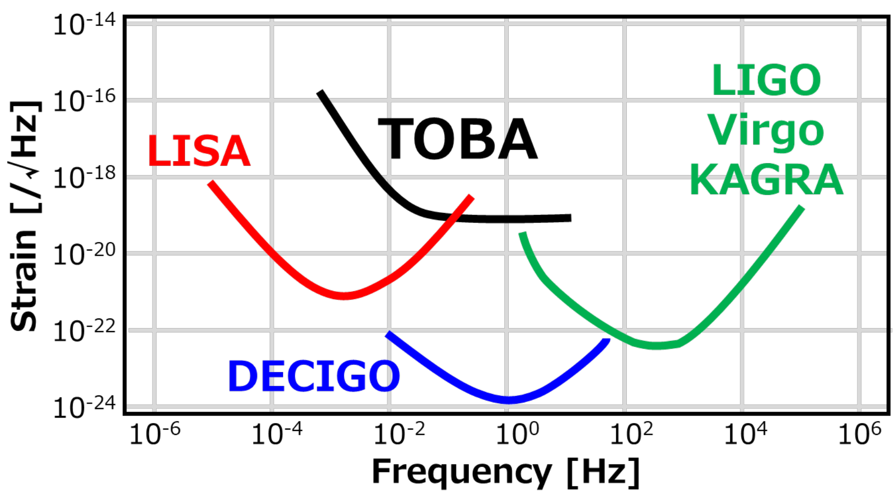
TOBA: TOrsion-Bar Antenna

- Originally proposed by Prof. Ando in 2010
  M. Ando+, [PRL 105, 161101 (2010)]
- Ground-based GW detector for low freq.
- Aim to detect the torsional rotation of test masses suspended horizontally
- The resonant frequency of torsional motion is low
  → Good sensitivity in low freq. even on the ground
  - Inexpensive
  - Easy to maintain
  - Science on the ground

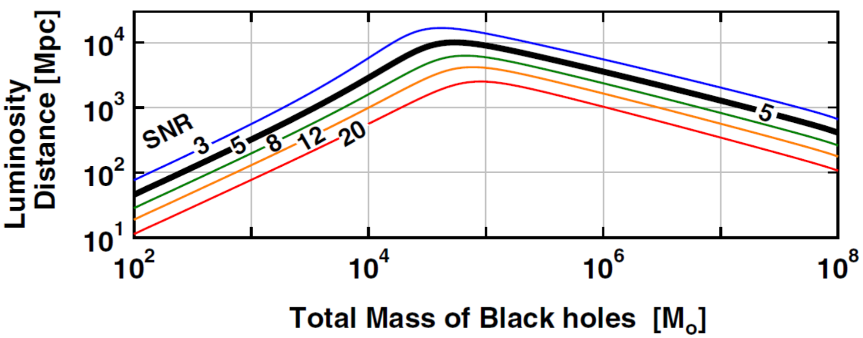




Science of TOBA

Astrophysics

- Intermediate mass BH binary merger
  - Within ~1 Mpc (Phase-III)
  - Within ~10 Gpc (Final)

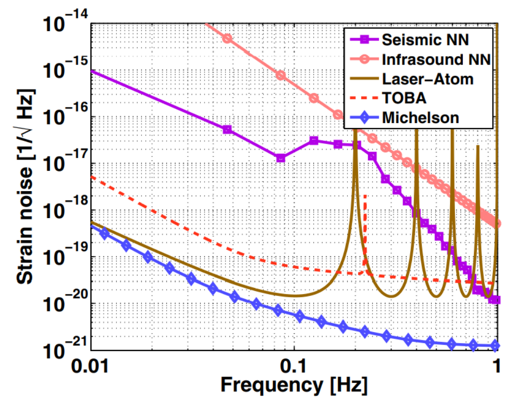


M. Ando+, PRL 105, 161101 (2010)

- GW stochastic background
  - Ω_{GW} ~10^{-7} (Final)

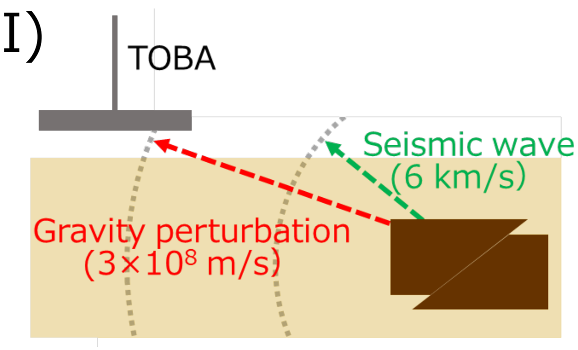
Geophysics

- Newtonian noise
  - First direct detection



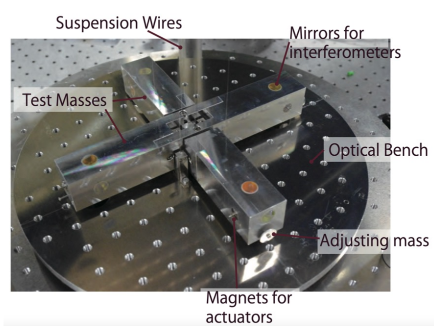
J. Harms+ PRD 88, 122003 (2013)

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

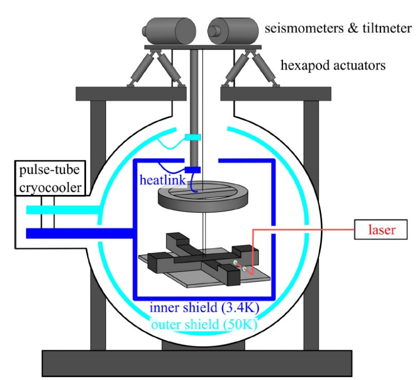


Development roadmap of TOBA

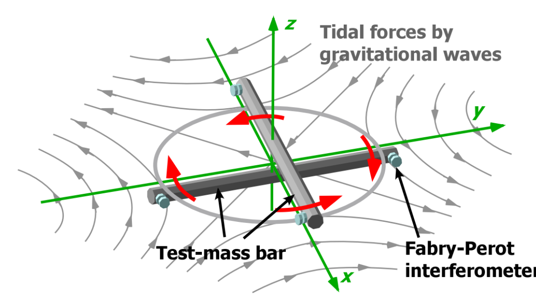
Phase-I	Phase-II	Phase-III (My Ph.D. thesis)	Final
Principle test		Technical demonstration	GW observation
10^{-8} /√Hz (Established)		10^{-15} /√Hz (Target)	10^{-19} /√Hz (Target)
~20 cm bars		35 cm bars	10 m bars
Room temp.		Cryo. Temp. (4 K)	Cryo. Temp. (4 K)



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



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

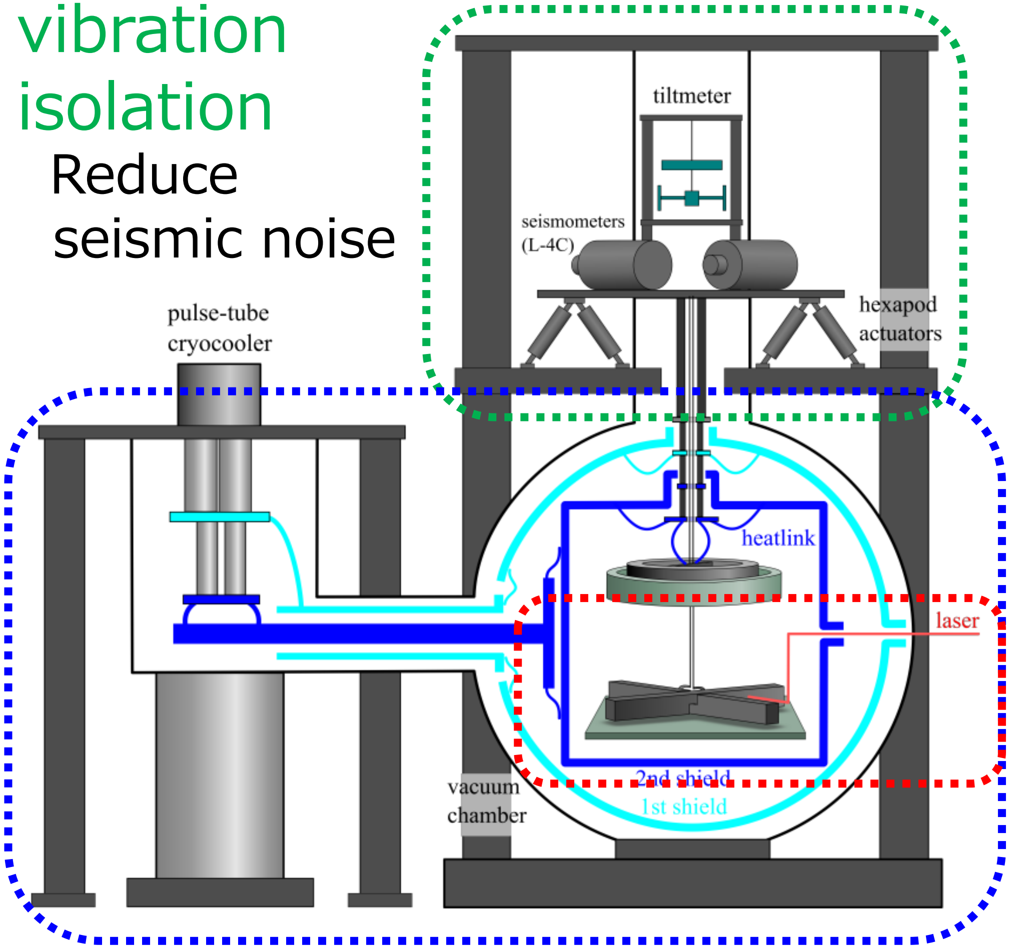


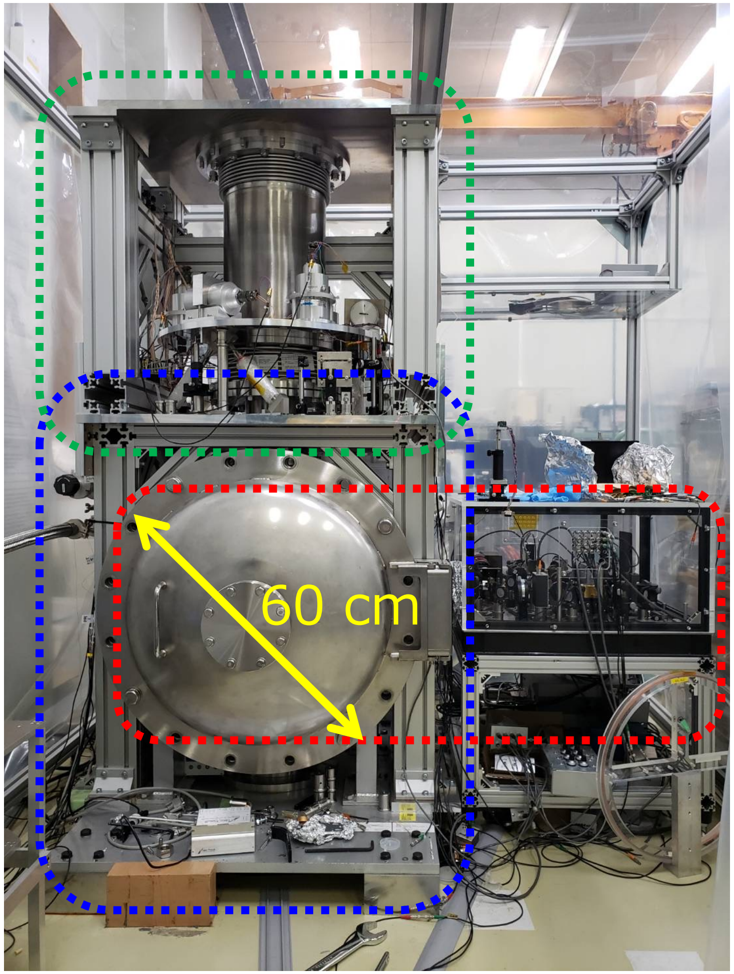
Configuration of Phase-III TOBA

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

Active vibration isolation

Reduce seismic noise





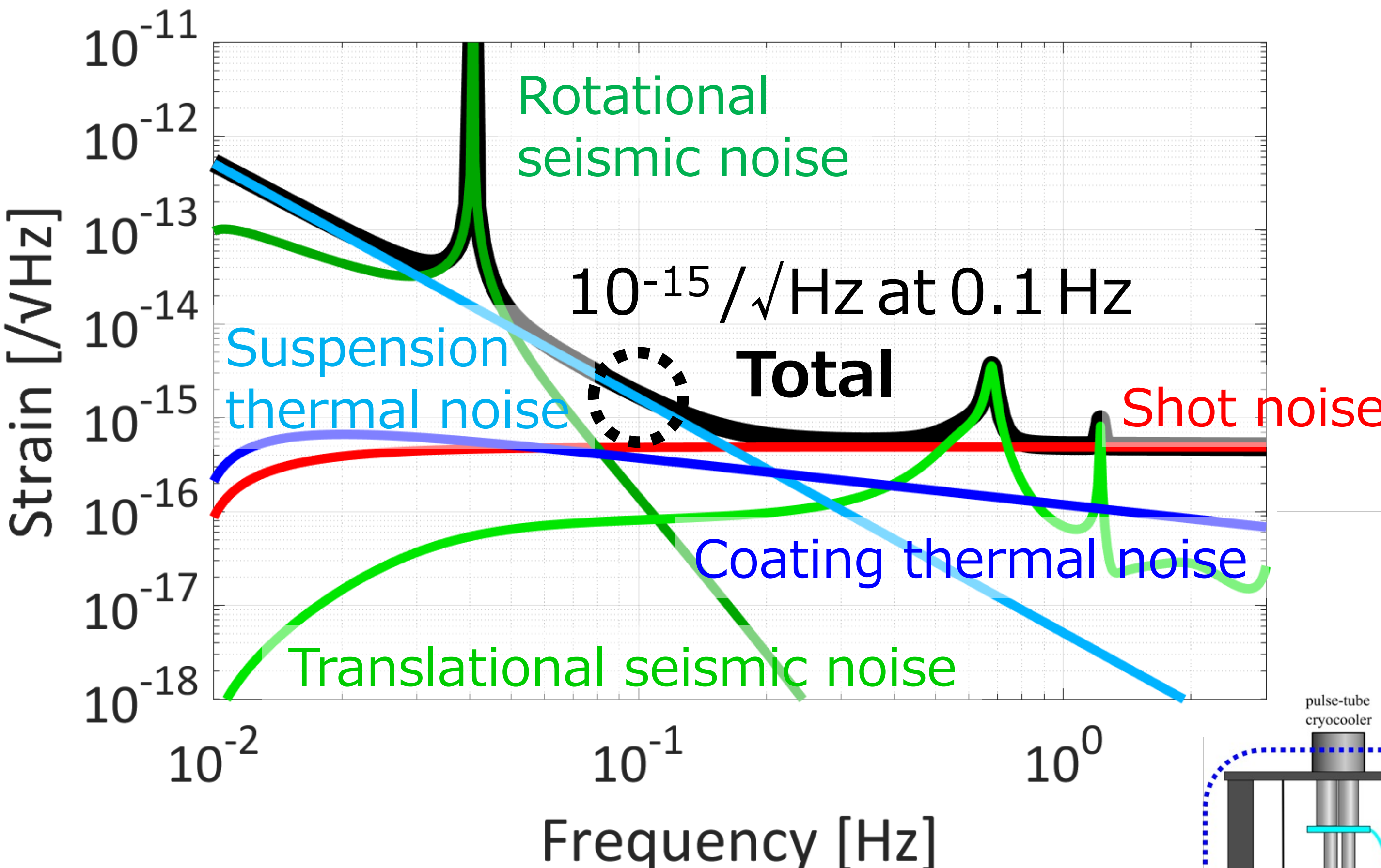
Cryogenic suspension

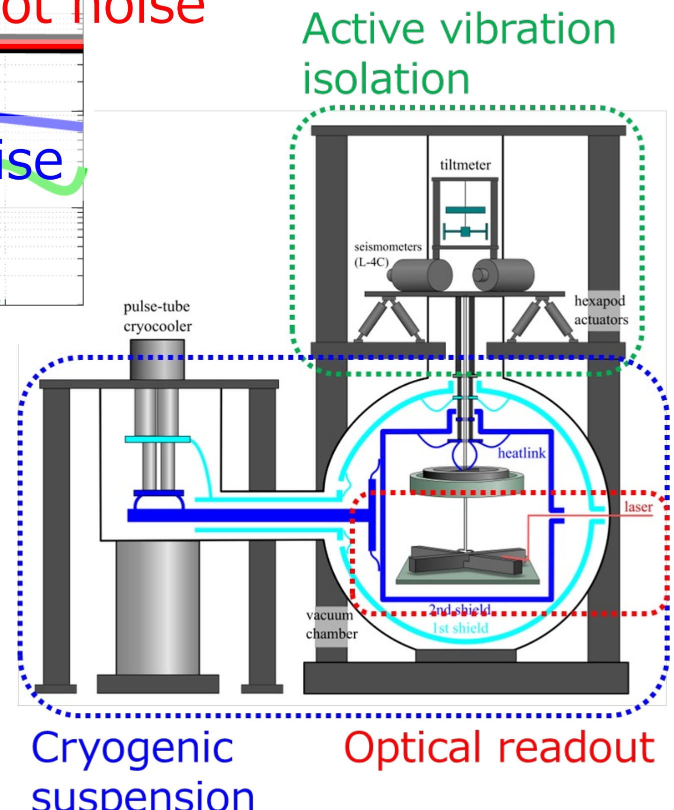
Torsion pendulums at 4 K

Optical readout

Detect the rotation of the pendulums
Plan to introduce **Coupled WFS**

Design sensitivity of Phase-III TOBA





Summary

- My research topics so far
  - Axion dark matter search with a ring cavity
  - Wavefront sensor with a coupled cavity

- My research topic for a Ph.D. course
  - Development of Phase-III TOBA overall

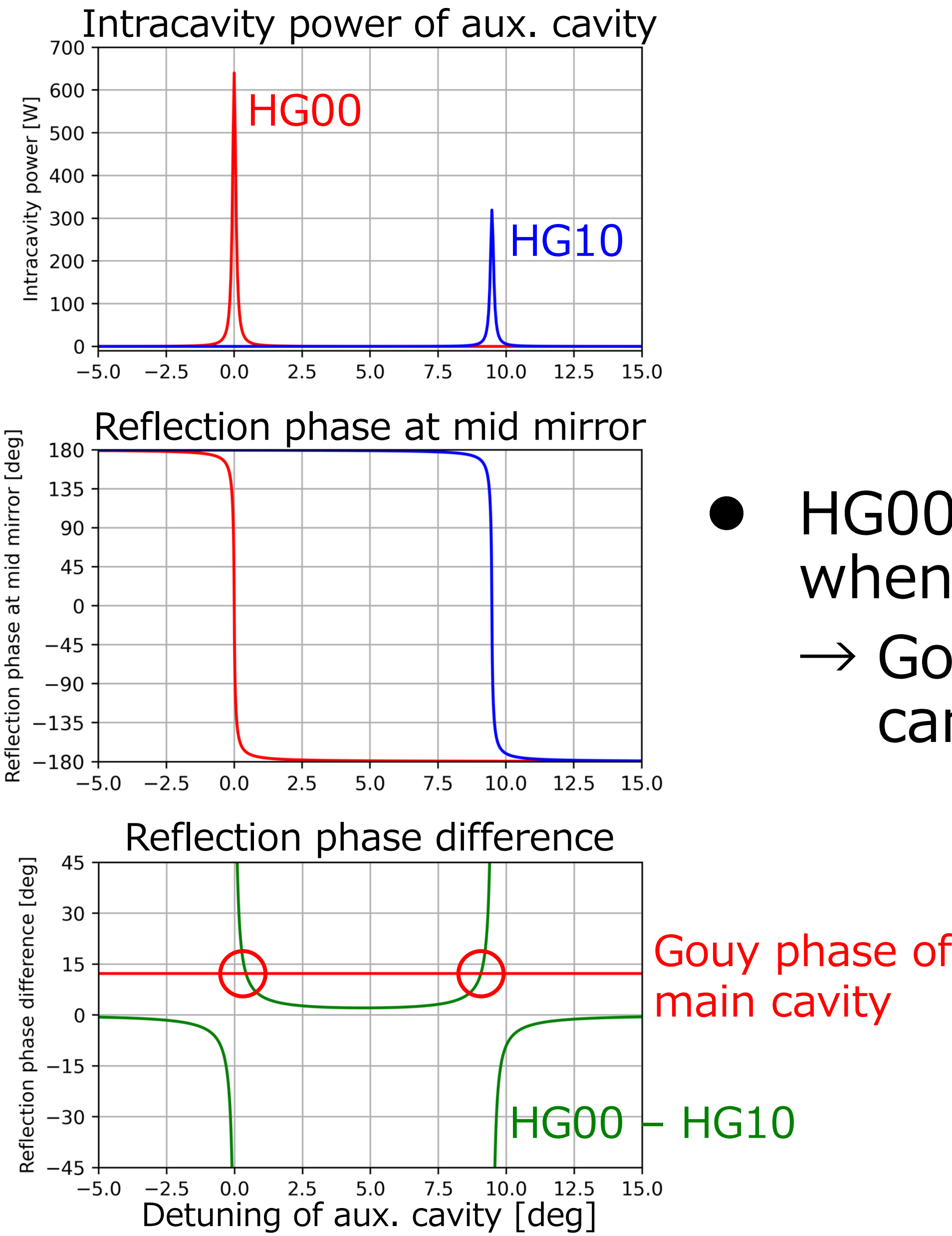
Thank you for listening.

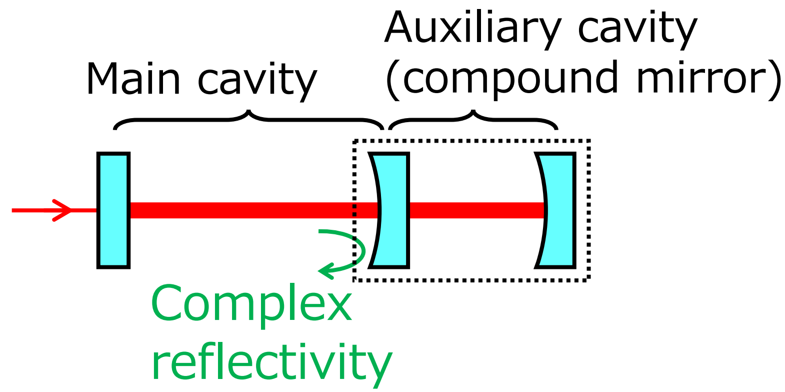
I am looking forward to learning a lot from your lab!!

JSR Fellowship This research is supported by JSR Fellowship, the University of Tokyo

Extra slides

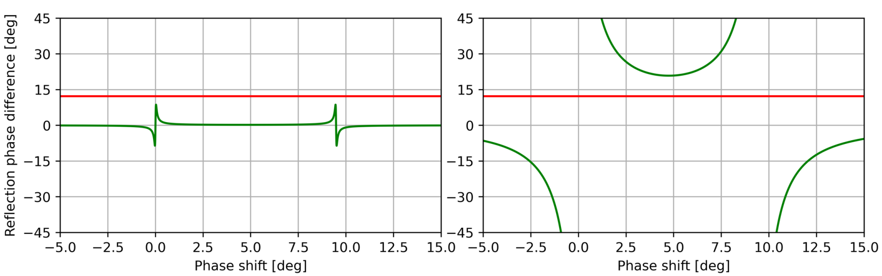
Phase compensation with aux. cavity





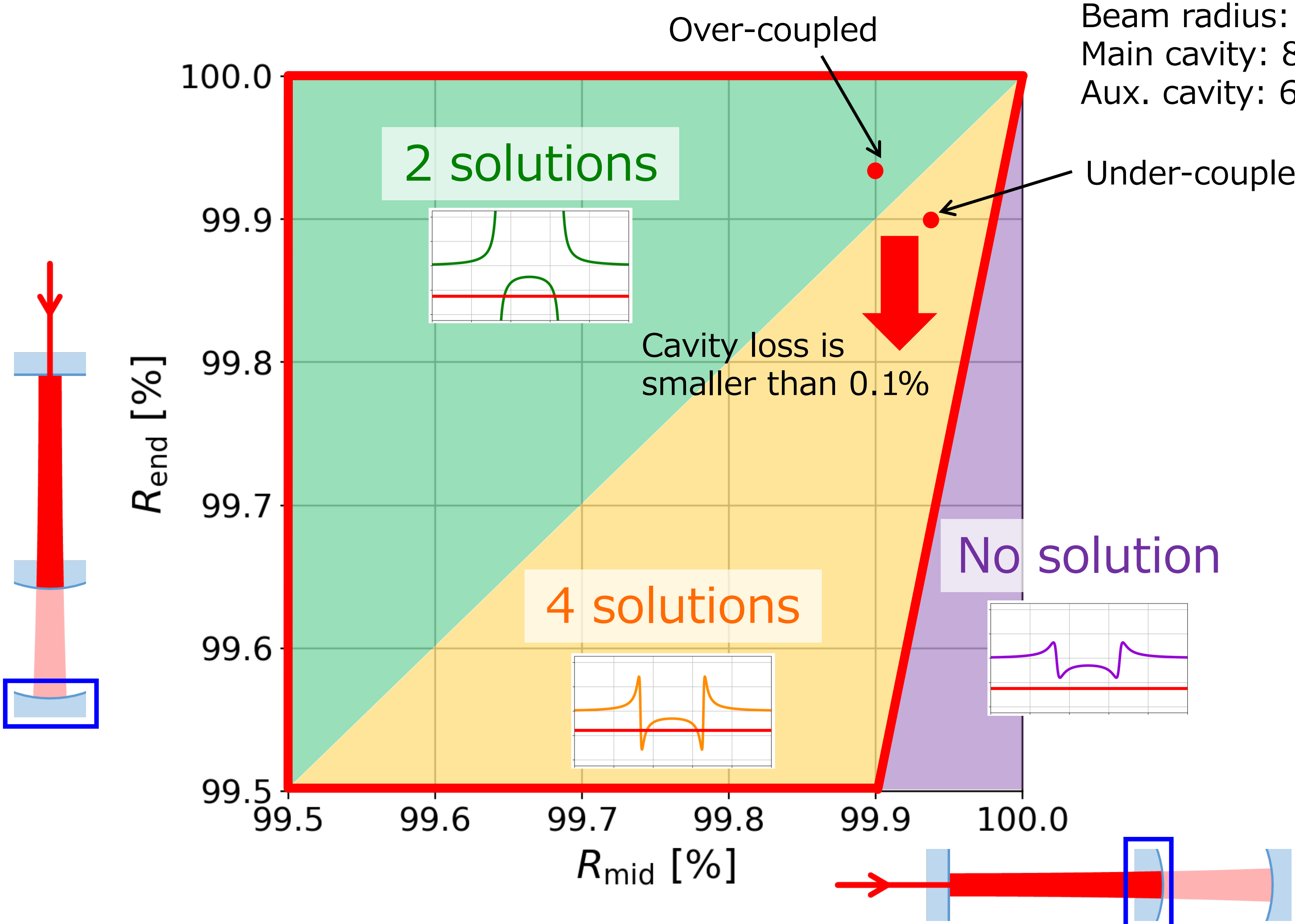
- HG00 and HG10 receive different when reflected at the auxiliary cavity
  → Gouy phase of the main cavity can be canceled

Aux. cavity cannot compensate Gouy phase depending on cavity parameters



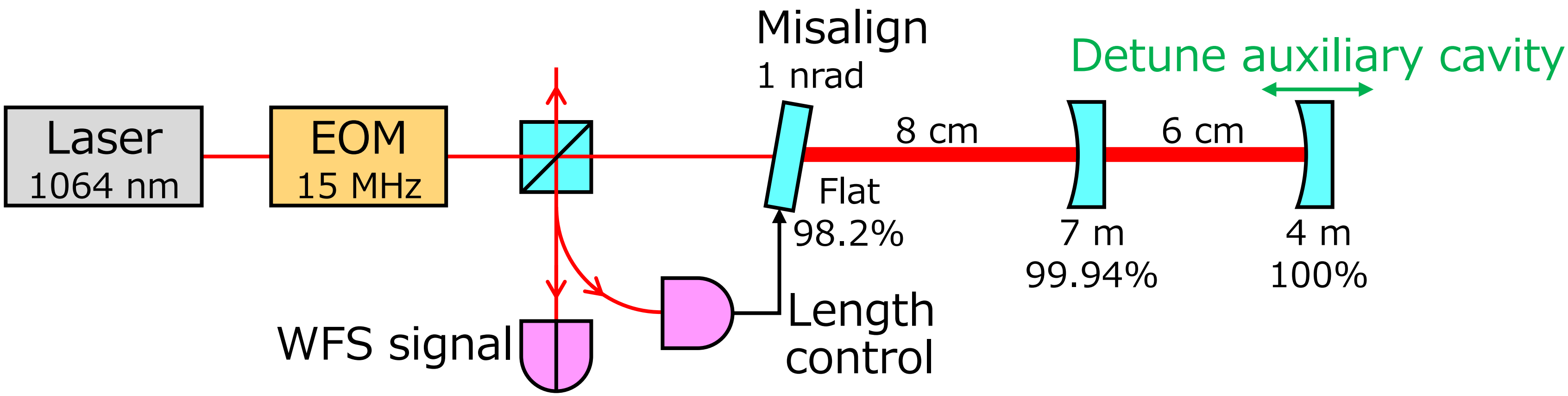
Robustness to cavity loss

Beam radius: 500 μm
Main cavity: 8 cm
Aux. cavity: 6 cm

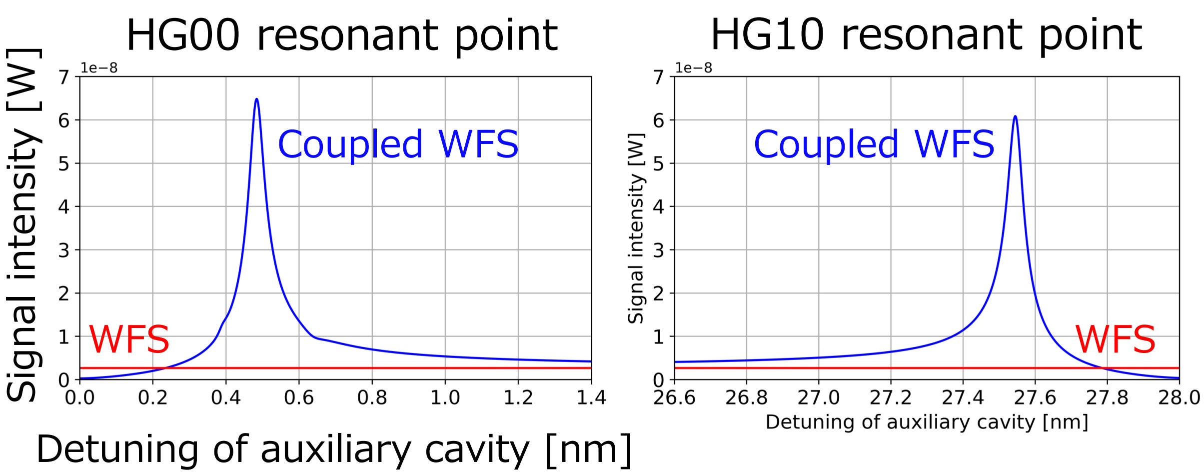


Simulation for Coupled WFS

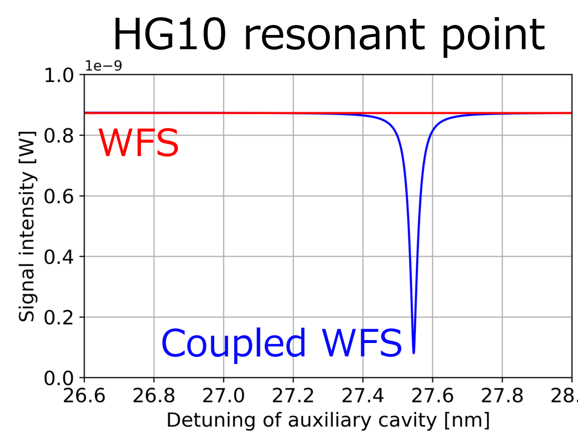
- Complicated configuration of Coupled WFS
  → Calculation with simulation software FINESSE



- Signal amplification around resonant points of HG00 and HG10

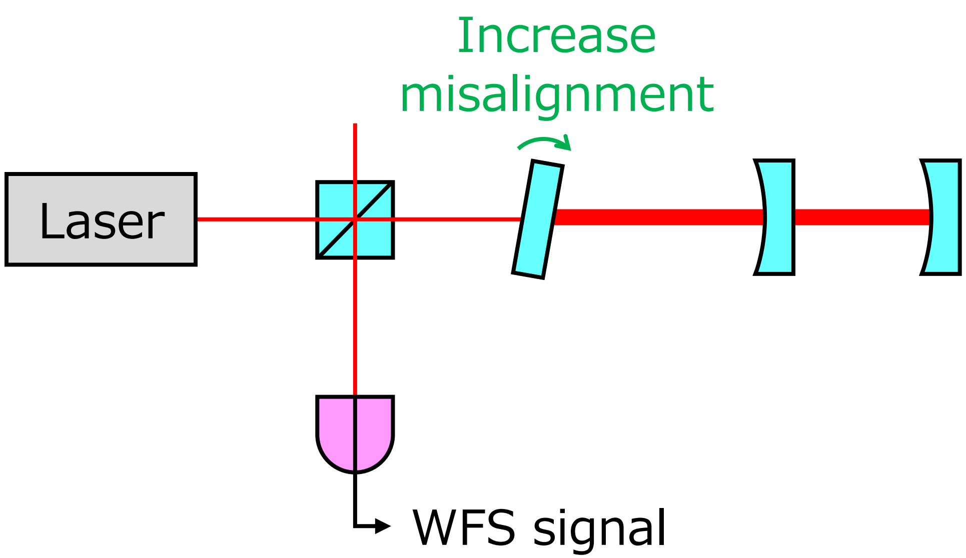


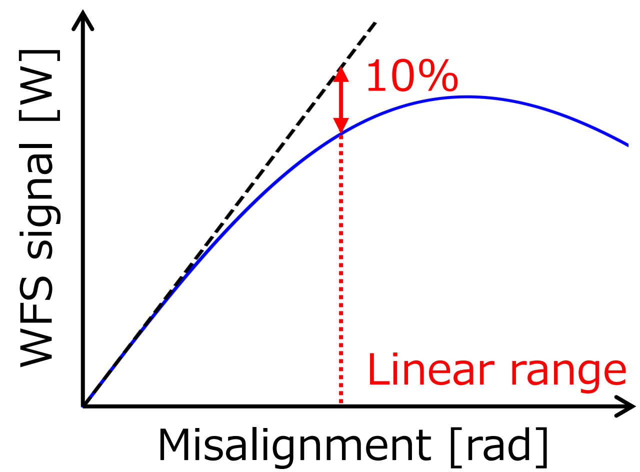
- No amplification to beam jitter noise



Simulation with FINESSE

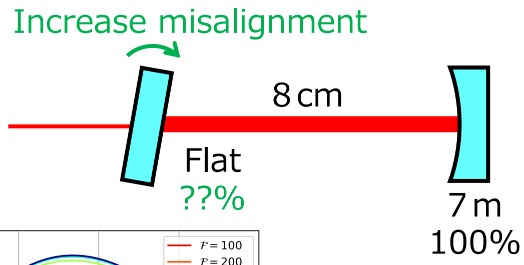
- No analytical solution for linear range
  → Use interferometer simulation software FINESSE
- Calculate Coupled WFS signal with increasing misalignment

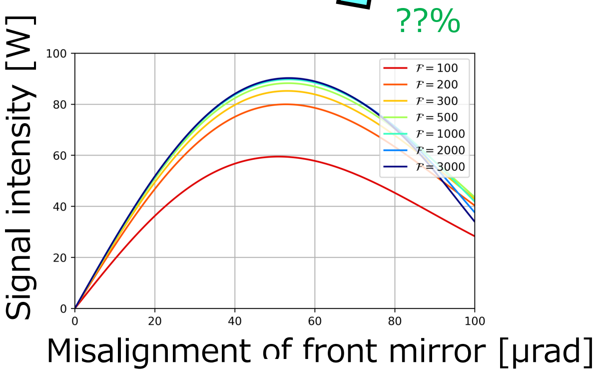


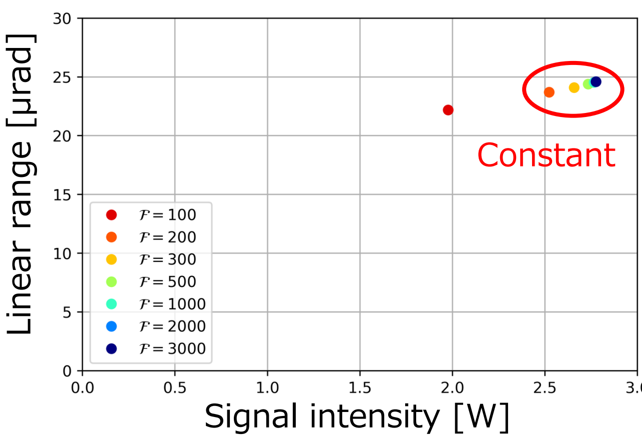


Linear range of Coupled WFS

WFS

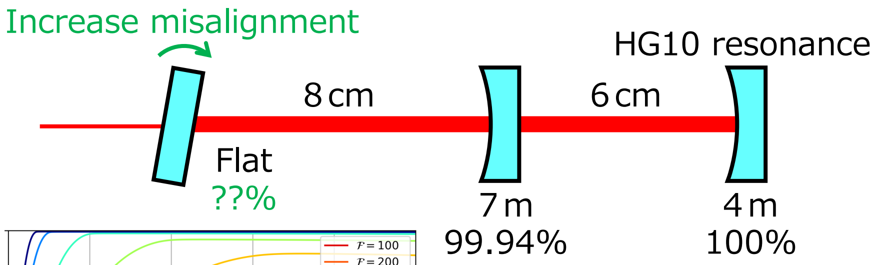


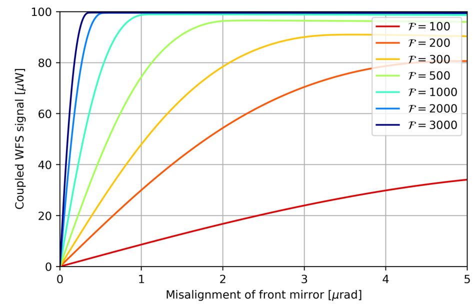


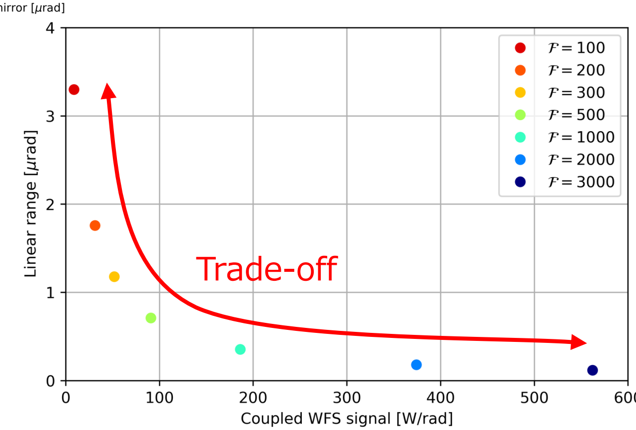


- Signal intensity and linear range are independent of finesse

Coupled WFS



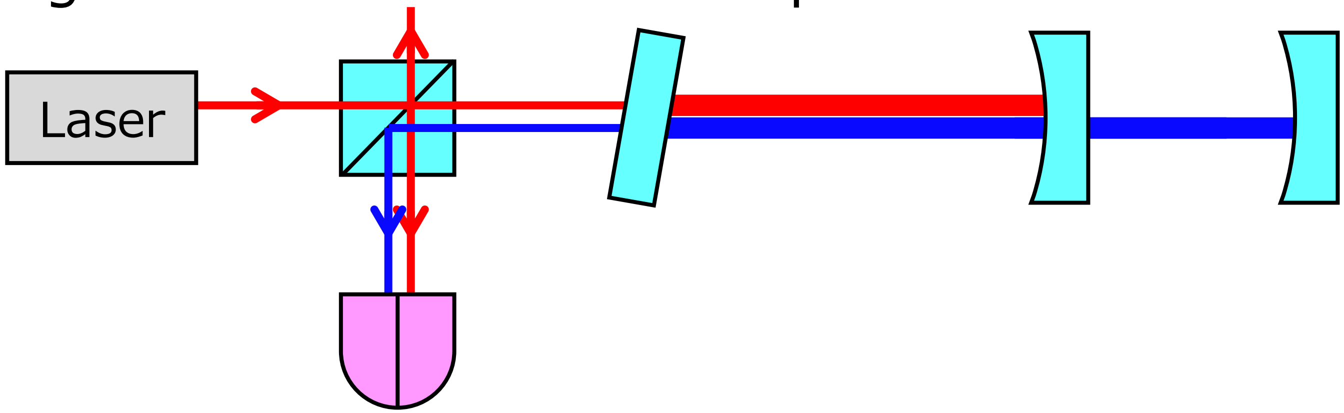




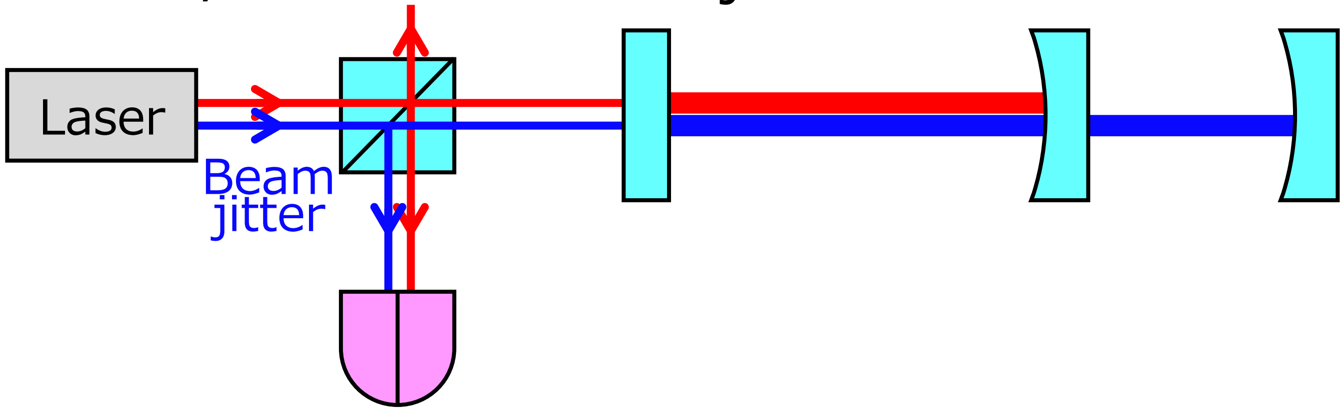
- The larger the finesse, the higher signal intensity, and the smaller the linear range

Beam jitter noise of Coupled WFS

- HG10 generated by mirror tilt is amplified in the cavity and goes out to the reflection port



- HG10 in beam jitter is also resonant in the cavity, but the amount in the incident and reflected light is the same (not amplified)
→ Good S/N ratio for beam jitter noise

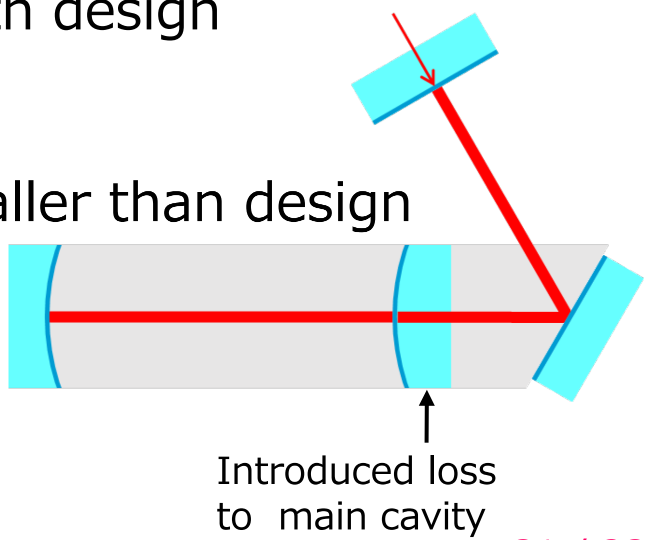


Evaluation of cavities

	Quantities	Design values※	Measured values
Main cavity	Finesse	225 – 667	200 ± 20
	Gouy phase [deg]	12.1 – 12.3	12.1 ± 1.0
	Mode-match ratio [%]	–	87 ± 2
Auxiliary cavity	Finesse	(3.14 - 5.23) × 10^3	(4.1 ± 0.2) × 10^3
	Gouy phase [deg]	9.25 – 9.71	9.54 ± 0.04
	Mode-match ratio [%]	–	94 ± 2

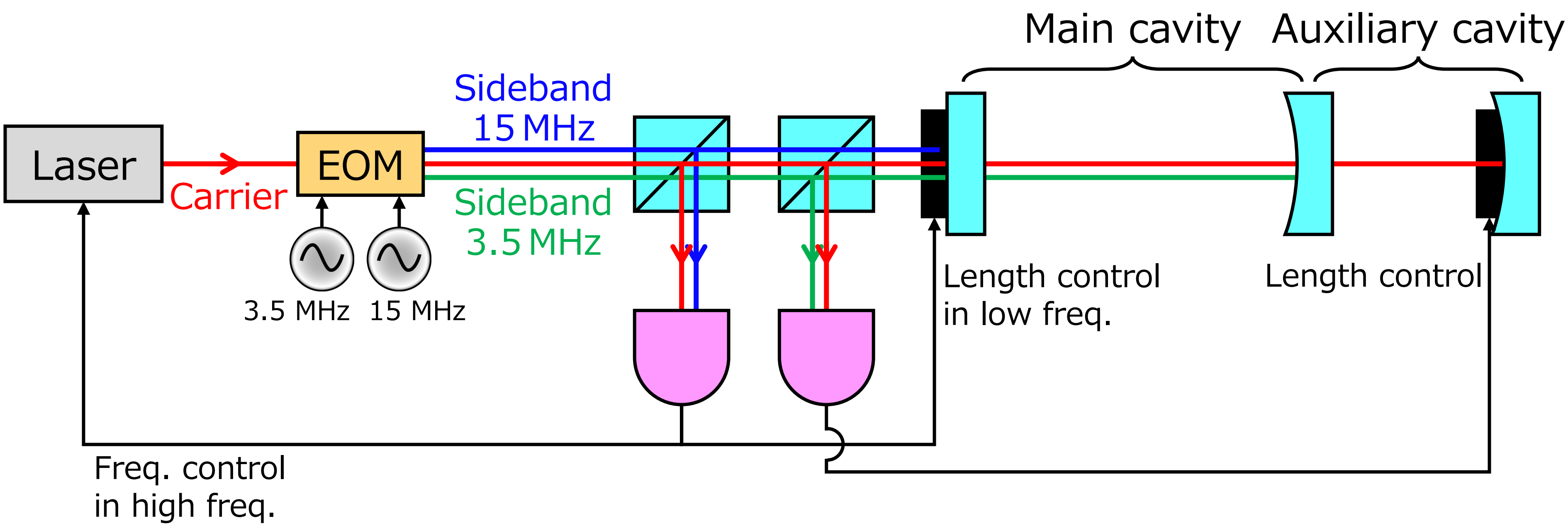
※ Calculated from Layertec spec values

- Measured finesse of aux. cavity is consistent with design
- Measured Gouy phase is consistent with design
  → Phase compensation is possible
- Measured finesse of main cavity is smaller than design
  → Loss in AR coating is the cause
- Mode match ratio is large enough



Control method of a coupled cavity

- PDH technique with two modulation frequencies
  - 15 MHz for the main cavity
  - 3.5 MHz for the auxiliary cavity
- Hierarchical control for the main cavity
  - To prevent transmitting disturbances from the main cavity to the aux. cavity through laser freq.



Results of cavity locking

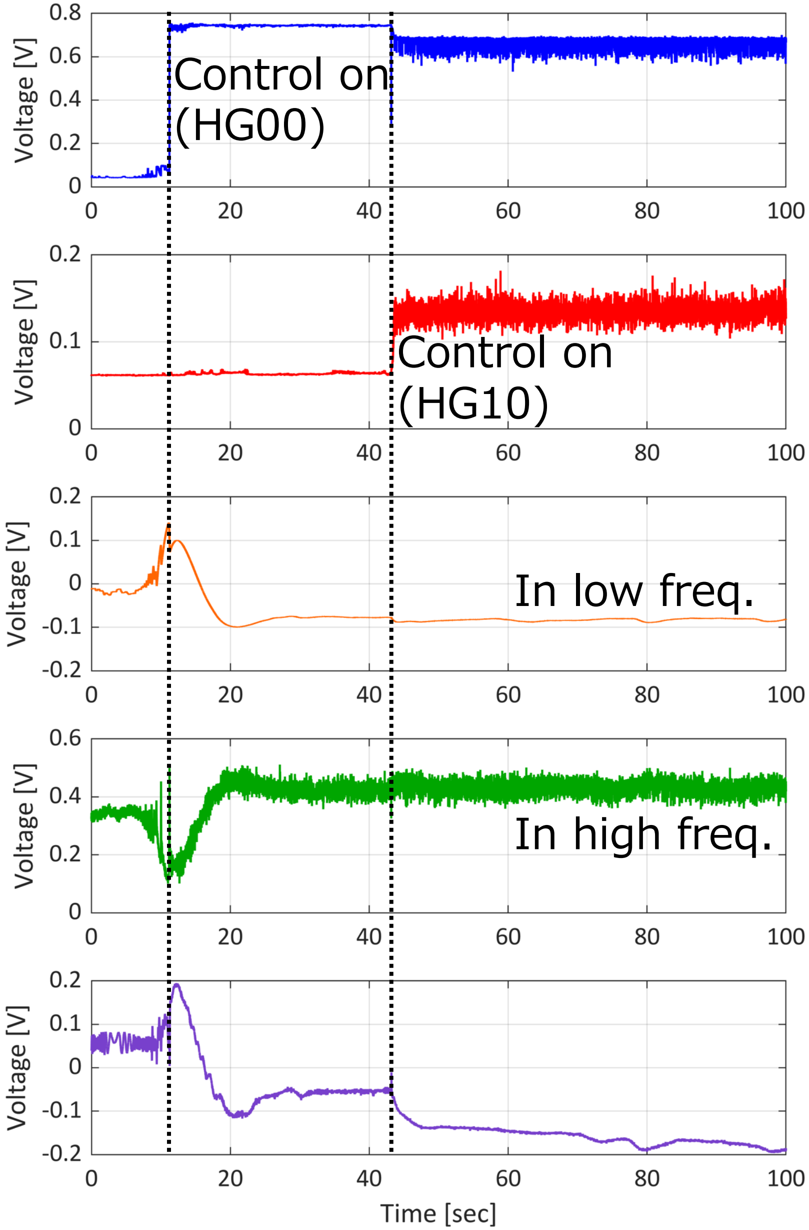
Trans. light of the main cavity

Trans. light of the aux. cavity

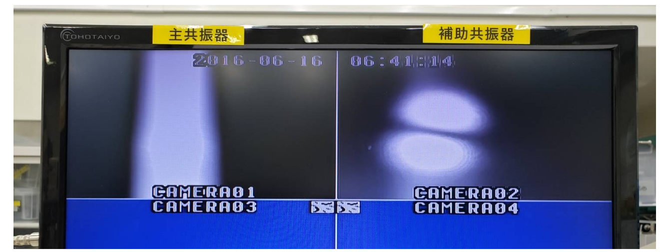
FB signal to the main cavity (front mirror)

FB signal to the main cavity (laser freq.)

FB signal to the aux. cavity (end mirror)



Transmitted light with CCD

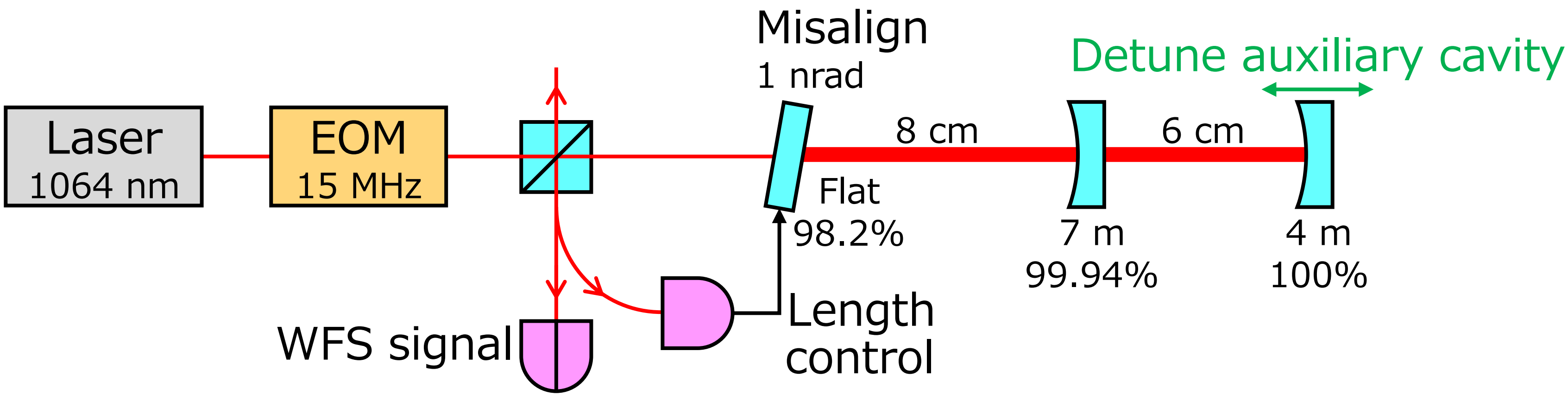


Main (HG00)   Auxiliary (HG10)

- Cavities were successfully locked to HG00 and HG10 simultaneously

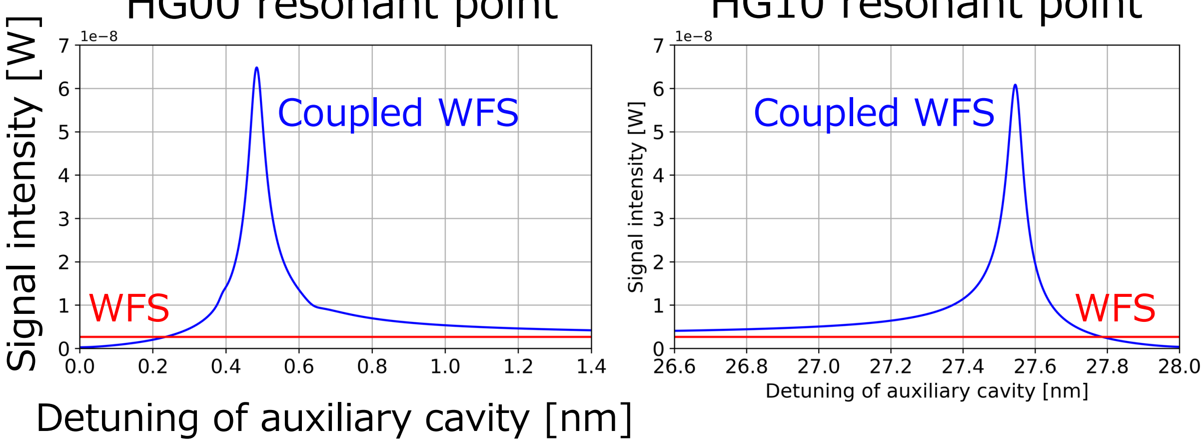
Simulation for Coupled WFS

- Complicated configuration of Coupled WFS
  → Calculation with simulation software FINESSE



- Signal amplification around resonant points of HG00 and HG10

HG00 resonant point   HG10 resonant point



- No amplification to beam jitter noise

HG10 resonant point