Angular Measurement with a Coupled Cavity for Torsion-Bar Antenna

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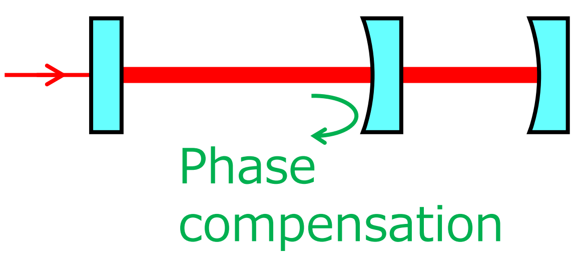
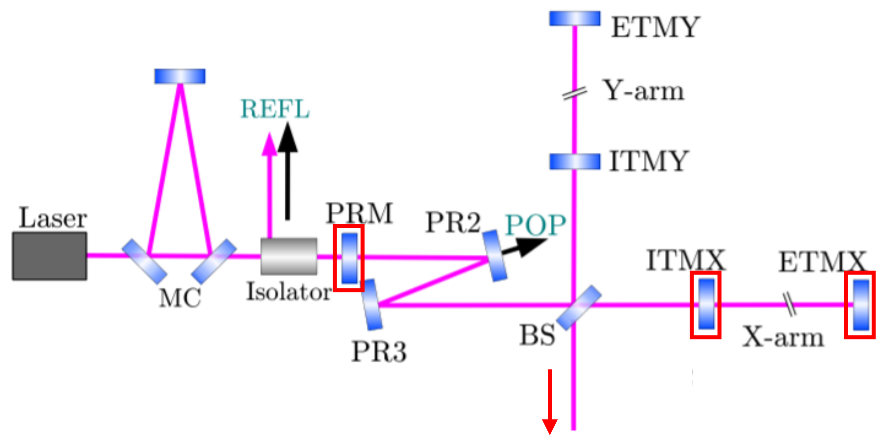
Overview

- Developing TOrsion-Bar Antenna (TOBA) to detect GW in low freq.
- Proposed WaveFront Sensor with a Coupled cavity (Coupled WFS) as an angular sensor for TOBA
  - Simulation with FINESSE
  - Experimental demonstration
- Application to KAGRA might be possible

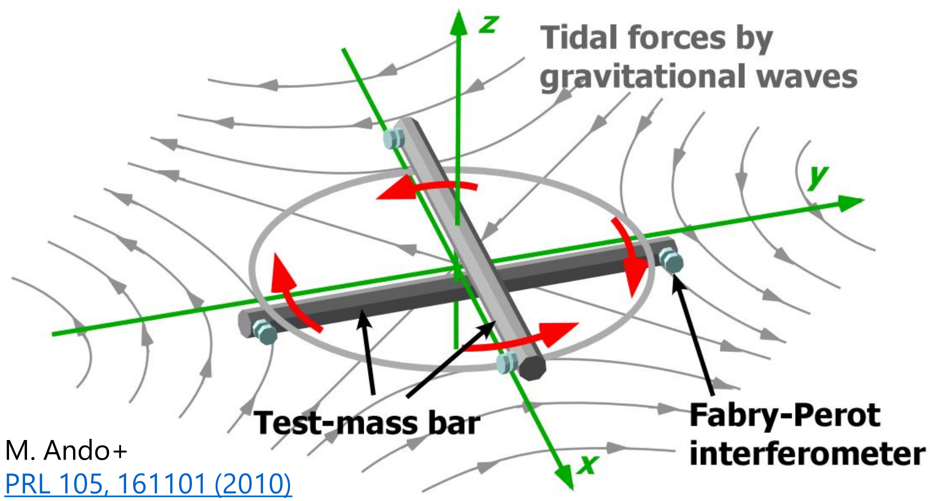




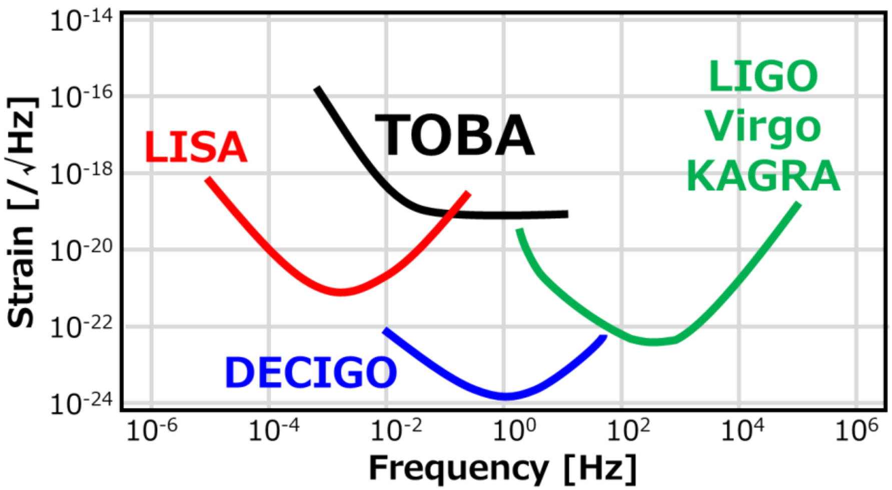
Y. Aso+ (2013)

TOBA: TOrsion-Bar Antenna

- Ground-based GW detector for low freq.
  - Final target: 10^{-19} /√Hz at 0.1 Hz
- 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



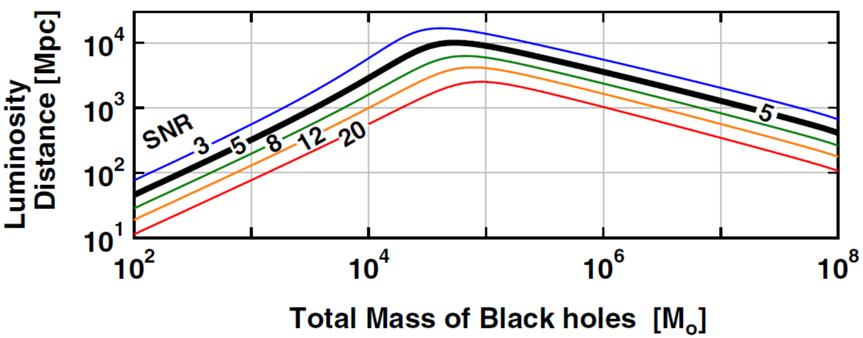
M. Ando+
PRL 105, 161101 (2010)



Science of TOBA

Astrophysics

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

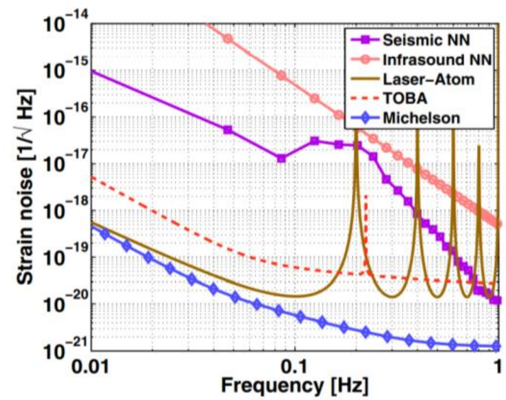


M. Ando+, [PRL 105, 161101 (2010)]

- **GW stochastic background**
  - $\Omega_{GW} \sim 10^{-7}$ (Final)

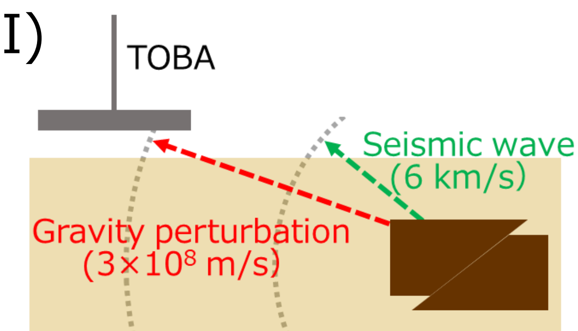
Geophysics

- **Newtonian noise**
  - First direct detection



J. Harms+
[PRD 88, 122003 (2013)]

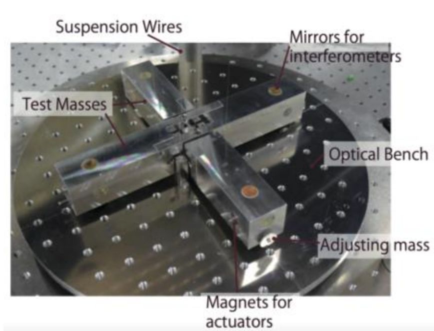
- **Earthquake early warning**
  - M7 earthquake at a distance of 100 km within 10 sec (Phase-III)



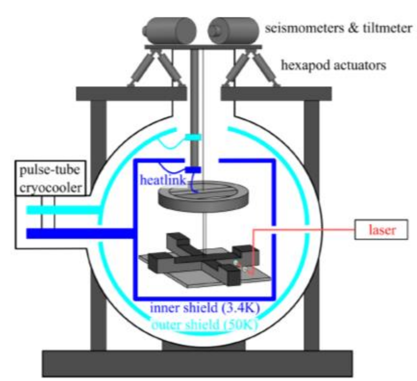
Development roadmap of TOBA

Phase-I → Phase-II → Now: Phase-III → Final

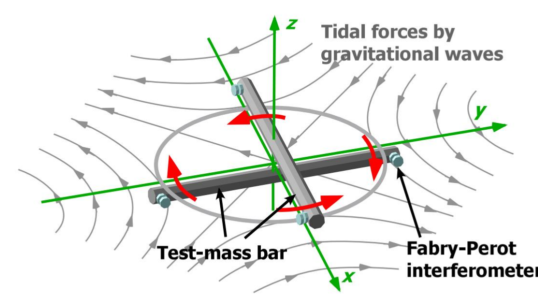
Phase-I / Phase-II	Phase-III (Now)	Final
Principle test	Technical demonstration	GW observation
10^{-8} /√Hz (Established)	10^{-15} /√Hz (Target)	10^{-19} /√Hz (Target)
~20 cm bars	35 cm bars	10 m bars
Room temp.	Cryo. temp. (4 K)	Cryo. temp. (4 K)



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



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

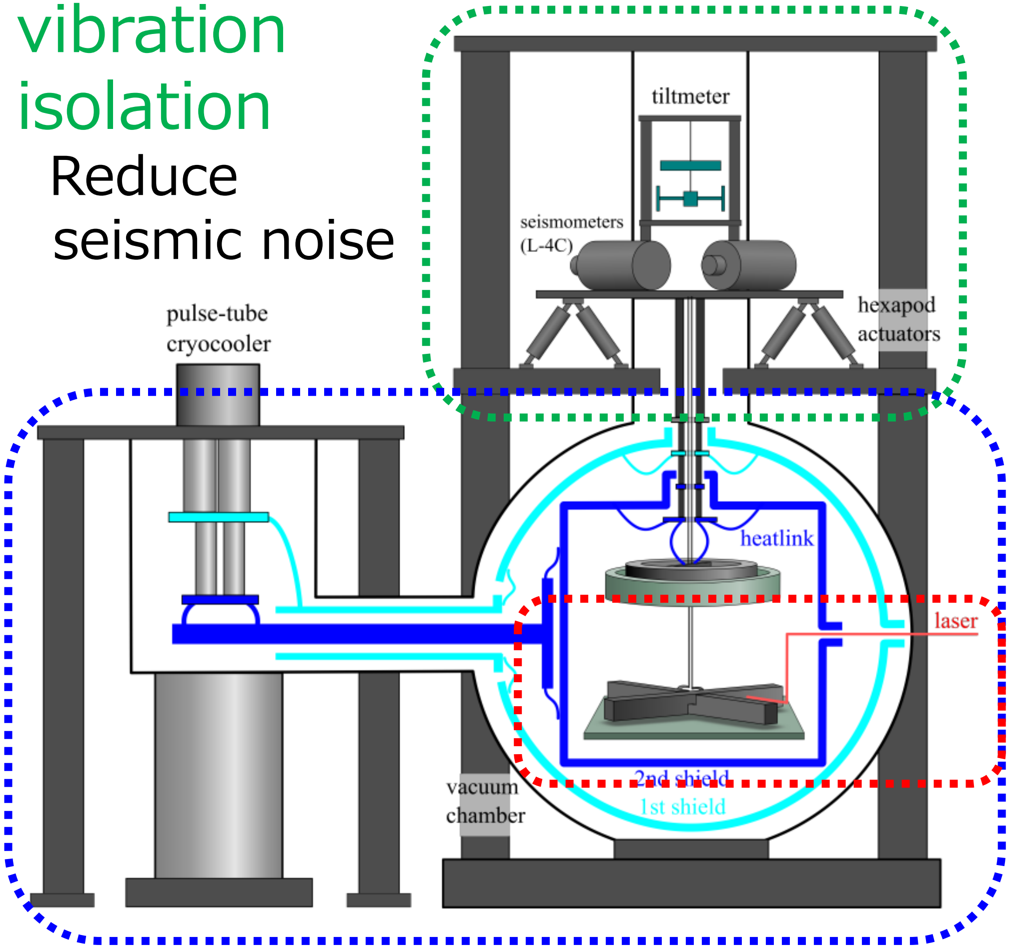


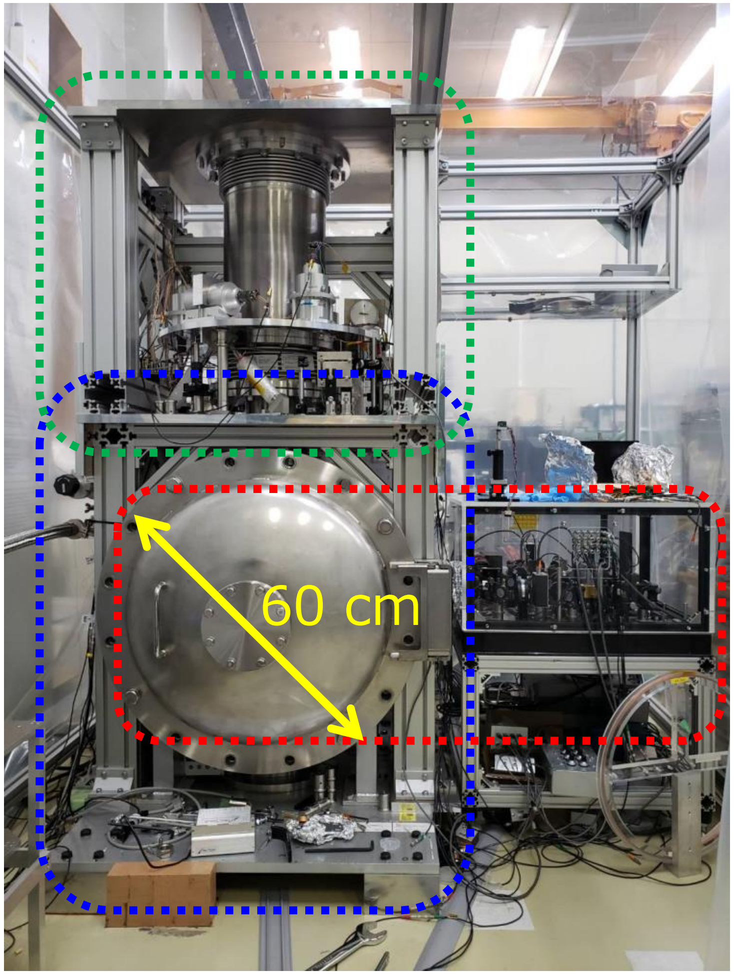
Configuration of Phase-III TOBA

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

Active vibration isolation

Reduce seismic noise





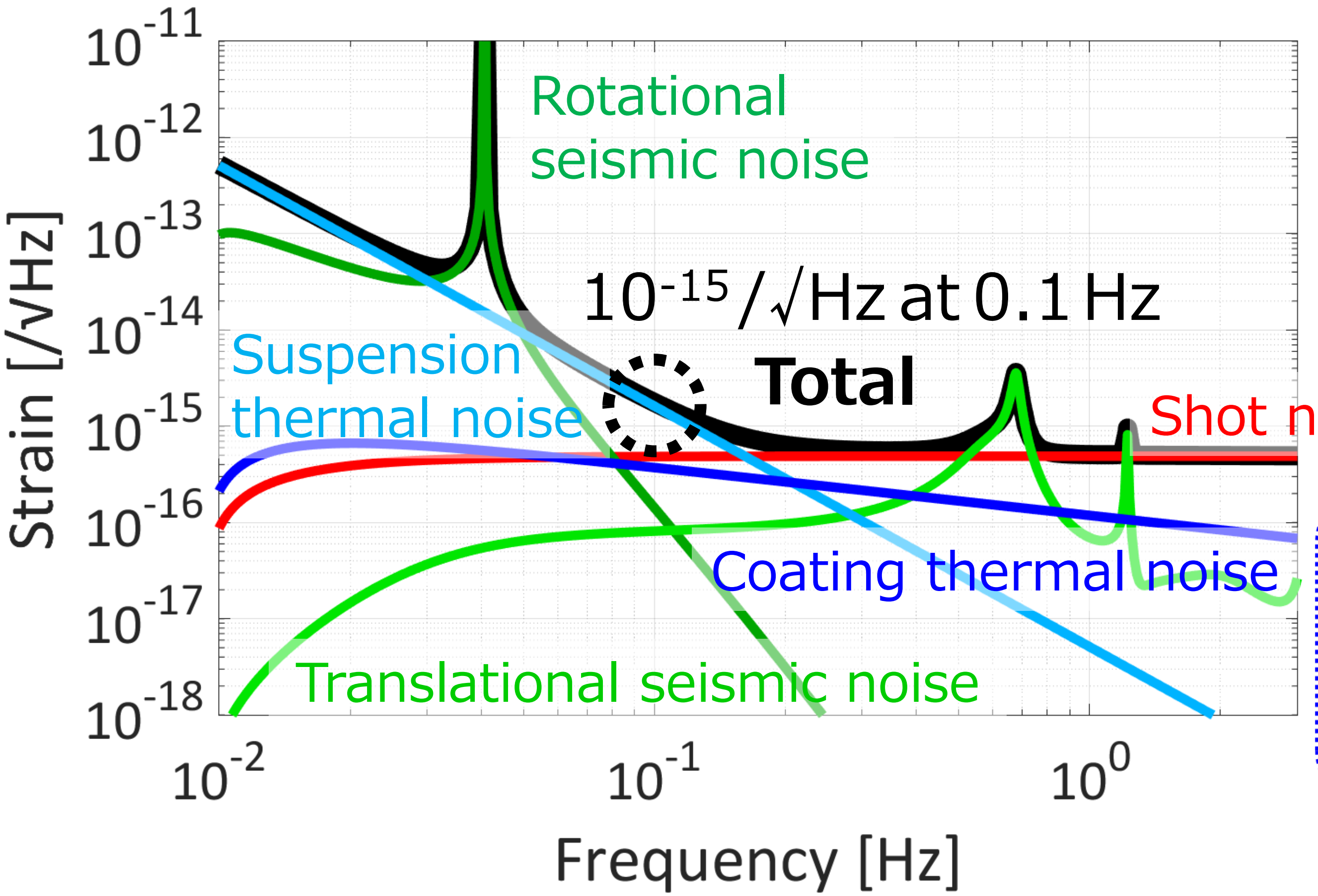
Cryogenic suspension

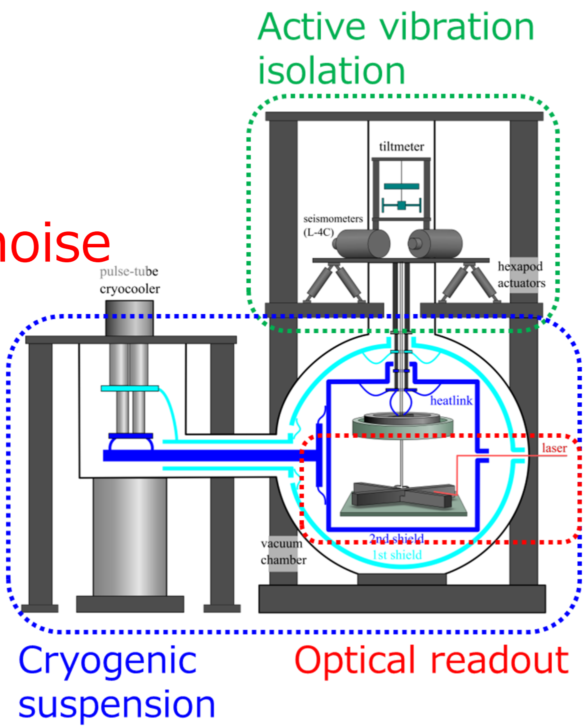
Torsion pendulums at 4 K

Optical readout

Detect the rotation of the pendulums

Design sensitivity of Phase-III TOBA

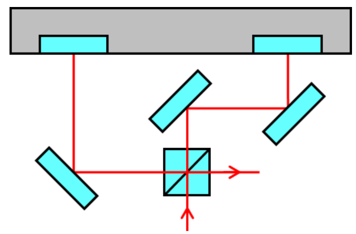
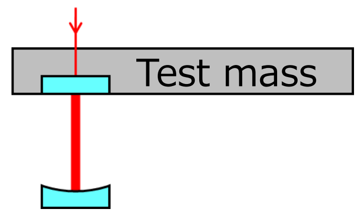
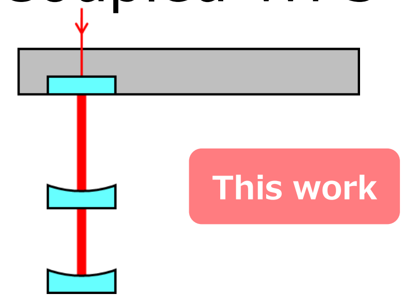




- Our group is developing elements
  - Suspension wire with high Q-value at 4 K
  - Cryogenic monolithic optics
  - Wavefront sensor with a coupled cavity (Coupled WFS)

Comparison of angular sensors

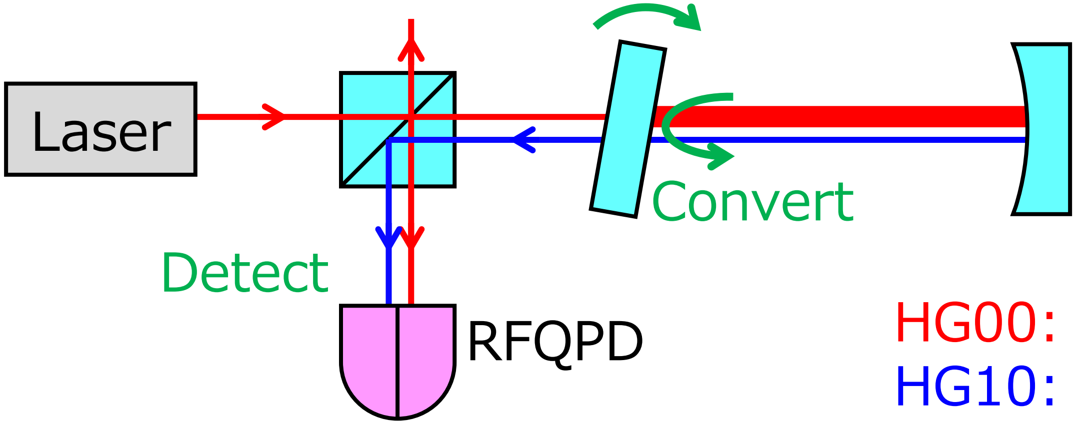
- Need a sensitive angular sensor
  to detect the rotation of torsion pendulums

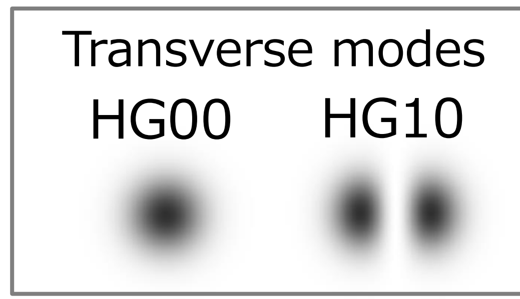
	Michelson interferometer 	Wavefront sensor 	Coupled WFS 
Shot noise Requirement: 5×10^{-16} rad/√Hz		No signal amplification	Signal amplification
Freq. noise	Non-parallel of two mirrors		
Beam jitter	Asymmetry of two light paths		No amplification of beam jitter
Thermal noise		Narrow range measurement	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





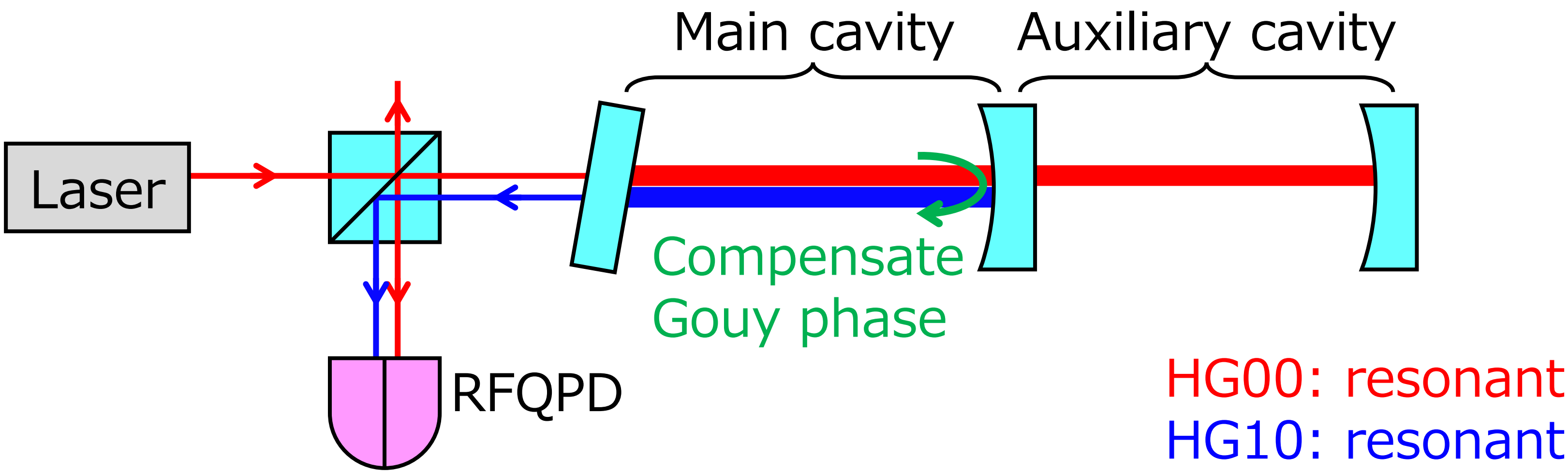
HG00: resonant
HG10: off-resonant

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

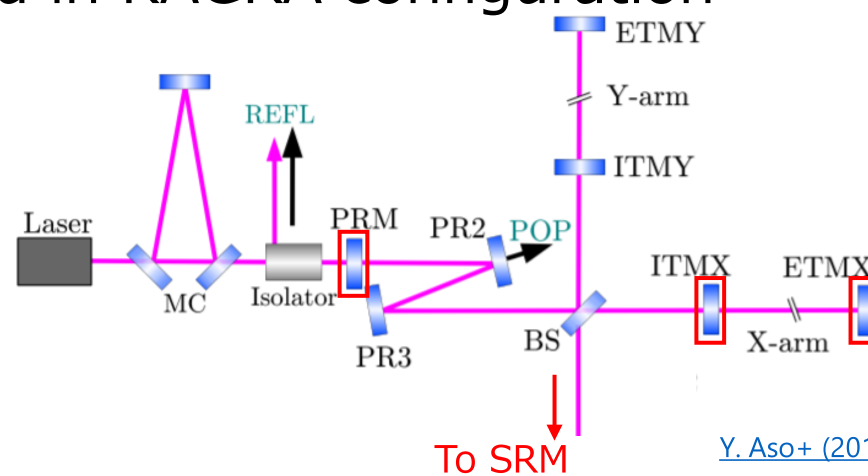
  → HG10 is not amplified in the cavity

Coupled wavefront sensor

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



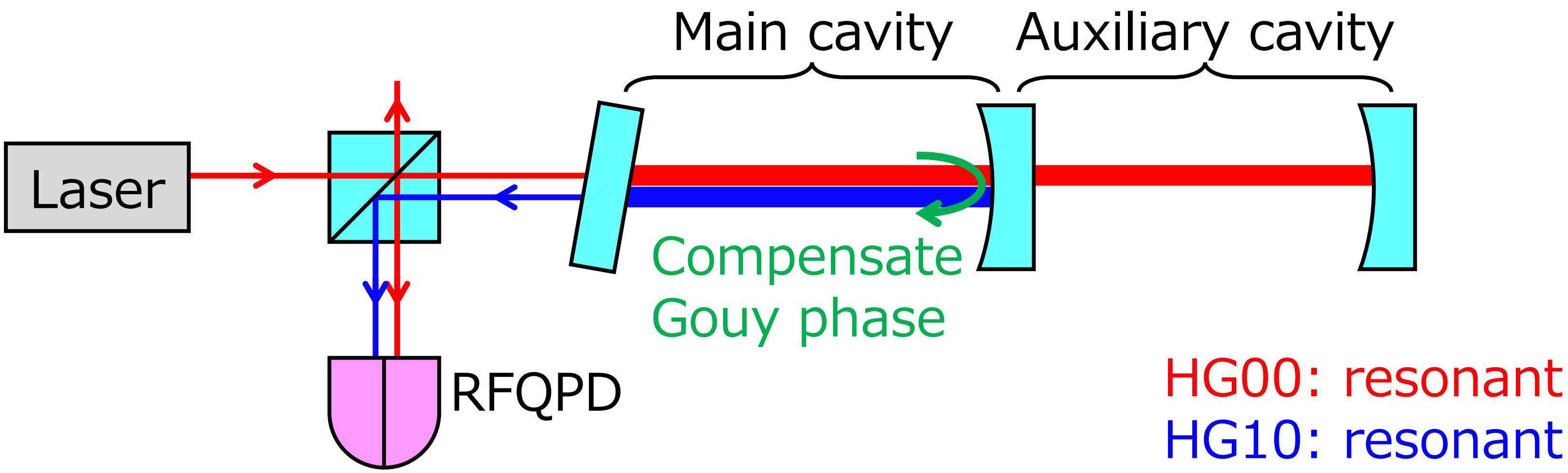
- Coupled WFS is included in KAGRA configuration
  - PRM – ITM - ETM



Y. Aso+ (2013)

Coupled wavefront sensor

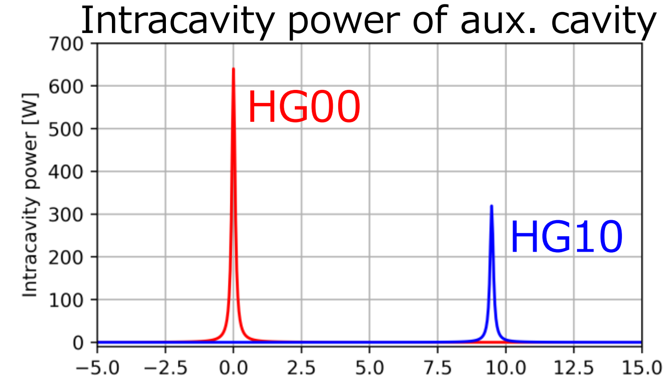
- Coupled wavefront sensor (Coupled WFS):
  wavefront sensor with a coupled cavity

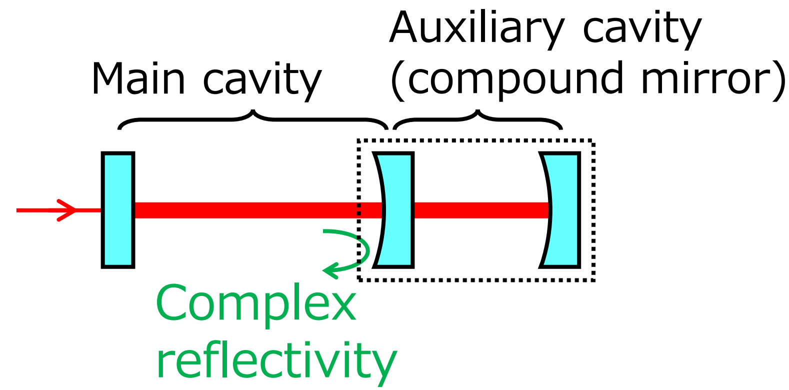


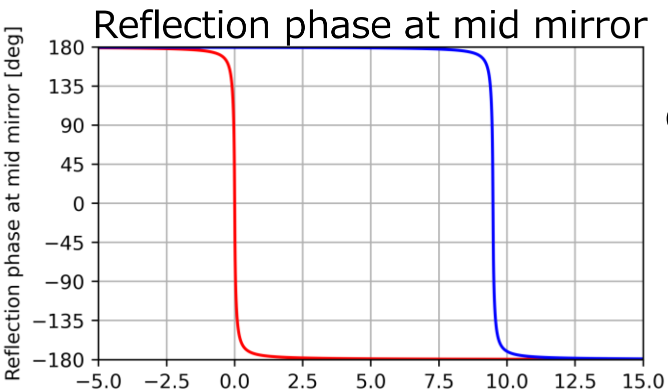
- HG00 and HG10 can resonate simultaneously due to Gouy phase compensation by the auxiliary cavity
  → HG10 is amplified in the main cavity
  → Coupled WFS signal is larger than WFS signal

- Beam jitter is not amplified in the main cavity
  → Better S/N ratio to beam jitter noise

Phase compensation with aux. cavity

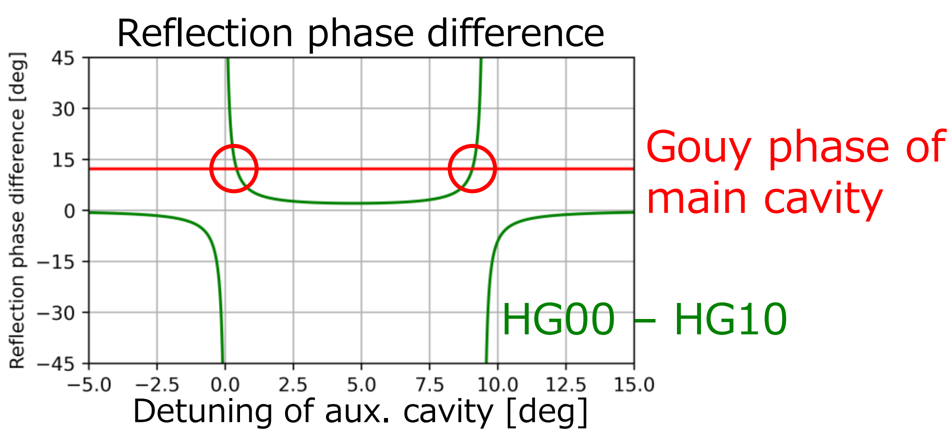




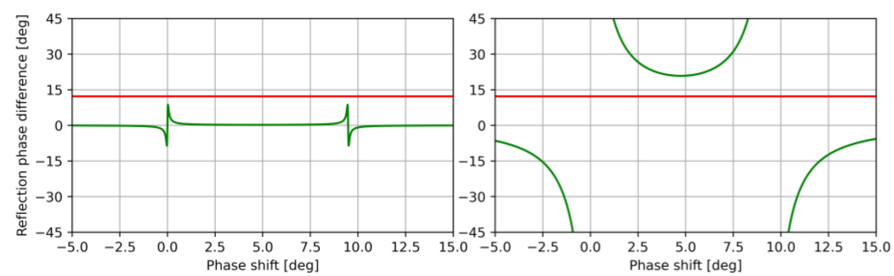


- HG00 and HG10 receive different phases when reflected at the auxiliary cavity

  → Gouy phase of the main cavity can be canceled

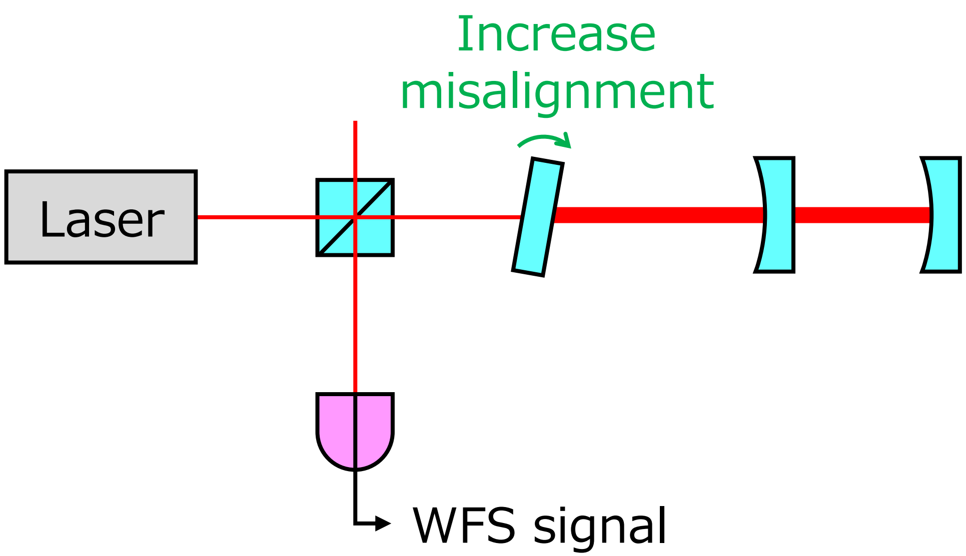


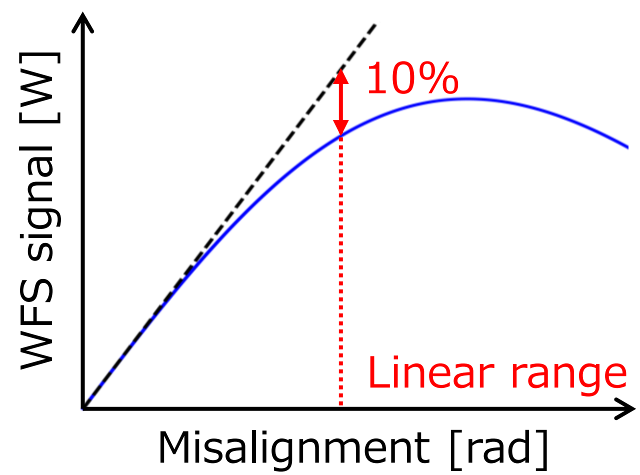
Aux. cavity cannot compensate Gouy phase depending on cavity parameters



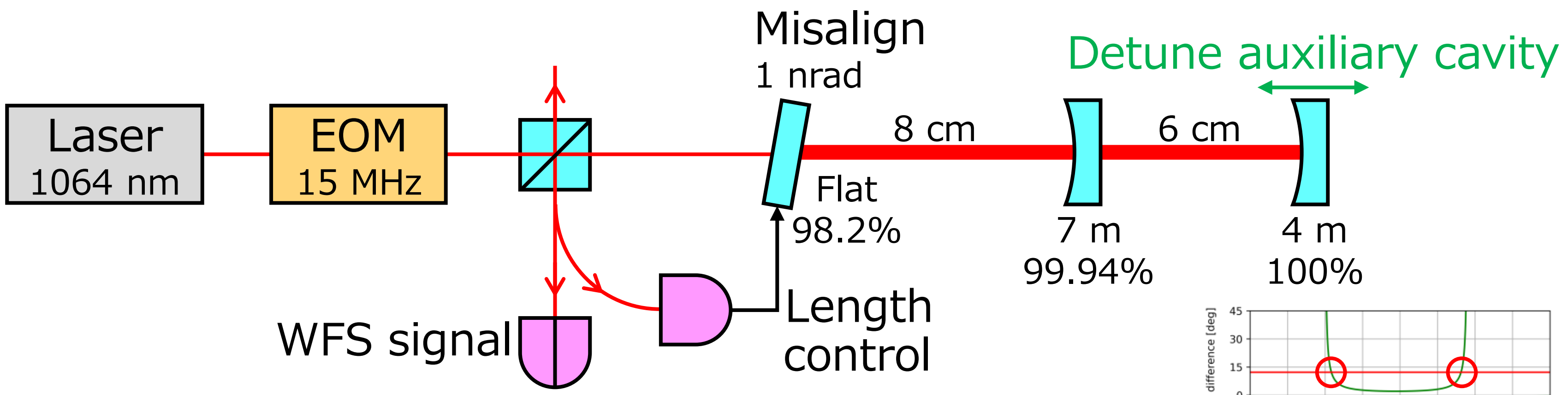
Simulation with FINESSE

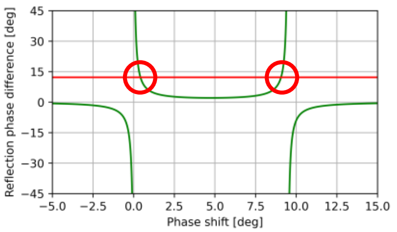
- A coupled cavity has a complicated configuration
- No analytical solution for linear range
  → Use interferometer simulation software FINESSE
- Calculate Coupled WFS signal with increasing misalignment



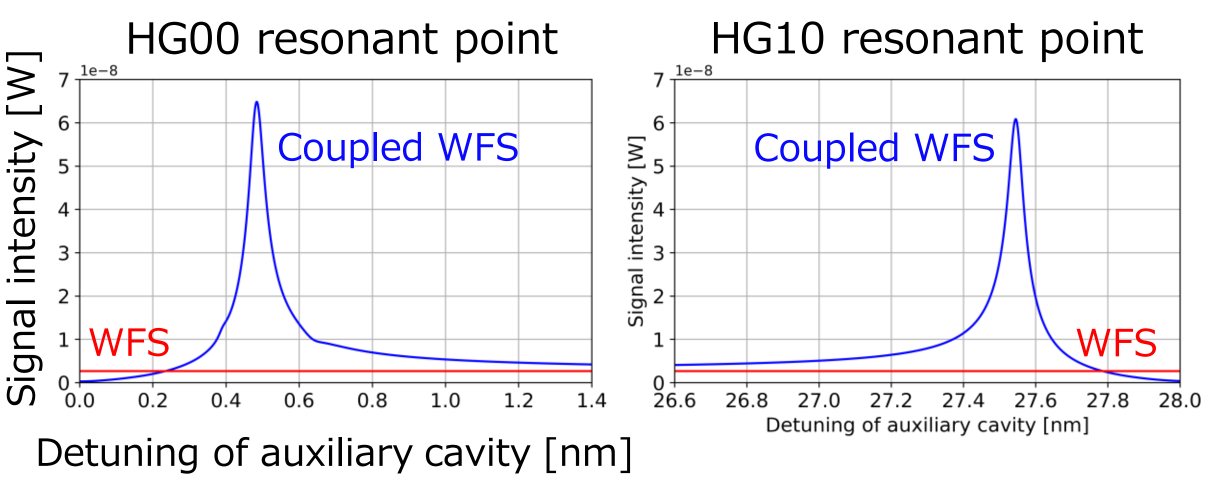


Simulation for signal amplification

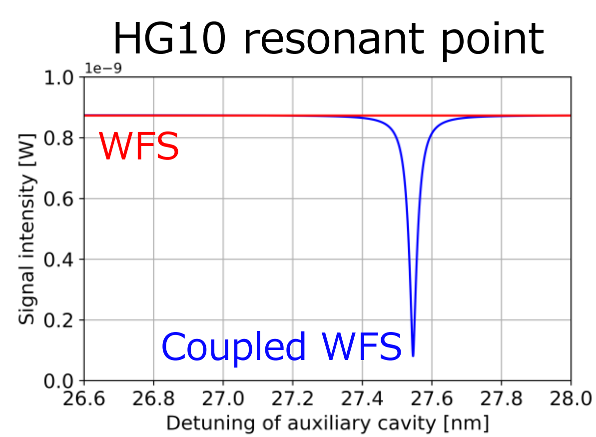




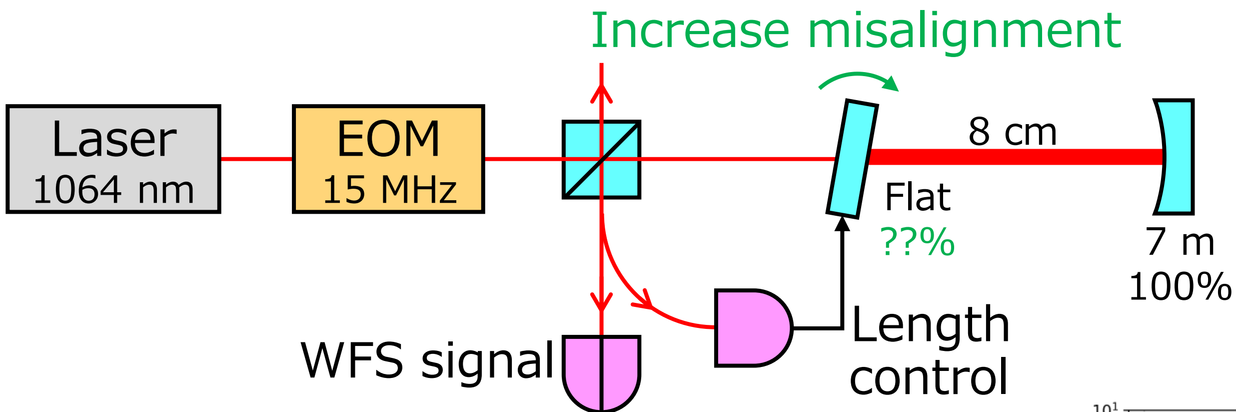
- Signal amplification around resonant points of HG00 and HG10

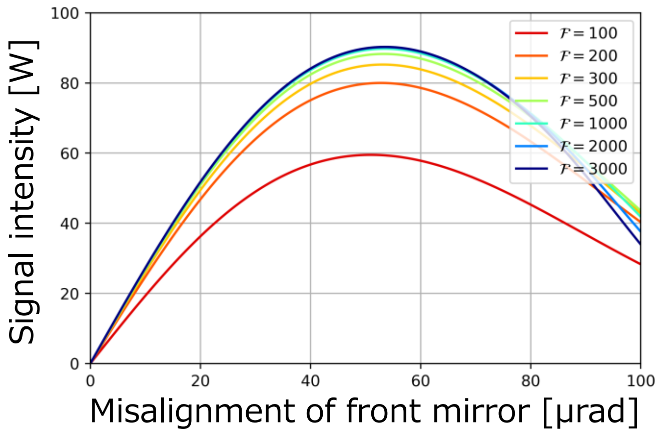


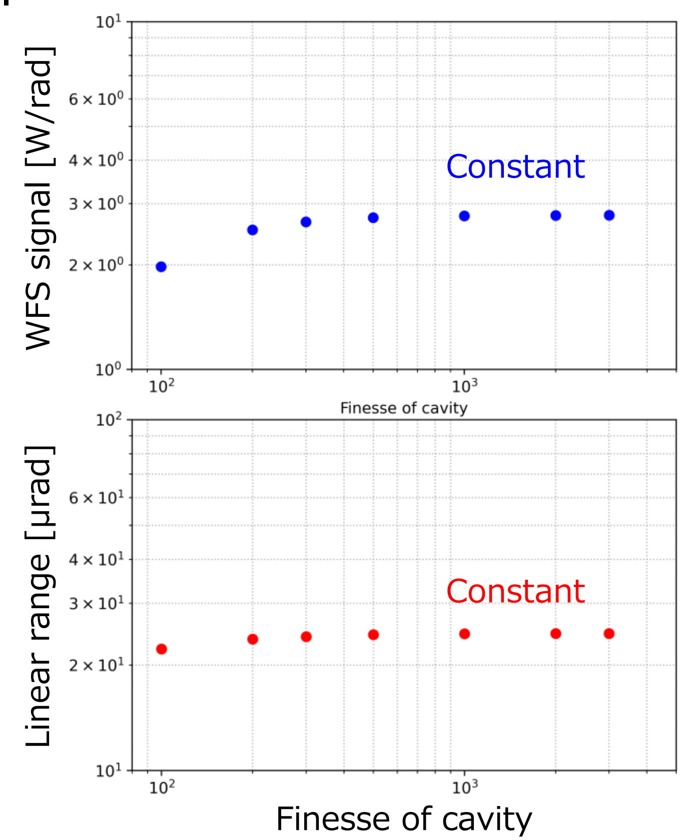
- No amplification to beam jitter noise



Simulation for linear range (WFS)

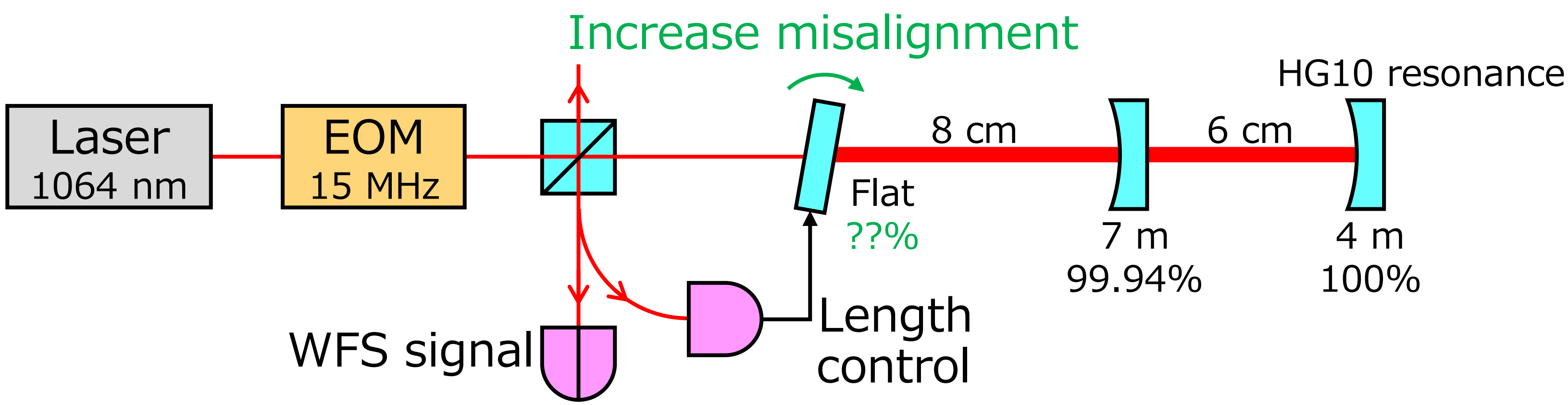


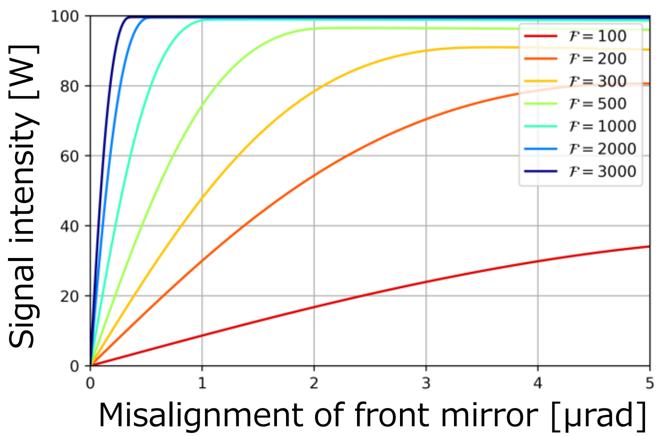


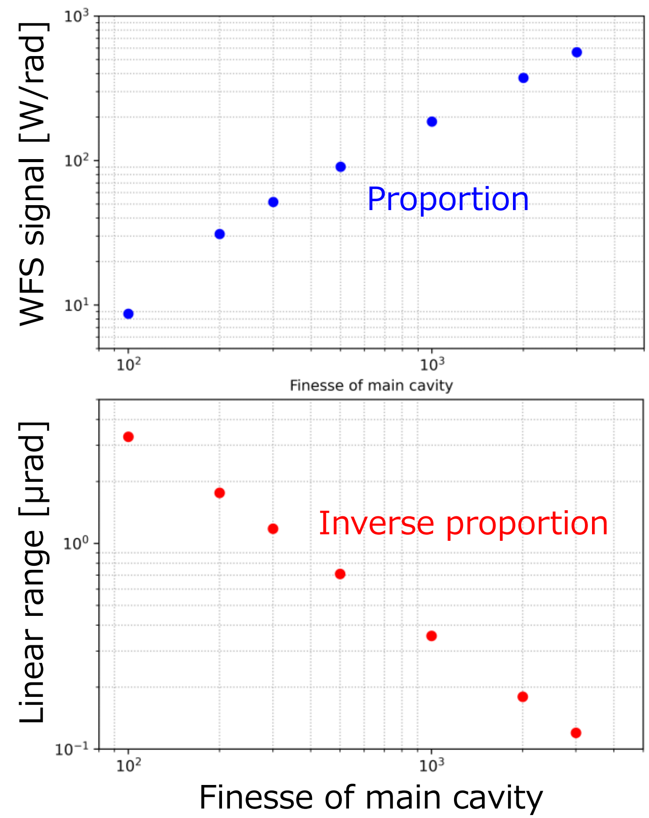


- WFS signal intensity and linear range are constant regardless of finesse

Simulation for linear range (Coupled WFS)





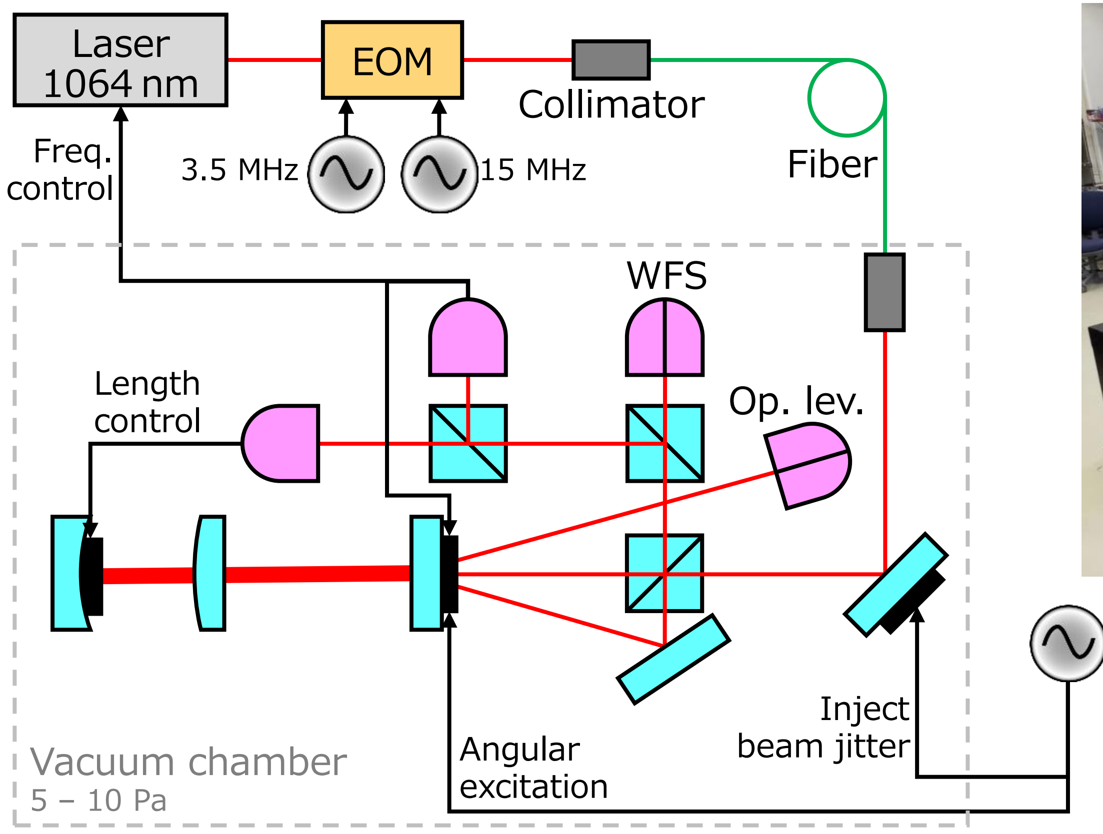


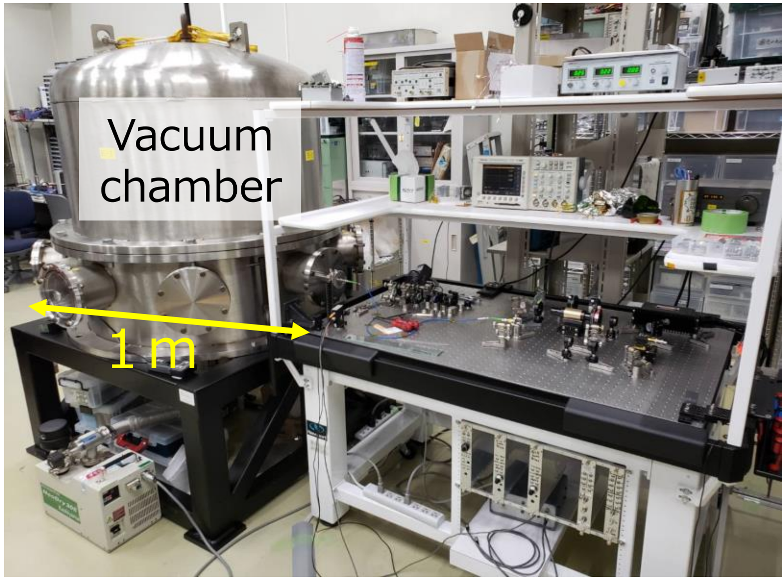
- Coupled WFS signal intensity is proportional to finesse
- Linear range is inverse proportional to finesse

Experimental demonstration

Goal

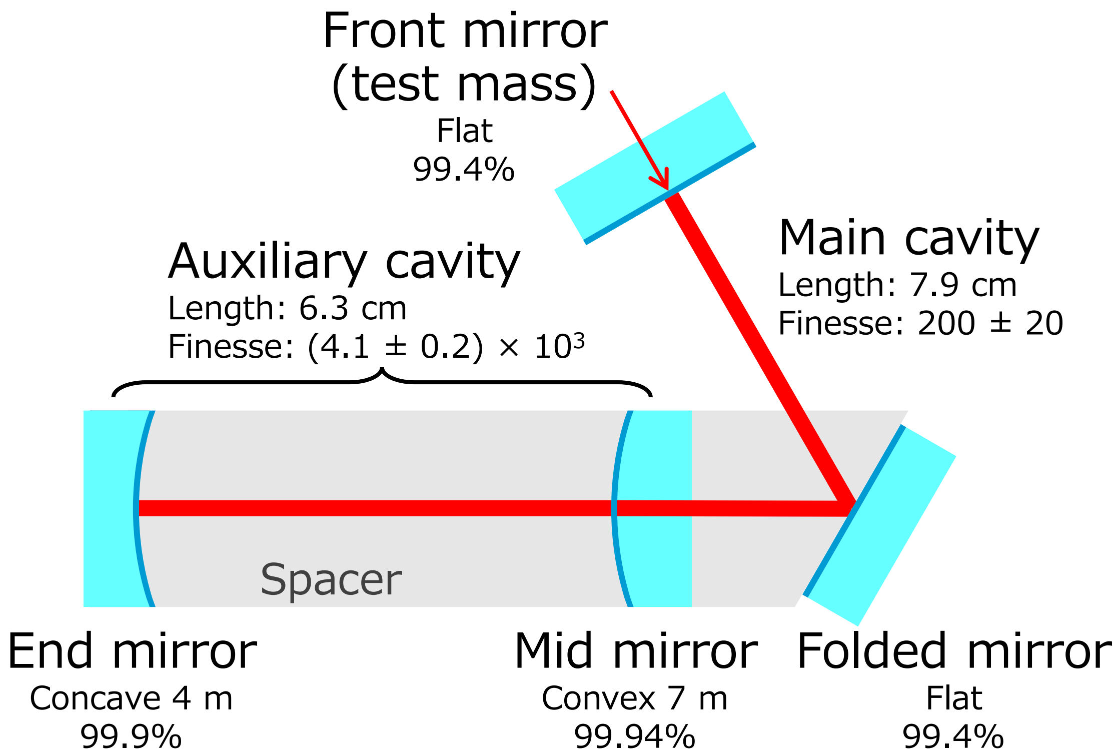
- Evaluate signal amplification
  - Compare the signal intensity of WFS and Coupled WFS
- Establish control method
  - PDH technique for both main and auxiliary cavities

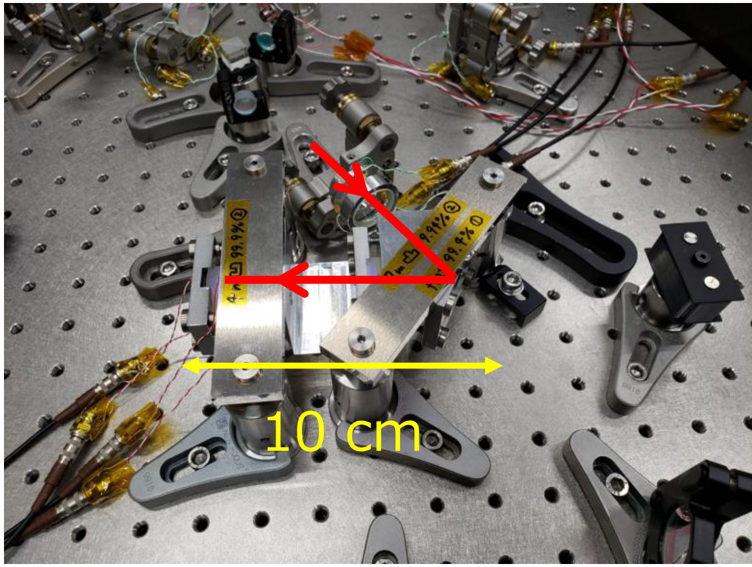




Design of coupled cavity

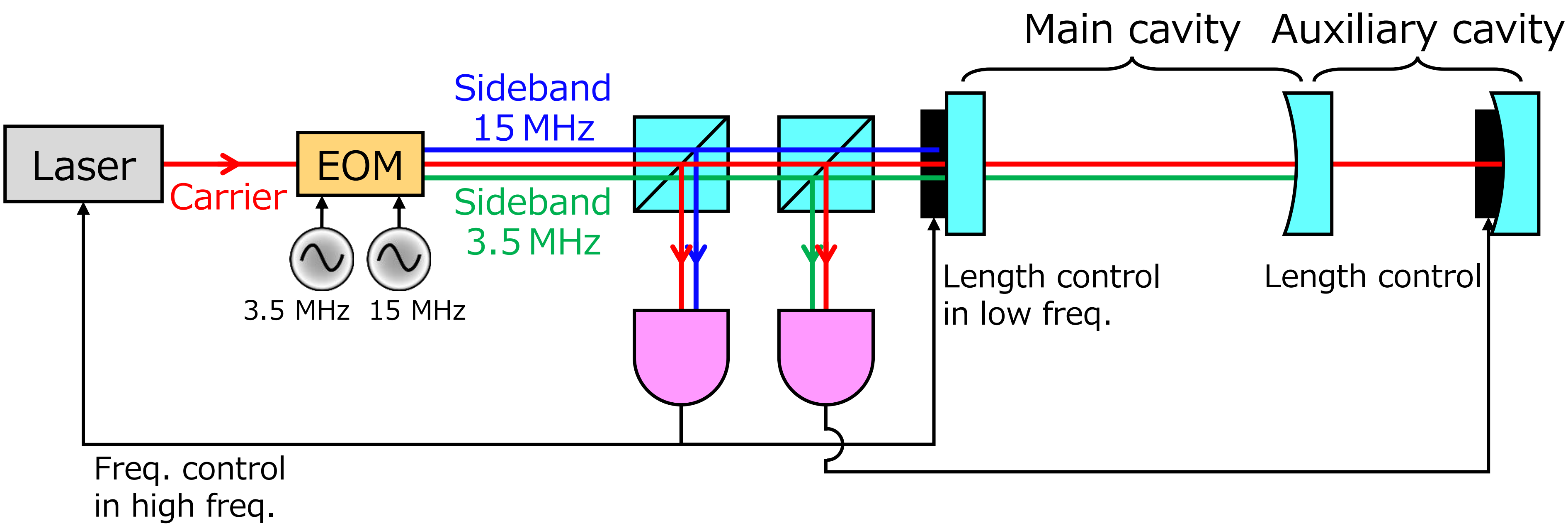
- Parameters are designed to enable phase compensation
  - Reflectivity and loss of the auxiliary cavity are important
    → HR coating is facing the auxiliary cavity
- The main cavity is folded to monitor the transmitted light
- Mirrors are fixed to a spacer to stabilize the alignment





Control method of 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

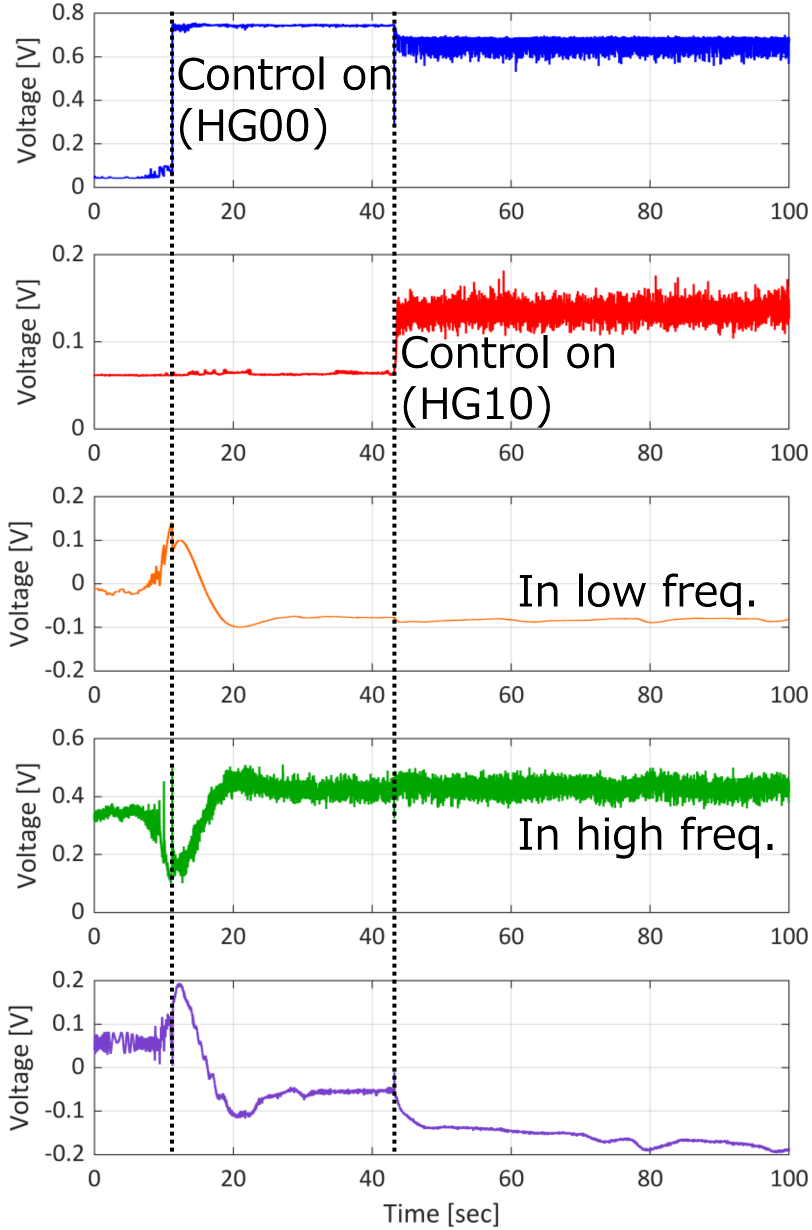
Trans. light of the main cavity

Trans. light of the aux. cavity

FB signal to the main cavity (front mirror)

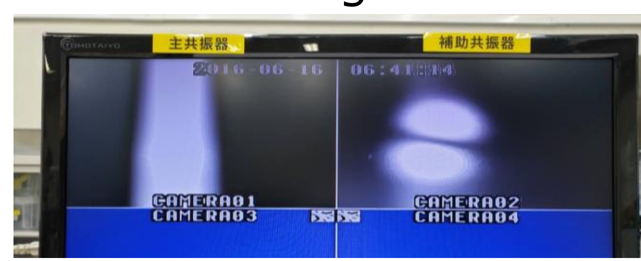
FB signal to the main cavity (laser freq.)

FB signal to the aux. cavity (end mirror)



- Cavities were successfully locked to HG00 and HG10 simultaneously
- However, fluctuation of power is large → Future plan

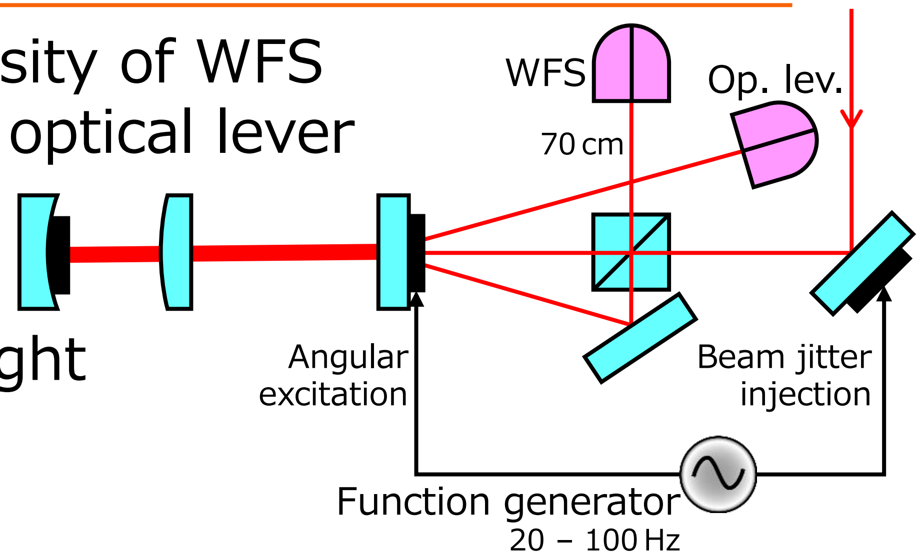
Transmitted light with CCD



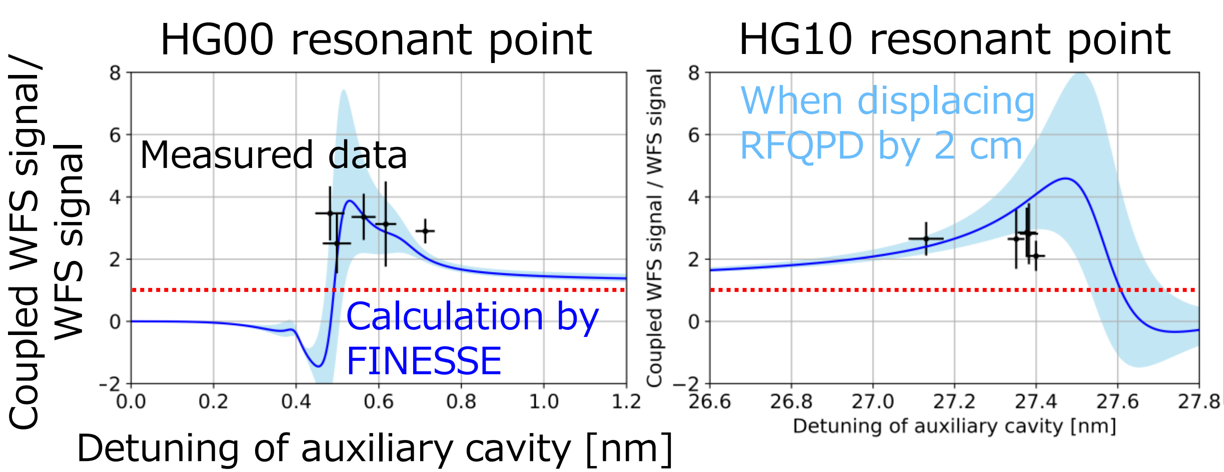
Main (HG00) Auxiliary (HG10)

Results of signal amplification

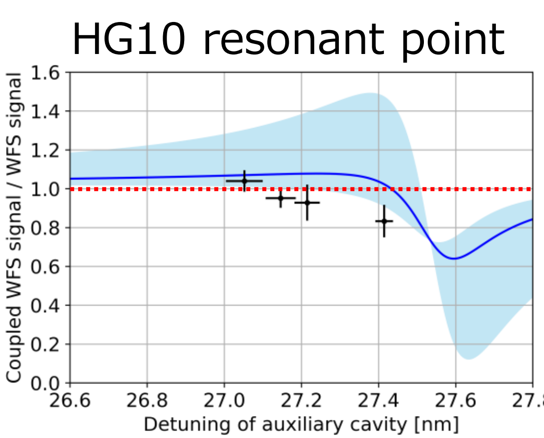
- Calibrated the signal intensity of WFS and Coupled WFS with an optical lever
- Calibrated the lock point of the auxiliary cavity with the power of trans. light



- Angular excitation for front mirror → Signal amplification

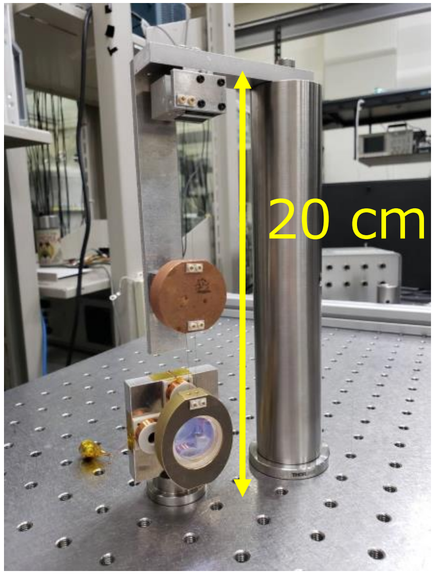


- Beam jitter injection → No amplification



Summary & Future plan

- Developing TOBA to detect GW in low freq.
- Proposed Coupled WFS as an angular sensor for TOBA
  - Application to KAGRA might be possible
- Simulation with FINESSE
  - Confirmed signal amplification
  - Revealed the relationship between linear range and finesse
- Experimental demonstration
  - Established control method
  - Evaluated signal amplification
  - Plan to suspend the test mass to stabilize the cavity lock



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