Current Status of TOBA

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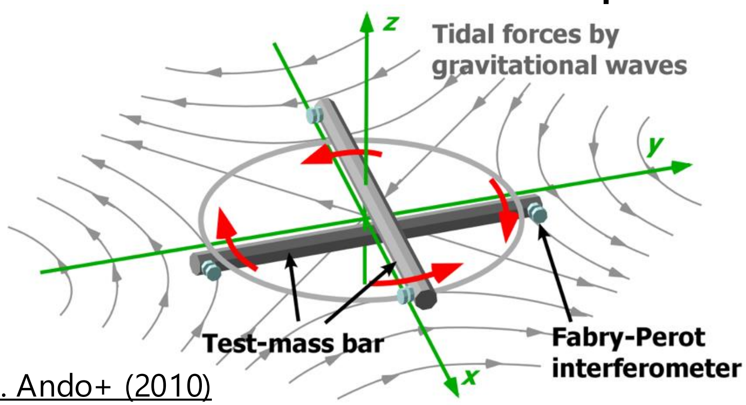
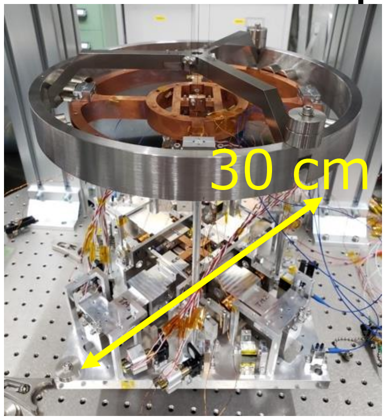
Overview

- Proposed Torsion-Bar Antenna (TOBA) to detect GW in 0.1-10 Hz
  - Target: 10^{-19} /√Hz at 0.1 Hz with 10-m scale torsion pendulums at 4 K
  - Science: intermediate-mass BH binary mergers, gravity gradient noise, earthquakes
- Developing prototype detector Phase-III TOBA
  - Target: 10^{-15} /√Hz at 0.1 Hz with 30-cm scale torsion pendulums at 4 K
  - Some essential components are under development



M. Ando+ (2010)



YO, PhD thesis (2024)

Contents

- Torsion-Bar Antenna
  - Principle
  - Scientific targets
- Phase-III TOBA
  - Development roadmap
  - Configuration
  - Design sensitivity
- Current status of Phase-III TOBA
  - Cryogenic suspension
  - Active vibration isolation
  - Cryogenic interferometer
  - Integration of optics and suspension (my work)

My slot: 45 minutes
My talk: ~30 minutes
Feel free to ask questions during my talk

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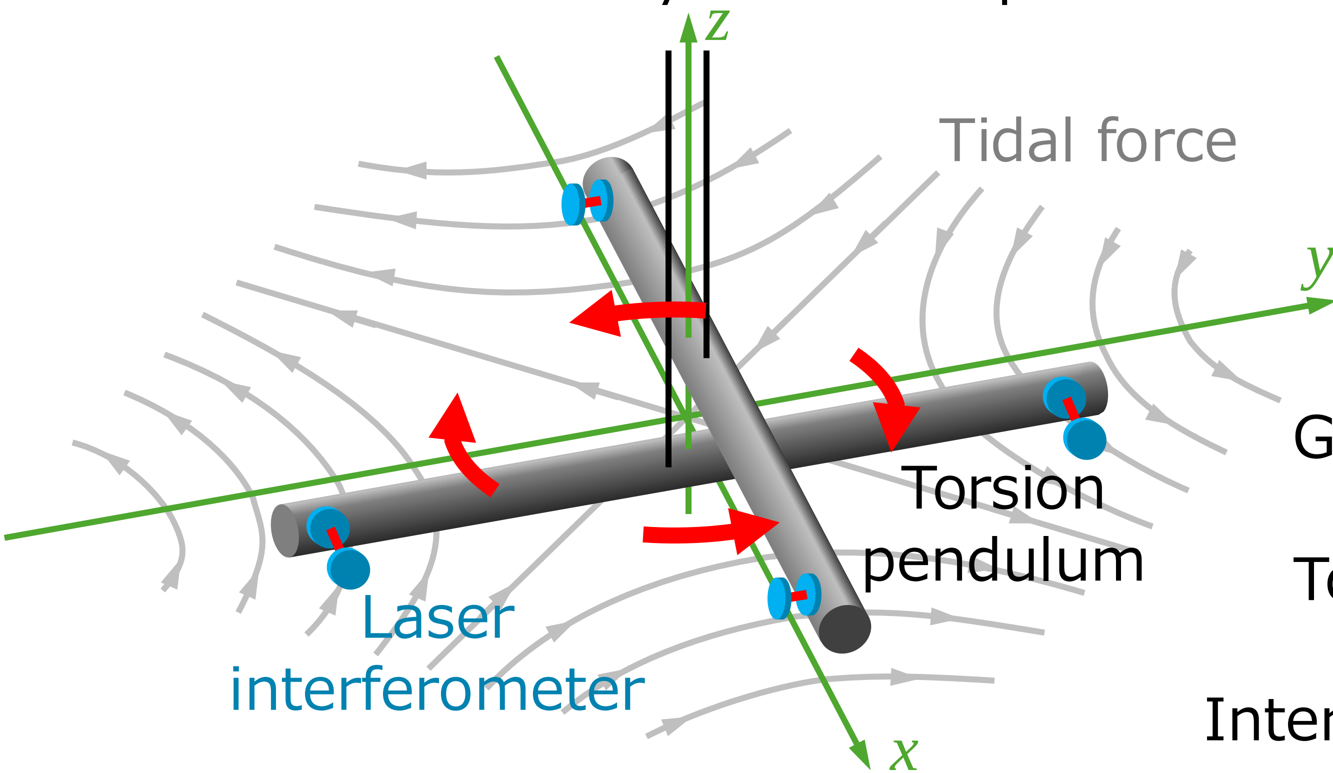
TOBA: Torsion-Bar Antenna

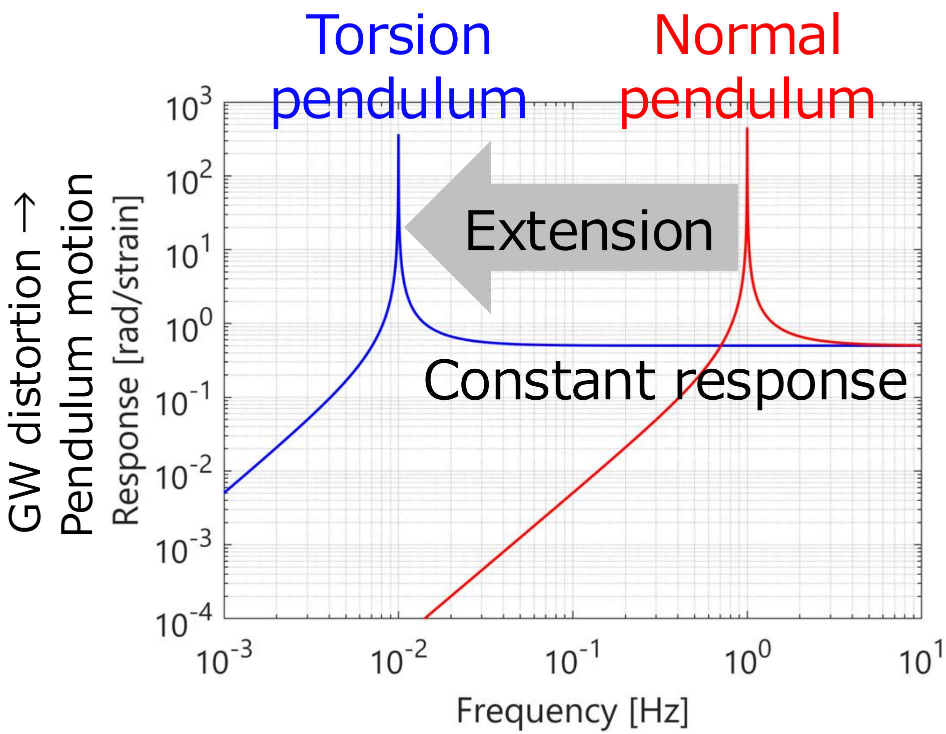
- Ground-based GW detector for low freq. (0.1-10 Hz)
  - Final target: 10^{-19} /√Hz at 0.1 Hz
- Aim to detect the torsional rotation of test masses suspended horizontally
- The resonant frequency of torsional motion is low (~1 mHz)
  → Good sensitivity in low freq. even on the ground

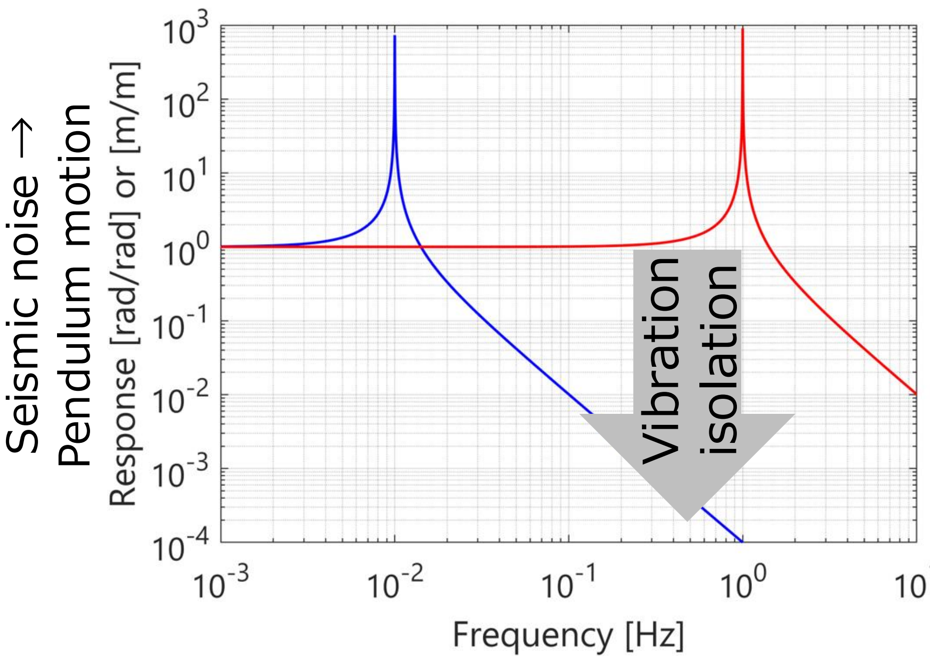


GW ⇒ Tidal force
↓
Torsional rotation
↓
Interferometric readout

Response of torsion pendulum

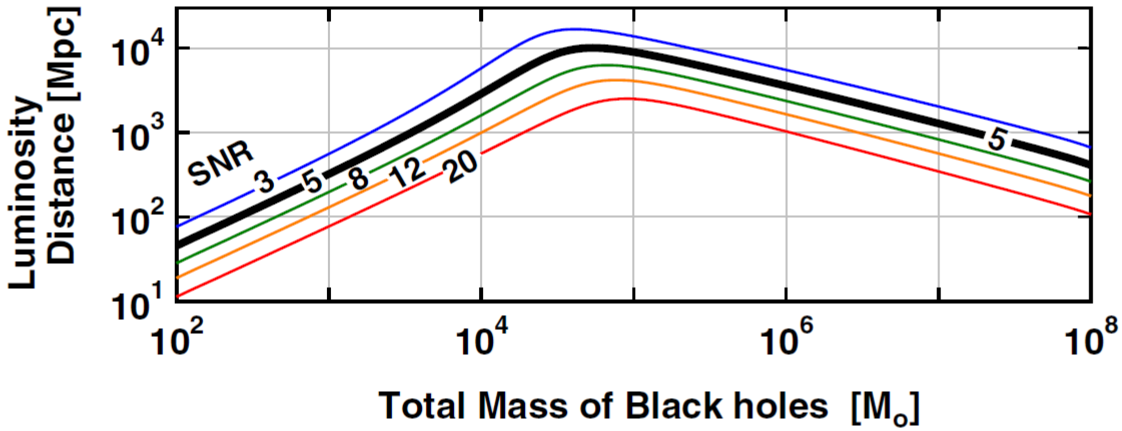
- Respond to GW like a free mass at frequencies higher than the resonance frequency
  → Extend bandwidth
- Passive vibration isolation at frequencies higher than the resonant frequency
  → Reduce seismic noise





Science of TOBA: GW in low freq.

- Intermediate-mass BH binary mergers
  - Within ~1 Mpc (Phase-III)
  - Within ~10 Gpc (Final)
    → Formation process of supermassive BHs

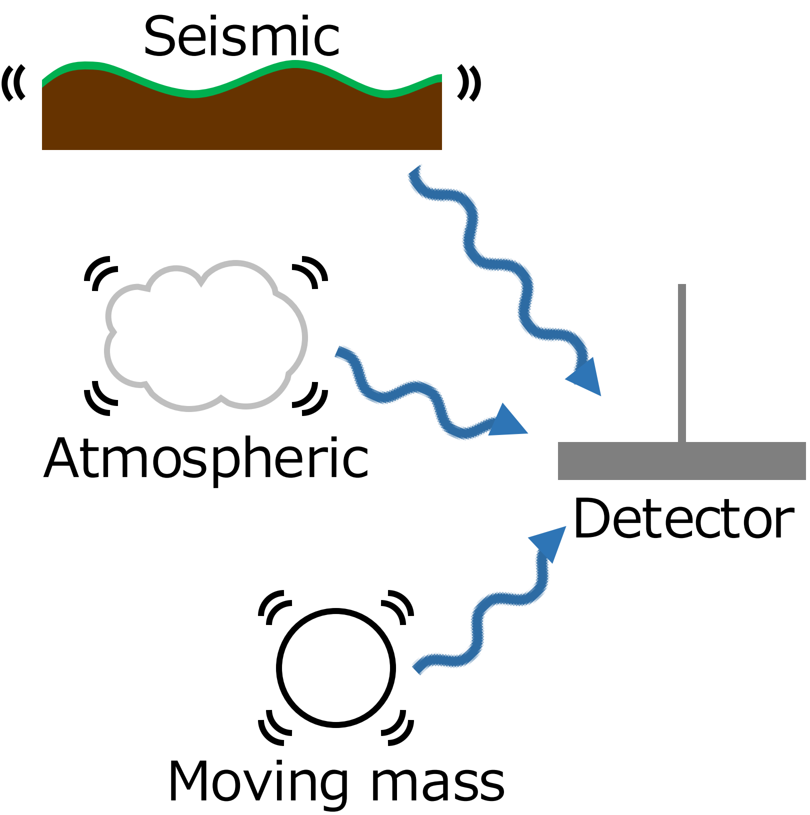


M. Ando+ (2010)

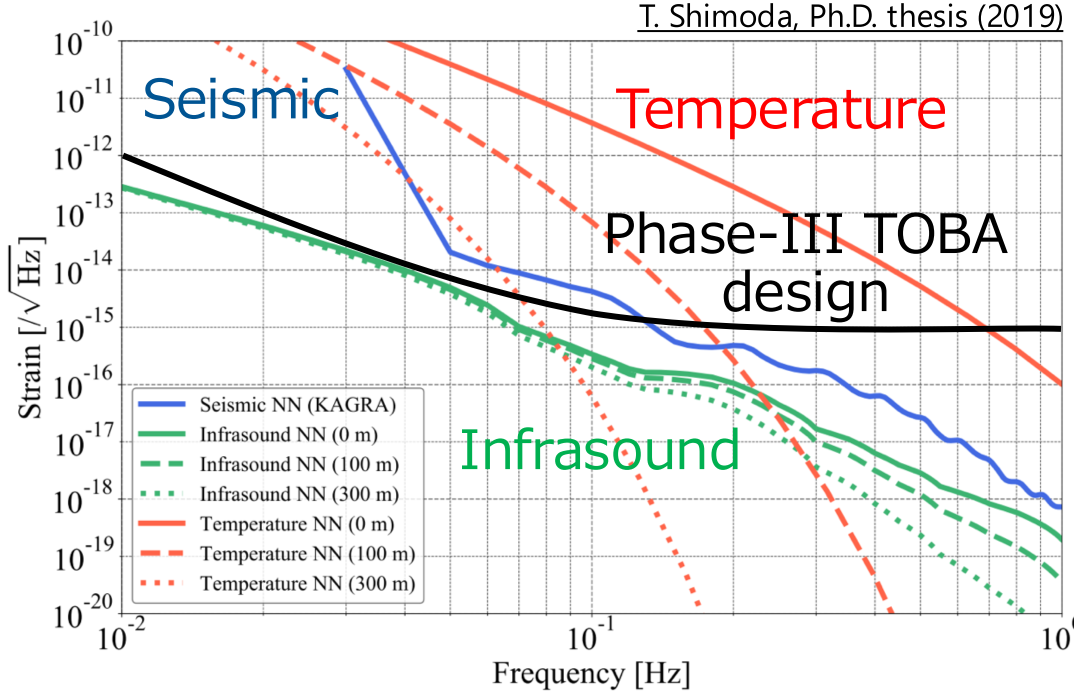
- GW stochastic background
  - Ω_{GW} < 10 at 0.1 Hz (Phase-III)
  - Ω_{GW} < 10^{-7} at 0.1 Hz (Final)
    → Direct exploration of the early universe

Science of TOBA: GGN

- Gravity gradient noise (Newtonian noise)
  - First direct detection (Phase-III)
    → Noise reduction
    for the 3rd generation GW detectors

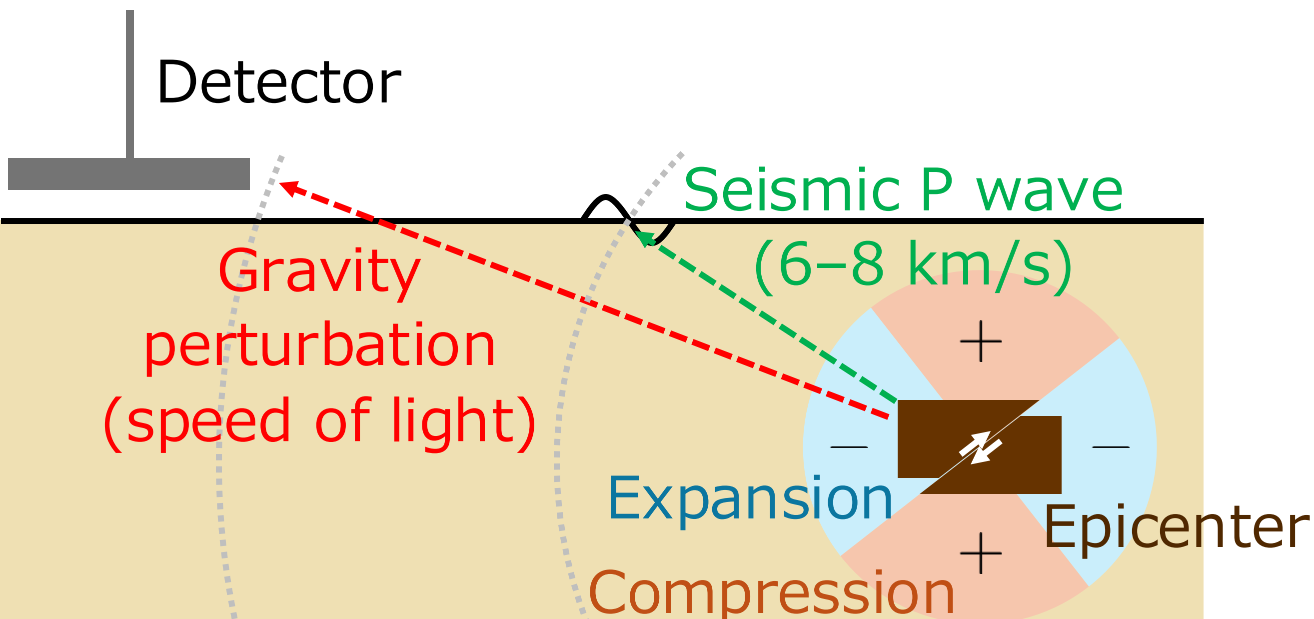


T. Shimoda, Ph.D. thesis (2019)

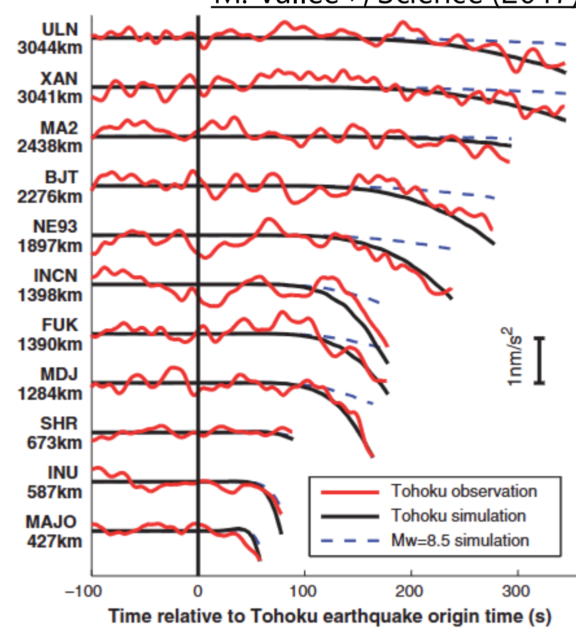


Science of TOBA: earthquake

- Earthquake detection using gravity perturbations generated by fault rupture
  - Faster detection and early warning than conventional methods using seismic P waves
  - Better accuracy of magnitude estimation
- Gravity perturbations were observed by post-event analysis
  → Aiming for higher accuracy and real-time detection

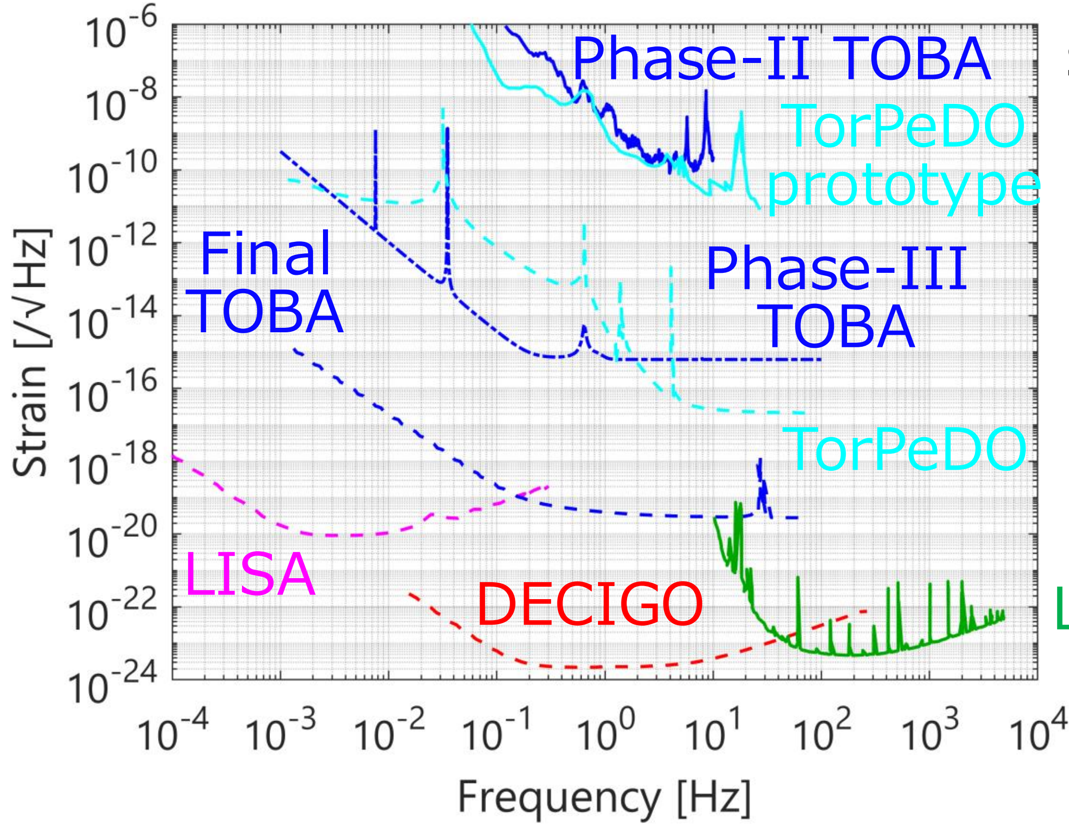


M. Vallée+, Science (2017)



TOBA and other GW detectors

- Spaceborne GW detectors: LISA・DECIGO K. Danzmann+, CQG (1996) S. Kawamura+, JPCS (2008)
  - Much better sensitivities
  - High costs for development
  - Difficulty of maintenance during operation M. Ando+, PRL (2010) D. J. McManus+, CQG (2017)
- Torsion pendulums: TOBA (UTokyo)・TorPeDO (ANU)



Solid: achieved
Dashed: proposed

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Development roadmap of TOBA

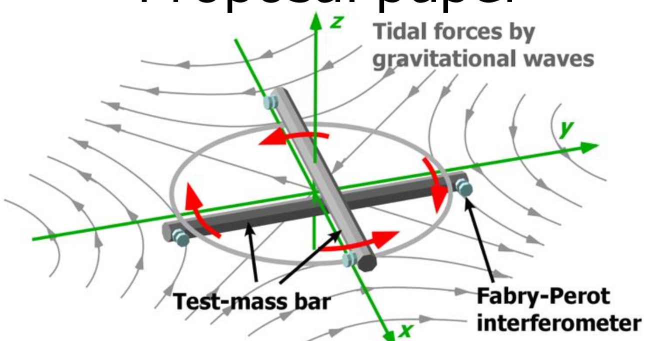
Phase-I TOBA
(2009-2011)

Phase-II TOBA
(2012-2014)

Principle test

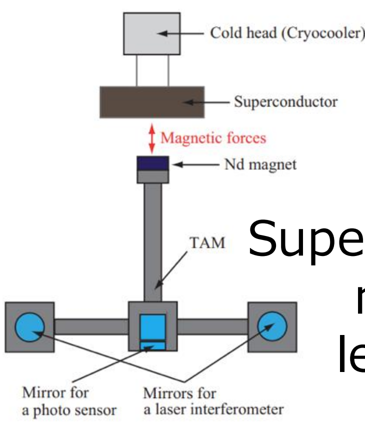
10^{-8} /√Hz (achieved)
20 cm bars
Room temp.

Proposal paper



M. Ando+ (2010)

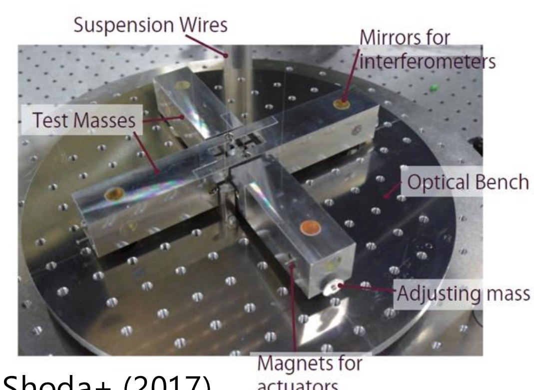
Phase-I TOBA



K. Ishidoshiro, PhD thesis (2009)

Superconducting magnet levitation

Phase-II TOBA

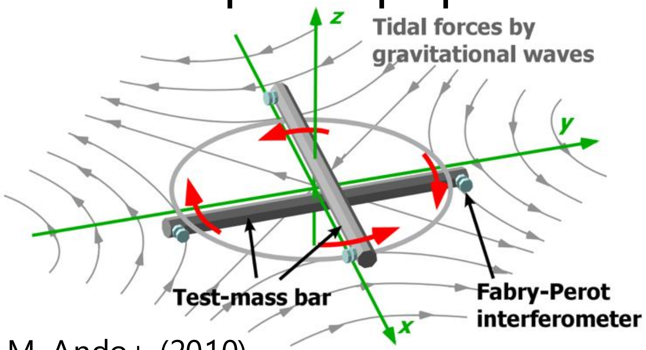


A. Shoda+ (2017)

Development roadmap of TOBA

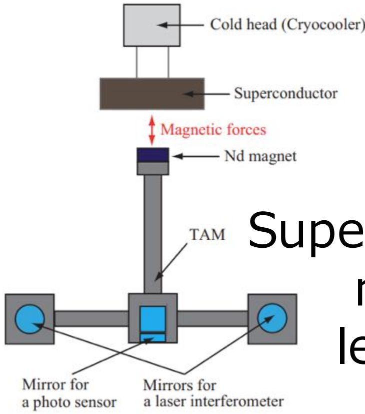
Phase-I TOBA (2009-2011) Phase-II TOBA (2012-2014)	Phase-III TOBA (2018-now)	Final TOBA (Future)
Principle test	Technical demonstration	GW observation
10^{-8} /√Hz (achieved) 20 cm bars Room temp.	10^{-15} /√Hz (target) 35 cm bars Cryogenic temp.	10^{-19} /√Hz (target) 10 m bars Cryogenic temp.

Proposal paper



M. Ando+ (2010)

Phase-I TOBA



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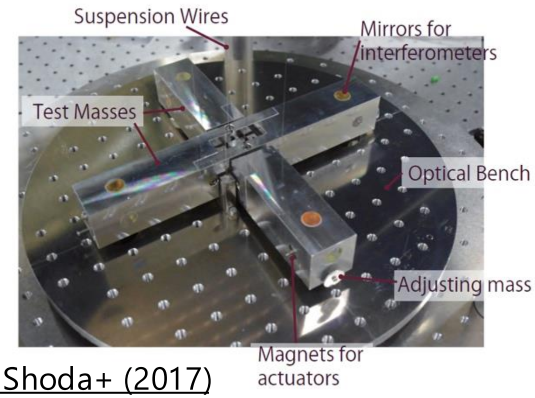
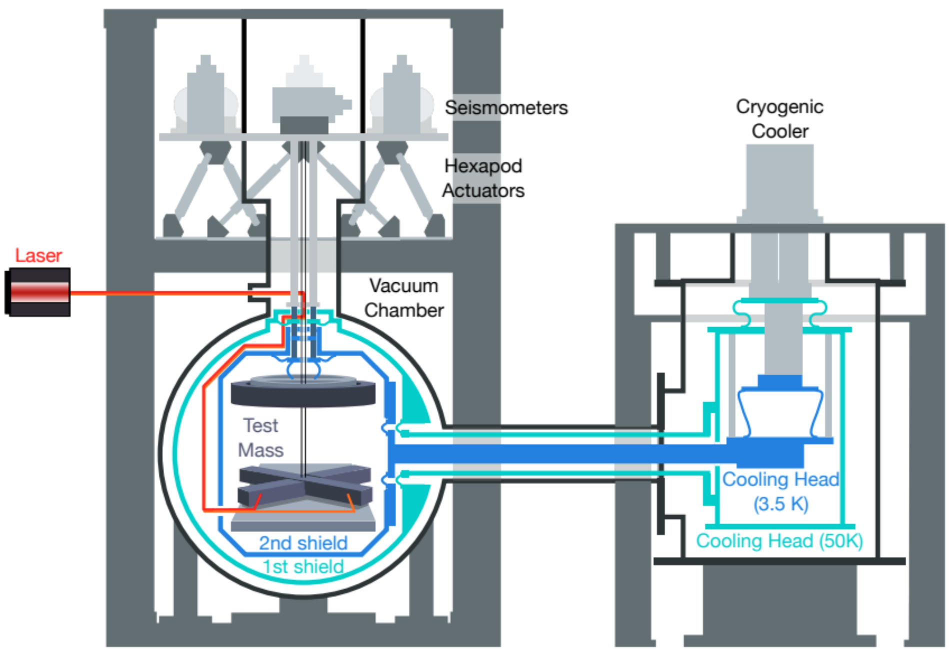
Phase-II TOBA



A. Shoda+ (2017)

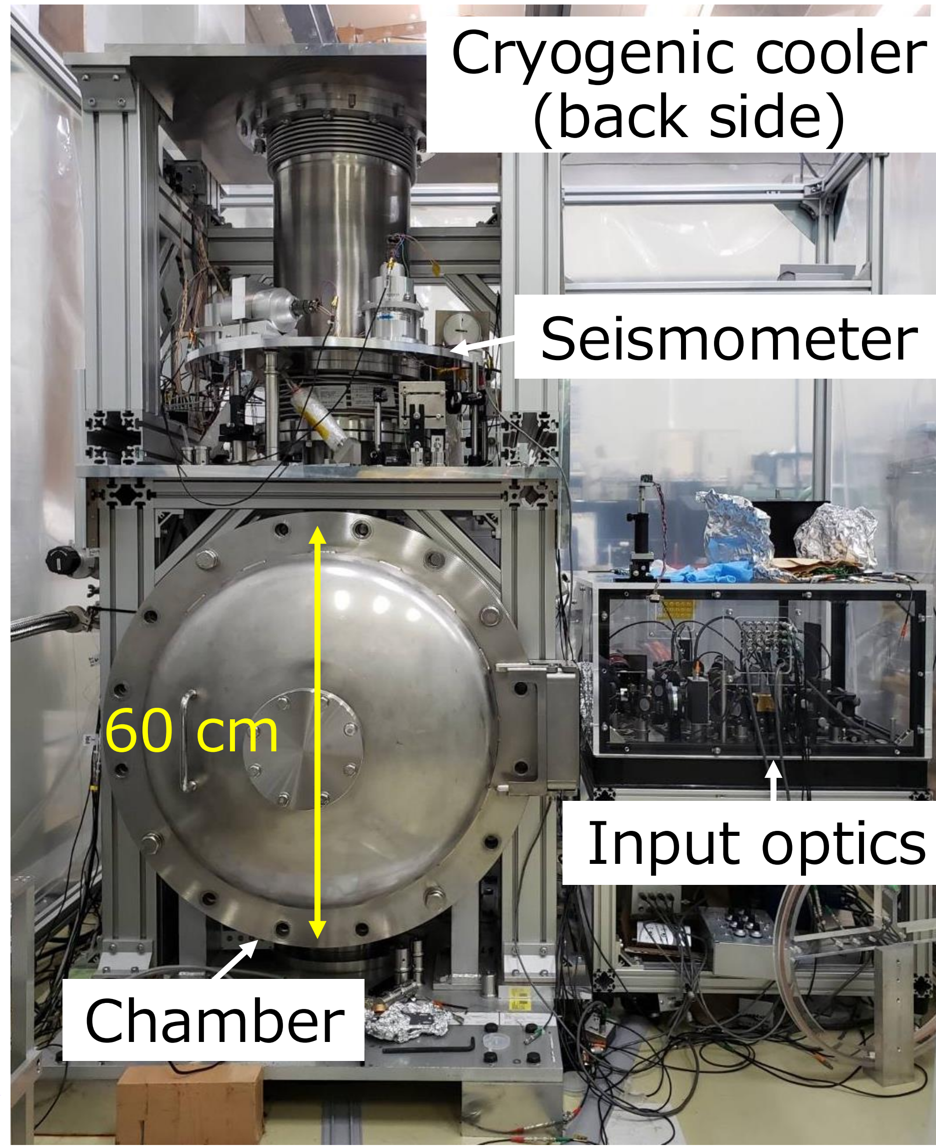
Configuration of Phase-III TOBA

- Laser interferometers
- Suspension
- Cryogenic cooler
- Active vibration isolation



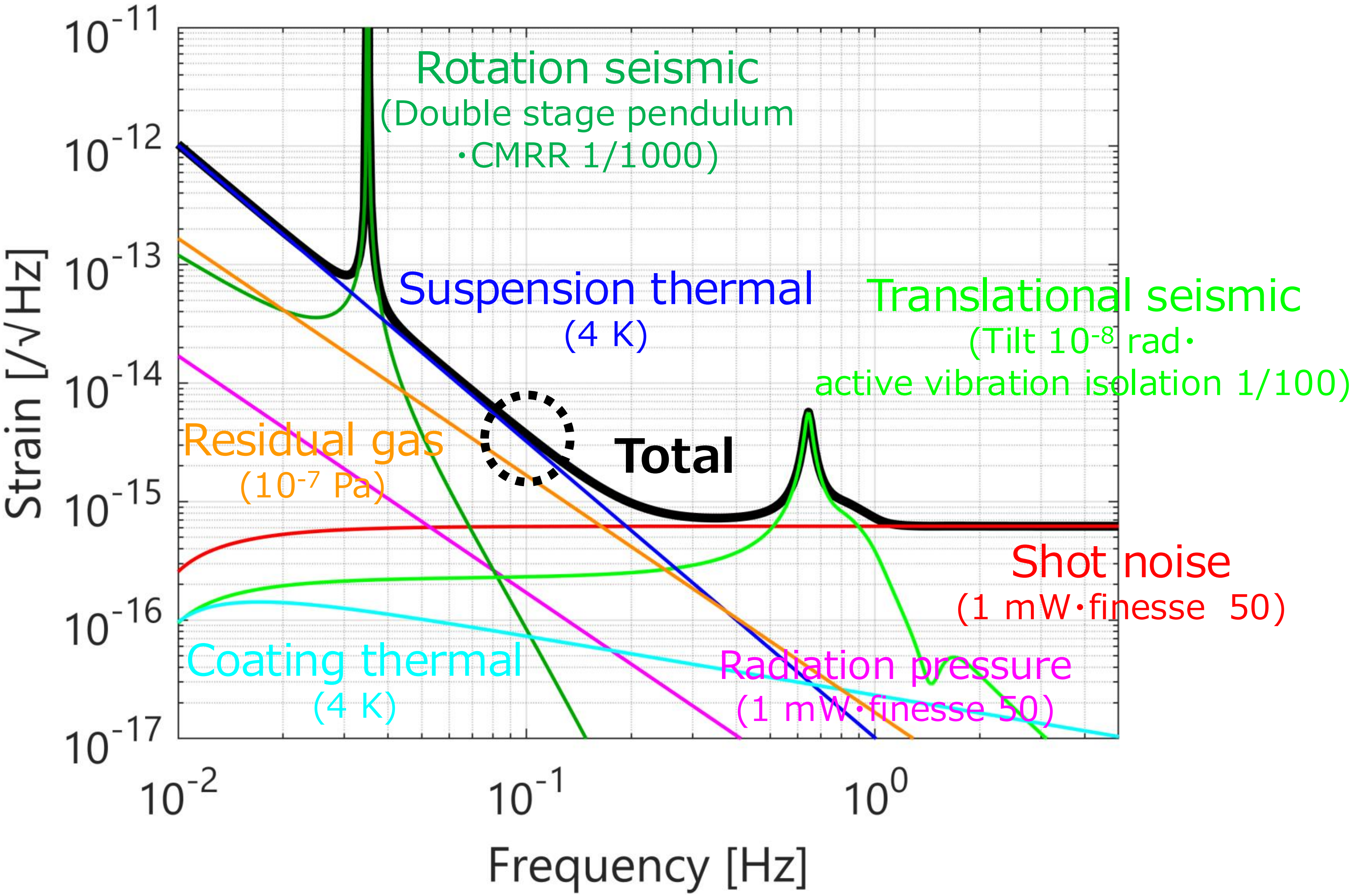
S. Takano, T. Shimoda, YO+ (2024)

We'll show you on the lab tour



Design sensitivity of Phase-III TOBA

- 3.7×10^{-15} /√Hz at 0.1 Hz



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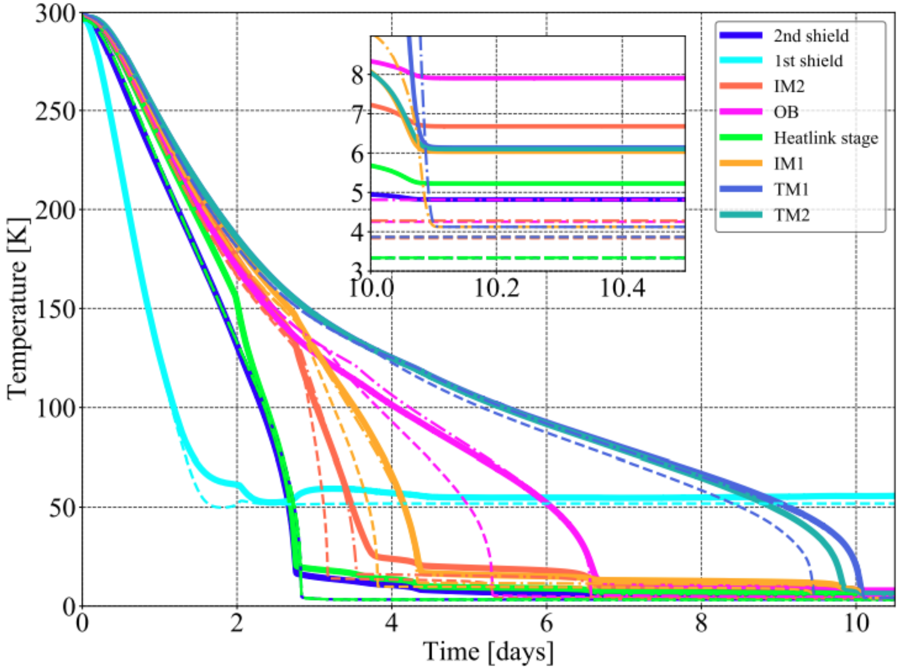
Status: cryogenic suspension

by T. Shimoda and C. P. Ooi

- Torsion pendulums were successfully cooled
  - Target: 4 K / result: 6.1 K
- Developing suspension wire made of sapphire for high Q factor
  - Target: 10^8 / result: 7×10^4 at 4 K



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

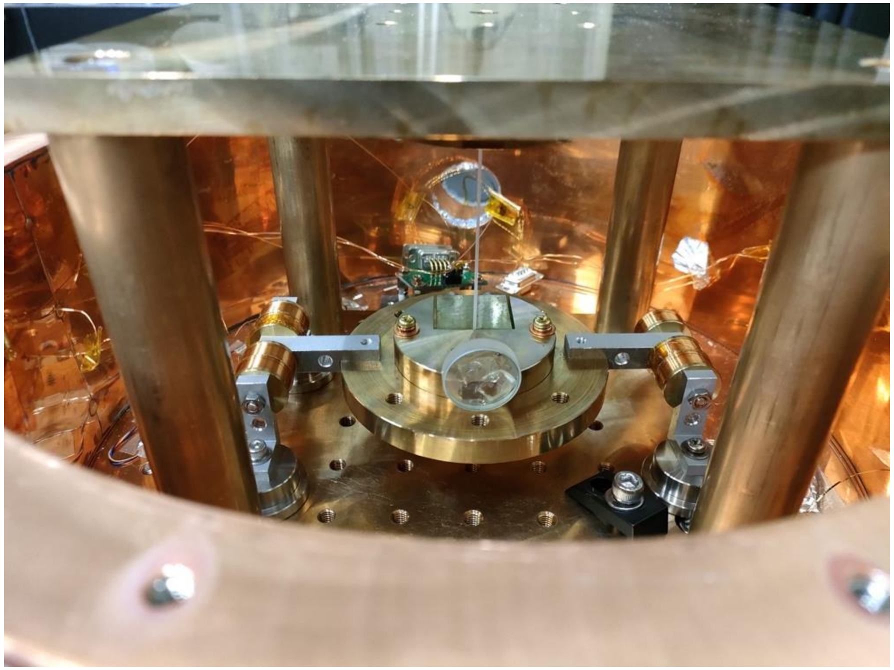
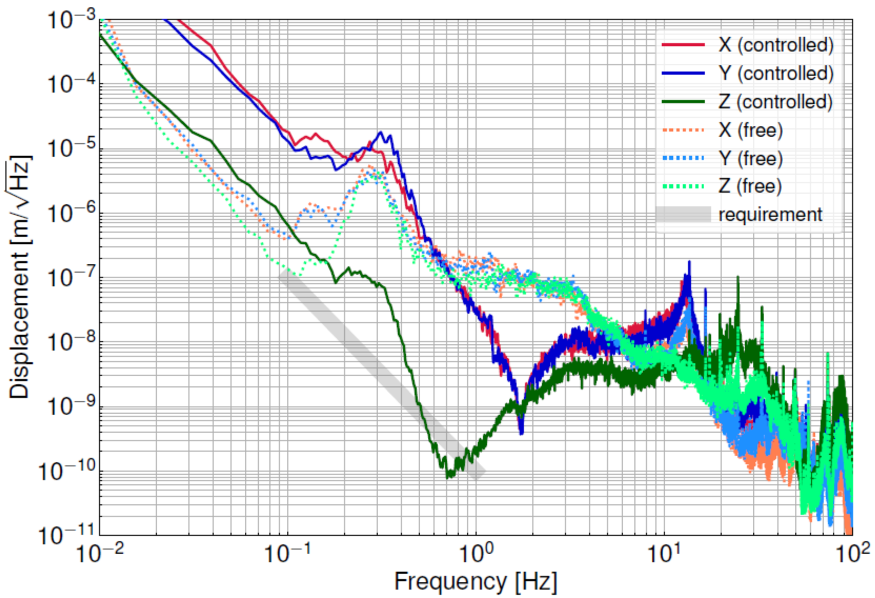


Photo by C. P. Ooi

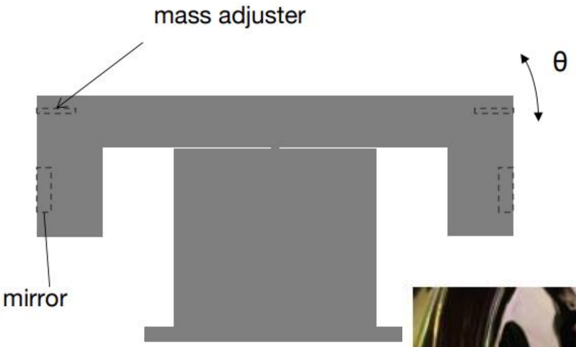
Status: active vibration isolation

by S. Takano and M. Cao

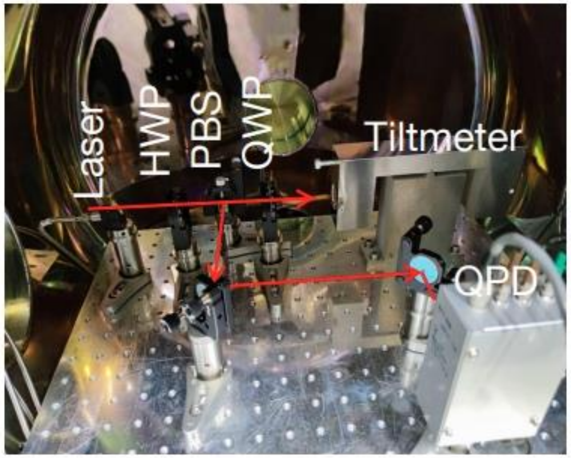
- 3 DoFs were controlled with geophones and piezo actuators
  - Vertical vibration suppressed by 10^{-3} at 0.7 Hz
  - Horizontal vibration suppressed by 3×10^{-2} at 1.7 Hz
- Developing a tiltmeter to reduce tilt-horizontal coupling



S. Takano+ (2024)



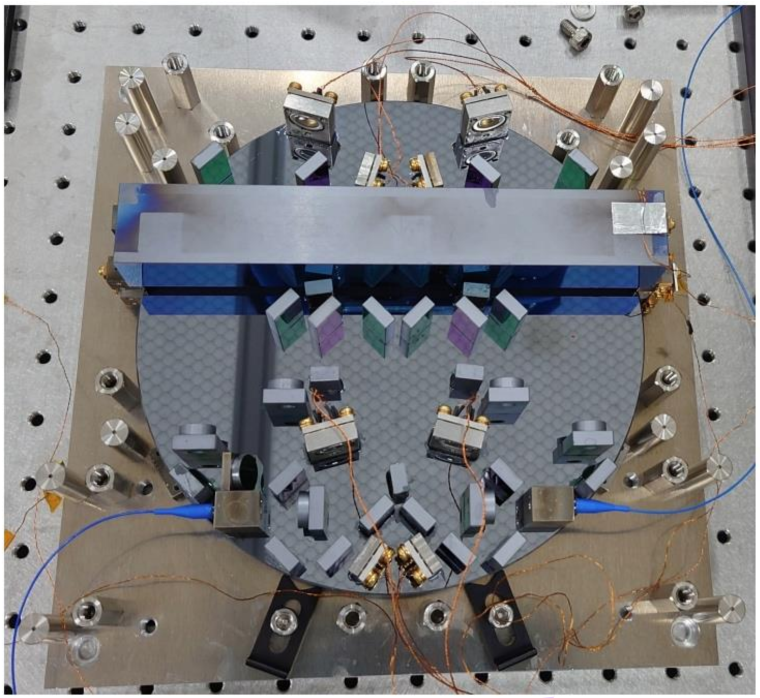
Figures by M. Cao

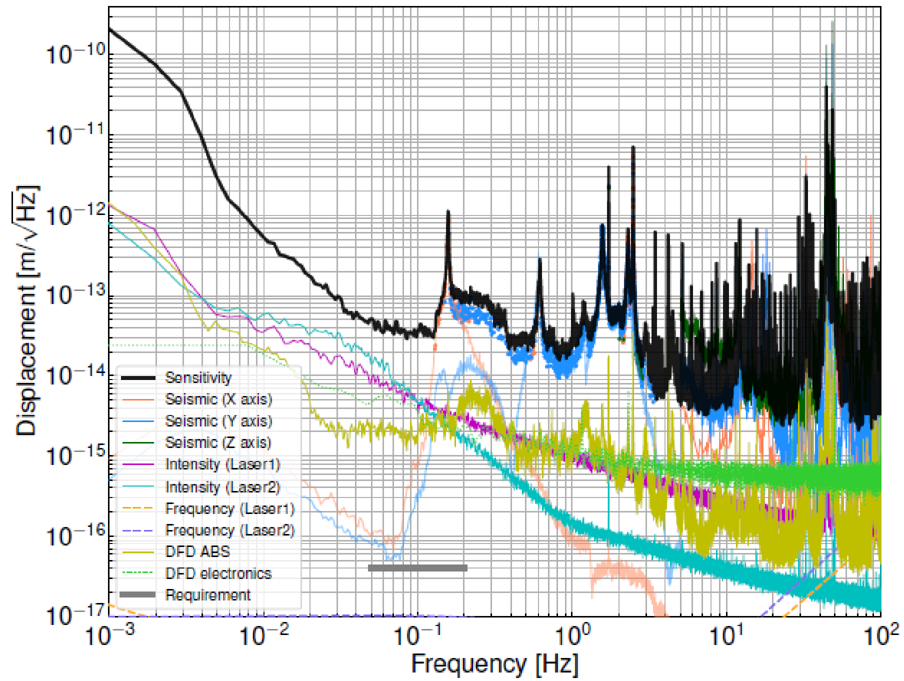


Status: cryogenic interferometer

by S. Takano

- Monolithic interferometer made of silicon was developed
  - Operated at 12 K more than one day
  - 4×10^{-14} m/√Hz at 0.1 Hz (comparable to LISA Pathfinder)





S. Takano+ (2024)
S. Takano, Ph.D. thesis (2024)

We'll show you on the lab tour
Satoru will introduce in today's final talk from AEI

Status: my work

- Goal : completion of optics and suspension system

Element development by previous researches

- Cryogenic torsion pendulum
- High-Q suspension wire
- Active vibration isolation
- Cryogenic interferometer

⇨

This study

Integration of optics and suspension (designed for cryogenic temp.)

⇨

Phase-III TOBA target sensitivity

- Silicon test mass
- Cooling
- Improvement of suspension wire
- Introduction of active vibration isolation

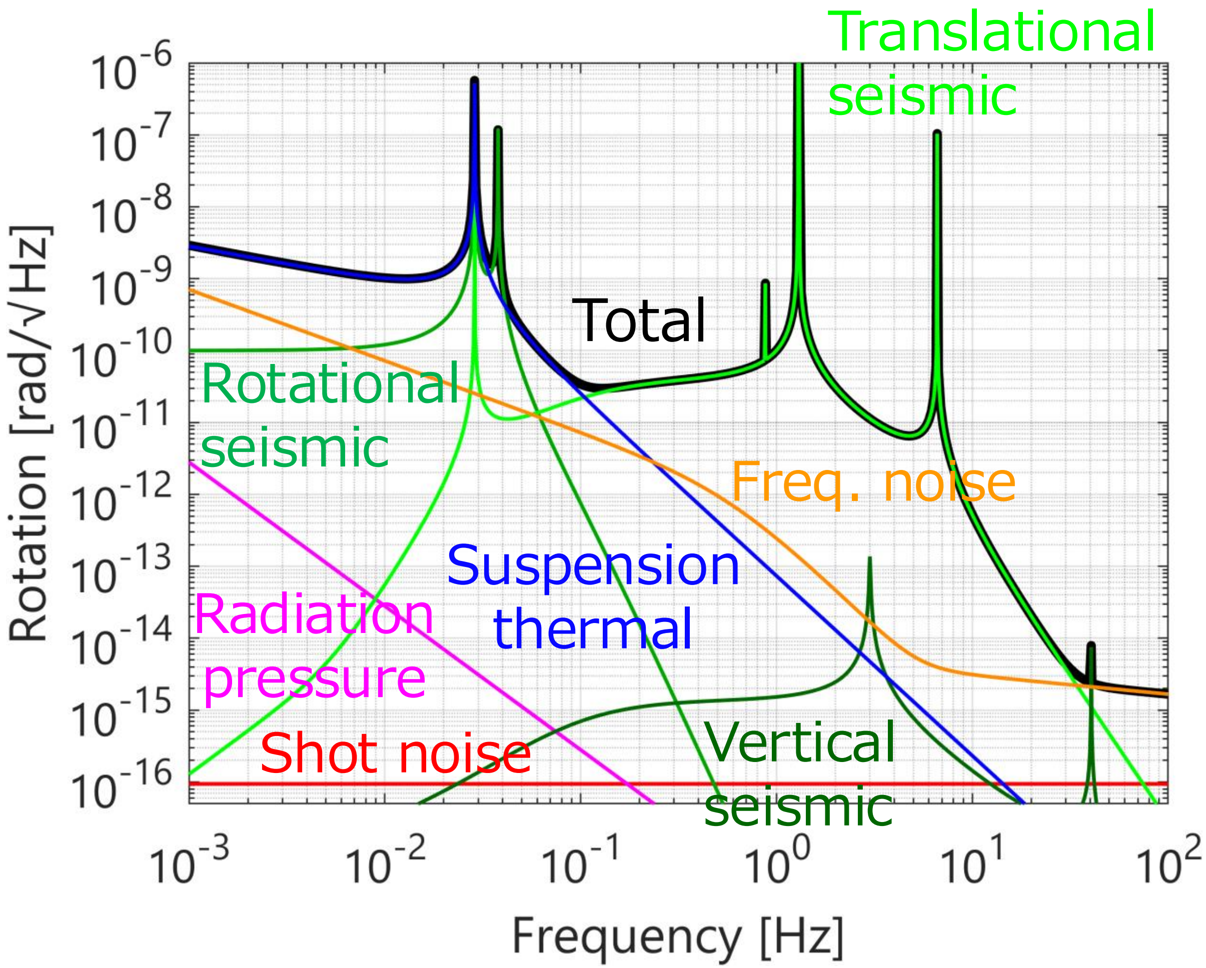
⇨

Final TOBA target sensitivity

Increase size

Design sensitivity of my work

- 3.4×10^{-11} rad/√Hz at 0.1 Hz



Optics

Wavelength	1550 nm
Power	1 mW
Finesse	300
Cavity length	23 mm
Distance btw two cavities	110 mm

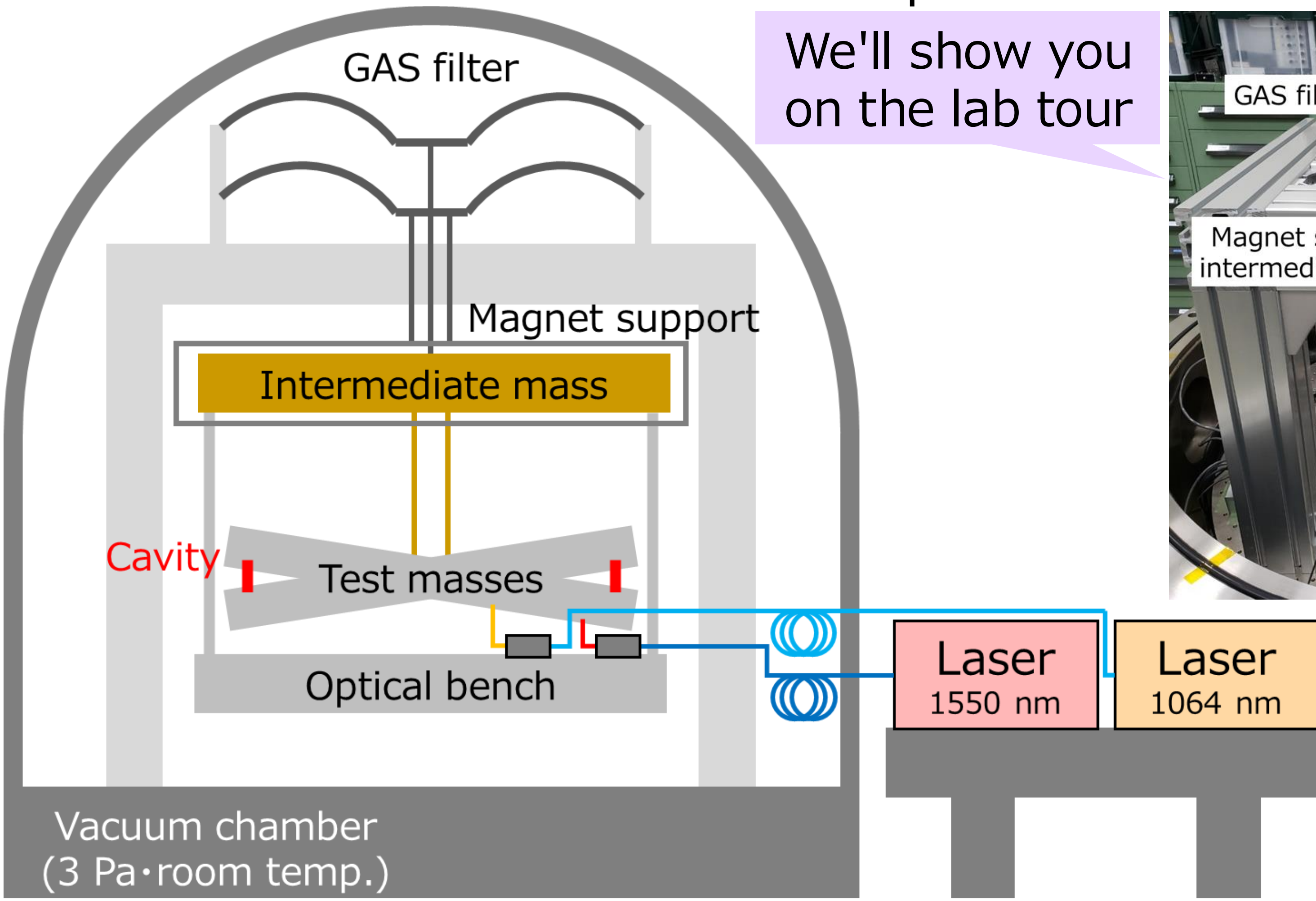
Suspension

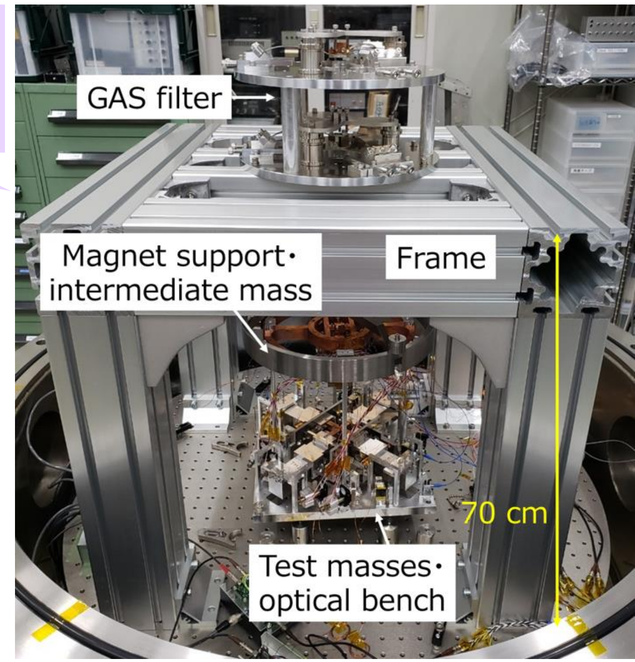
Moment of inertia	0.010 kg m^2
Torsional resonance	28.7 mHz
Q factor of wire	10^3
Tilt of bars	10^{-4} rad
CMRR	1/50
GAS resonance	3 Hz
Temperature	300 K

Entire experimental setup

- Suspension inside the vacuum chamber
- Laser source outside the chamber
- Laser is introduced into the optical bench via optical fiber

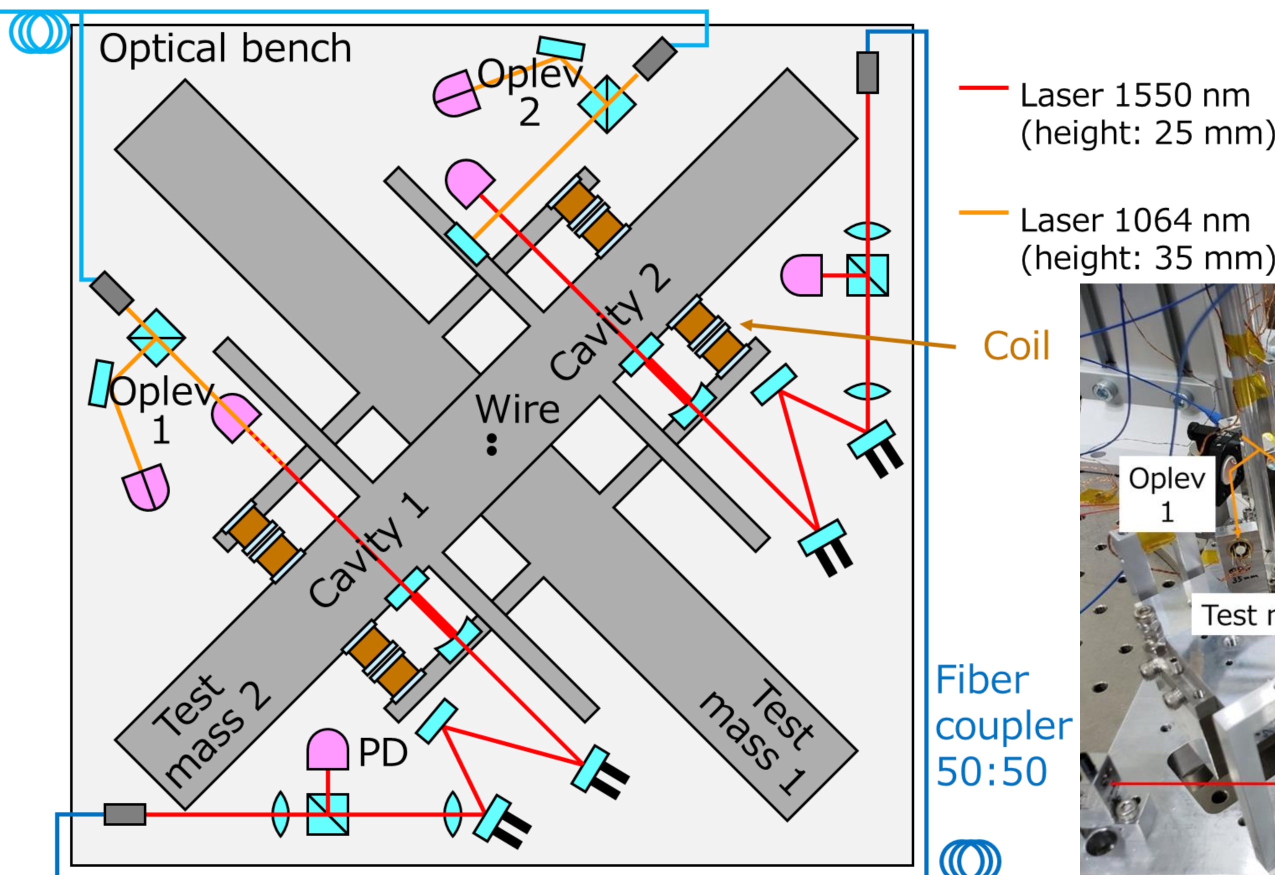
We'll show you on the lab tour

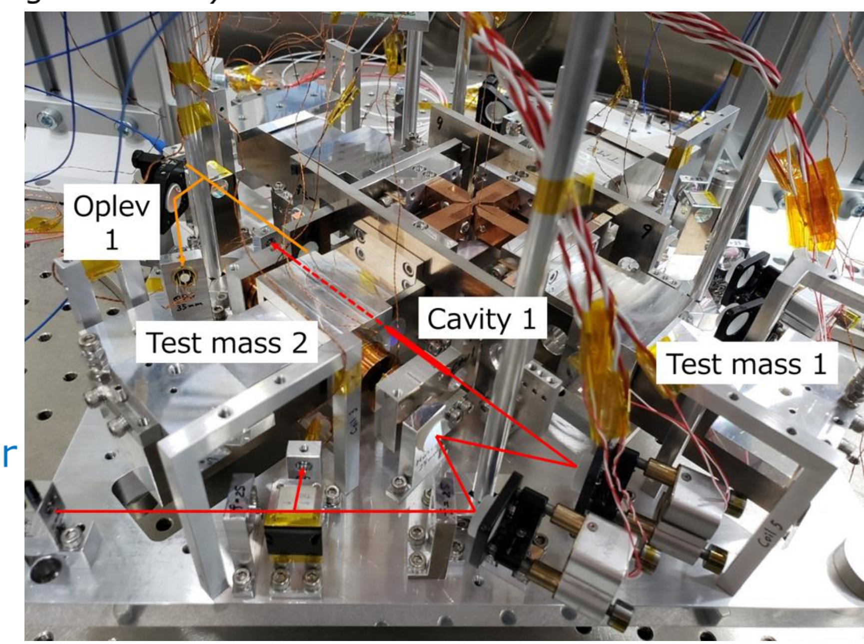




Design of optics

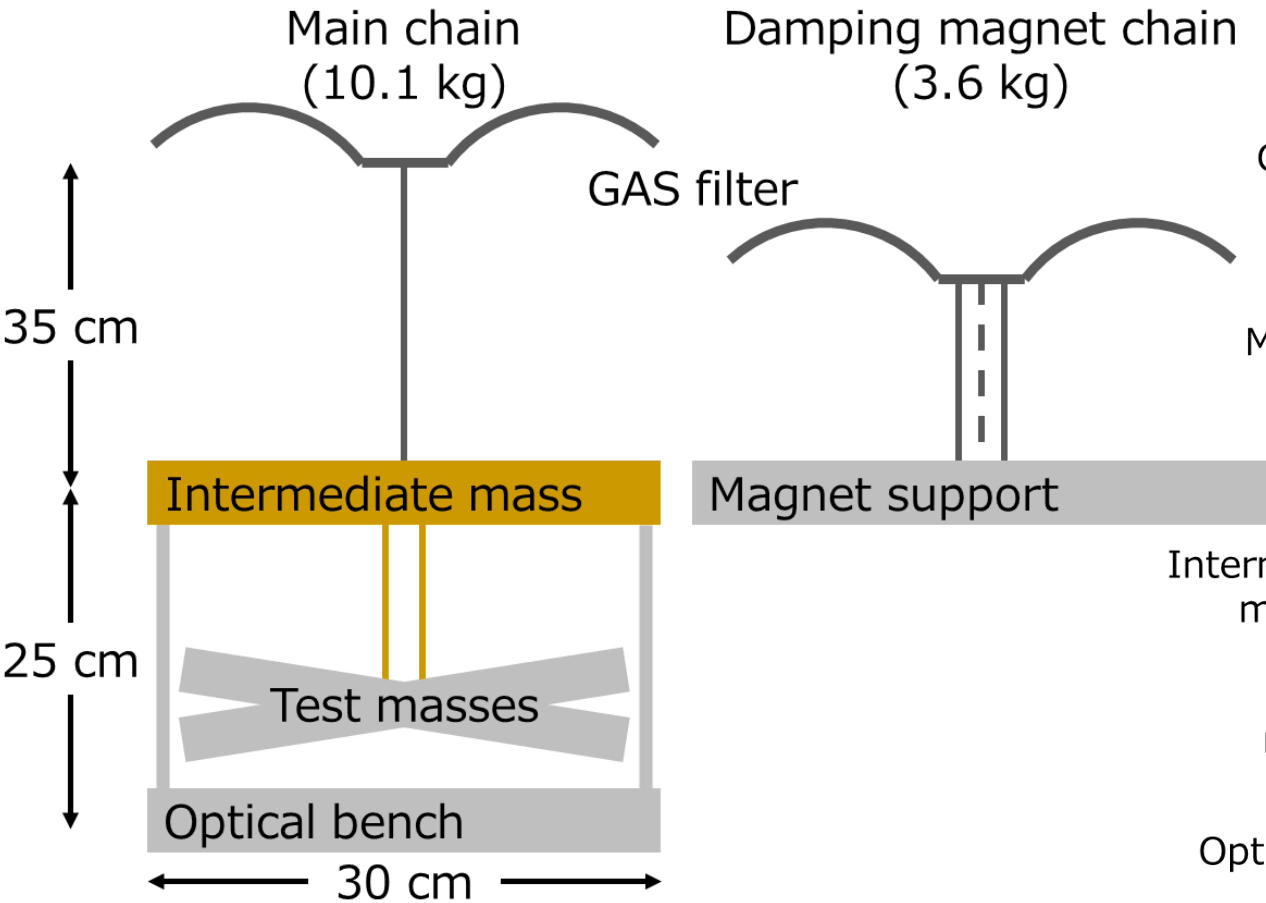
- Differential Fabry–Pérot cavities btw two test masses to detect torsional rotation as cavity length variation
- Feedback control by coil-coil actuator to lock the cavities
- Optical levers are installed as auxiliary sensors

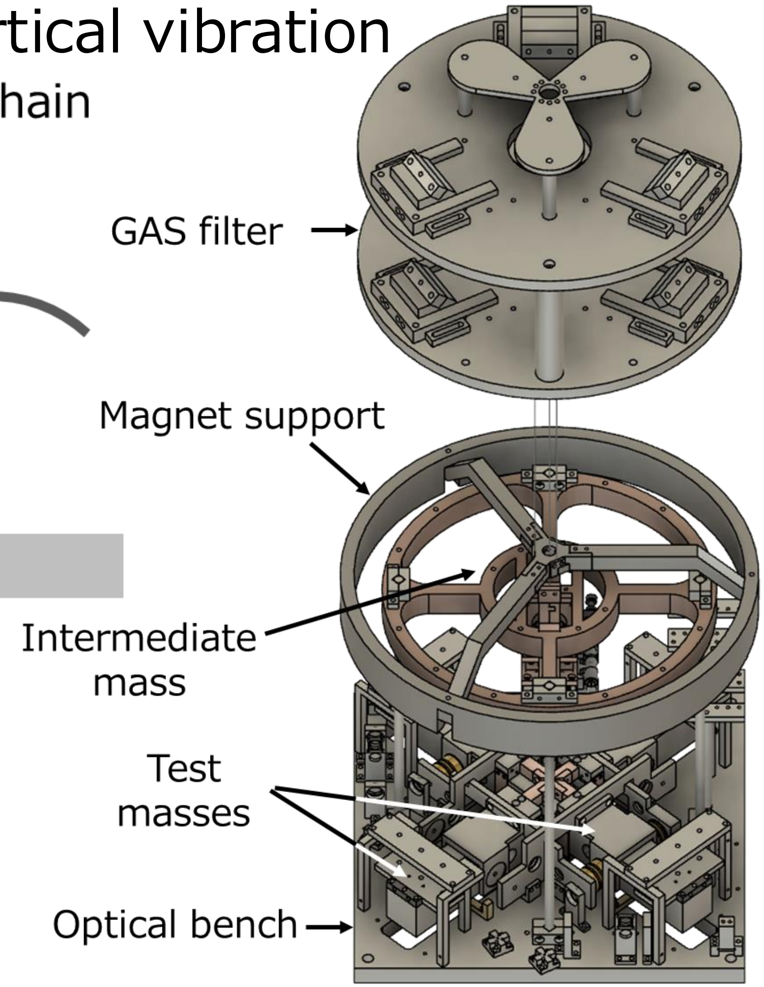




Design of suspension: overall

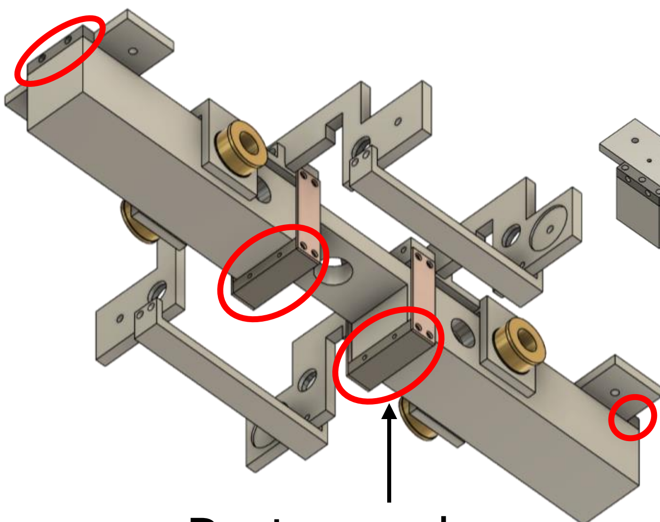
- Test masses and optical bench are suspended from the intermediate mass
- Damping magnet support is also suspended
- GAS filter is installed to reduce vertical vibration

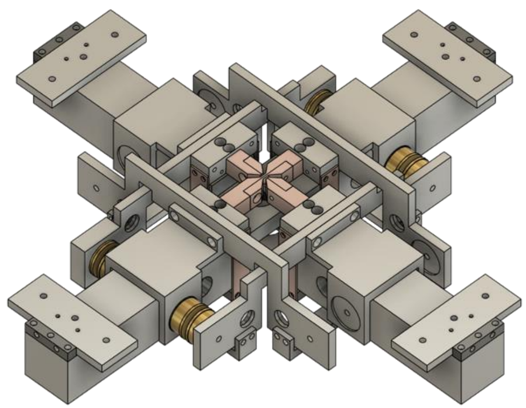


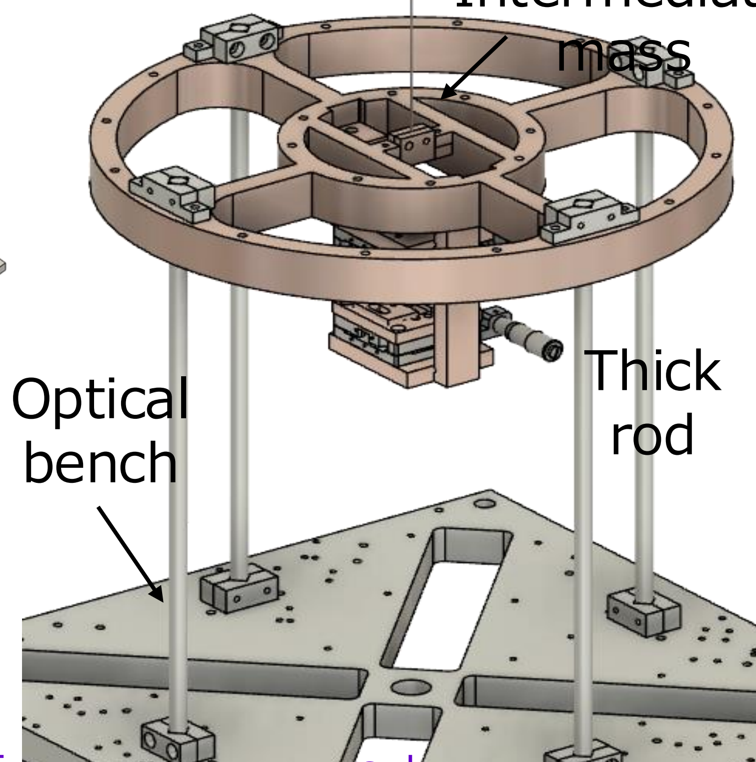


Design of suspension: detail

- Parts made of invar are glued to test masses without screwing to prevent silicon from cracking
- Aluminum was used instead of silicon in this work
  - Silicon: 2.33 g/cm^3, aluminum: 2.7 g/cm^3
- Optical bench was suspended from the same intermediate mass as the test masses to reduce vibration noise





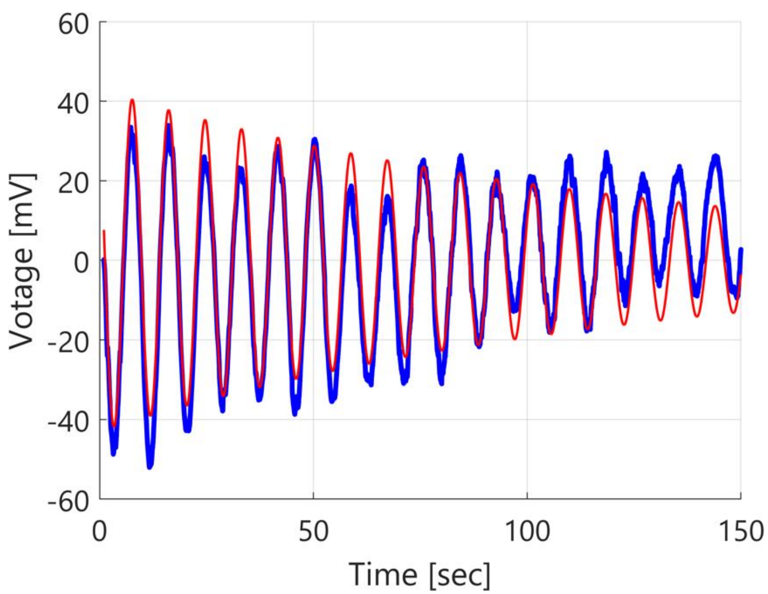


Summary of results

		Results of this work	Design of this work	Design of Phase-III TOBA
Optics	Optical lever	Detection	Auxiliary sensor	Auxiliary sensor
	Differential Fabry–Pérot cavities	Finesse ~300 First for TOBA Unlock	Finesse 400 Lock and detection	Lock and detection
Suspension	Test mass	Aluminum (for cryogenic temp.) First for TOBA		Silicon
	Torsional resonant freq.	117 mHz	28.7 mHz	7.7 mHz
	Q factor	~50	10^3	10^8
	Tilt of test mass	$\sim 2\times10^{-3}$ rad	10^{-4} rad	10^{-8} rad
	Resonant freq. of GAS filter	First for TOBA 3-4.5 Hz	3 Hz	3 Hz
Temperature		300 K	300 K	4 K
Sensitivity at 0.1 Hz		3×10^{-7} /√Hz	3×10^{-11} /√Hz	4×10^{-15} /√Hz

Result: resonant freq. and Q factor

- Measured after excitation of torsional modes by coil-coil actuators (ring-down method)
- Measured under atmospheric pressure and vacuum

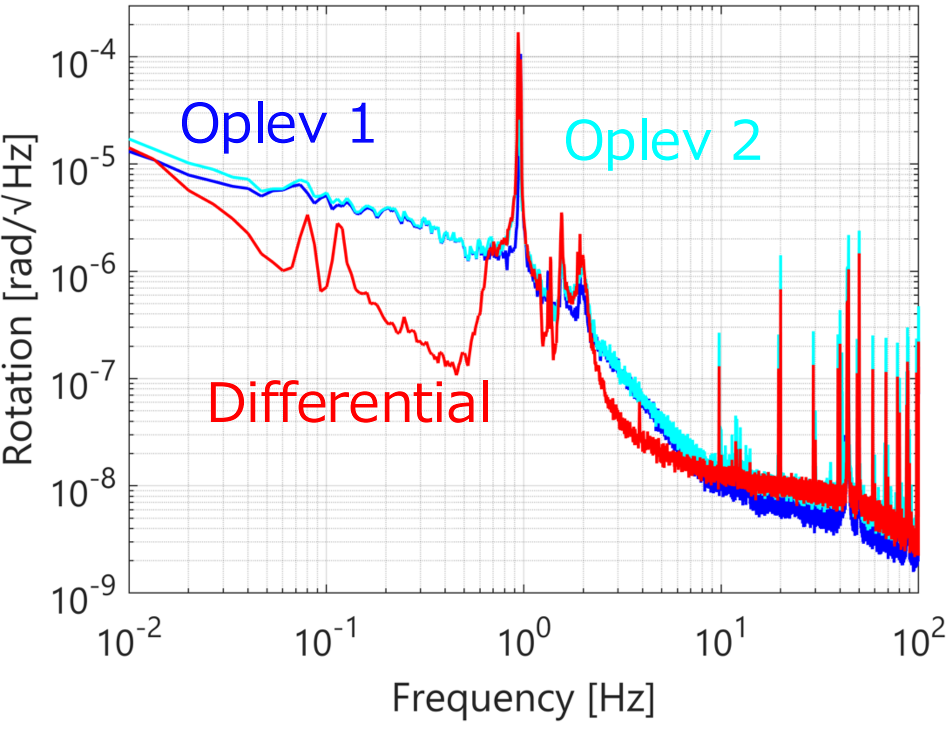


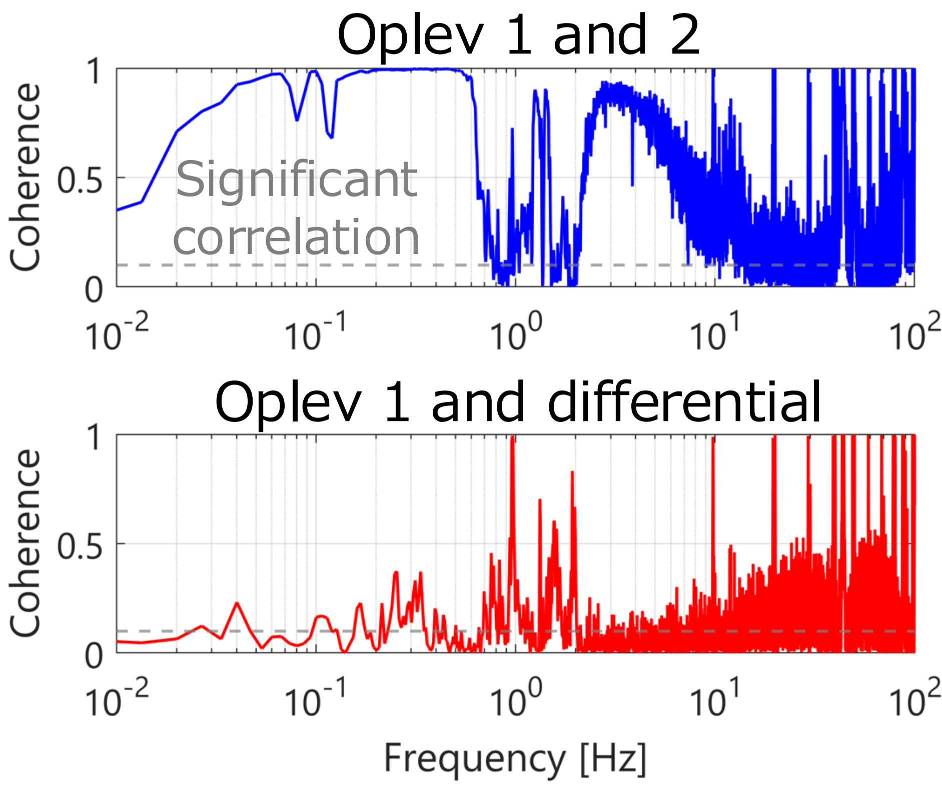
	Design	Test mass 1	Test mass 2
Torsional resonant freq. [mHz]	28.7	117.9±0.1 (10^5 Pa)	117.9±0.1 (10^5 Pa)
		117.1±0.1 (3.5 Pa)	117.3±0.1 (3.5 Pa)
Q factor	1000	55.2±0.4 (10^5 Pa)	39.8±0.2 (10^5 Pa)
		66.8±1.5 (3.5 Pa)	46.5±0.3 (3.5 Pa)

- Due to the increased restoring force by wires of coils
  → Use of thinner wire / non-contact current supply / cavity control without coil-coil actuators

Result: sensitivity of optical levers

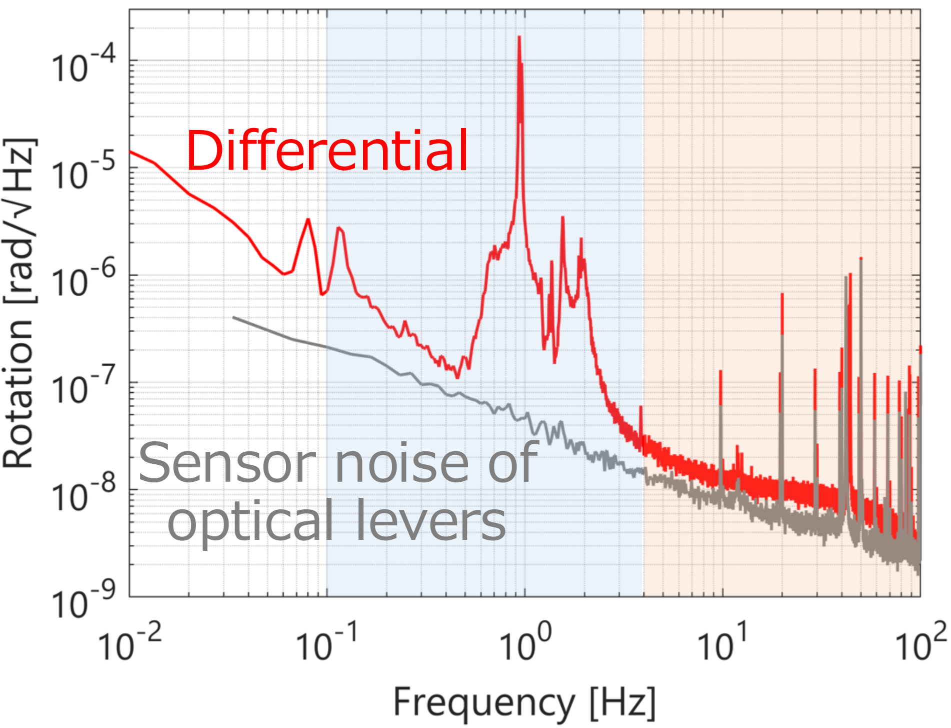
- Torsional rotation was measured with optical levers
- Common mode rejection between two test masses
- 1.1×10^{-7} rad/√Hz at 0.4 Hz

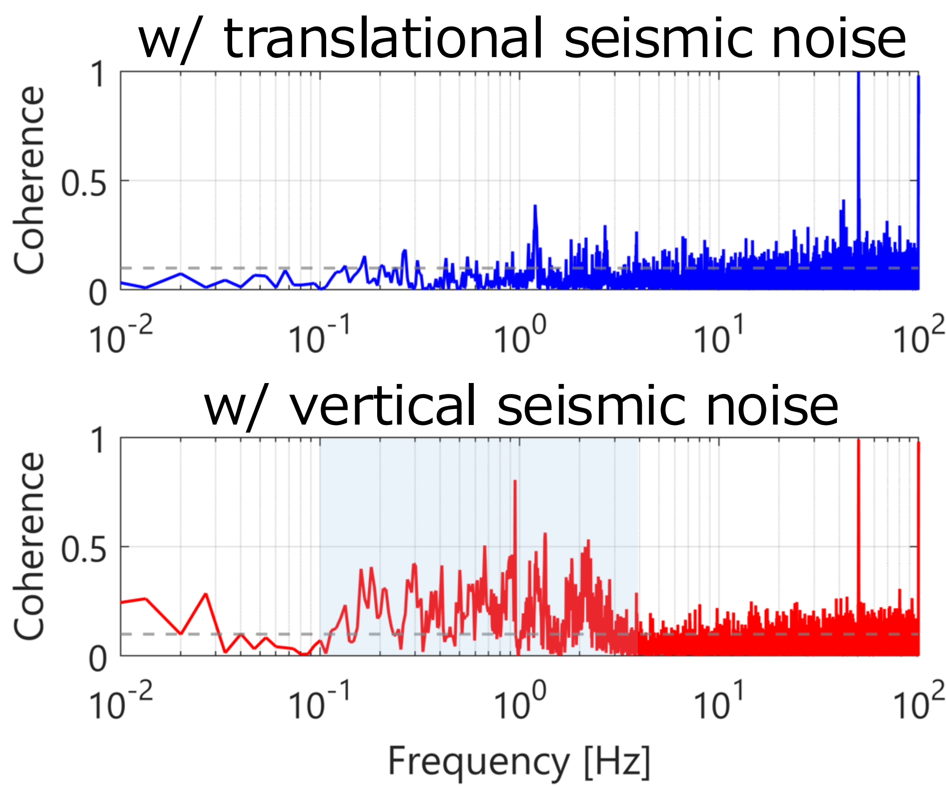




Discussion of noise sources

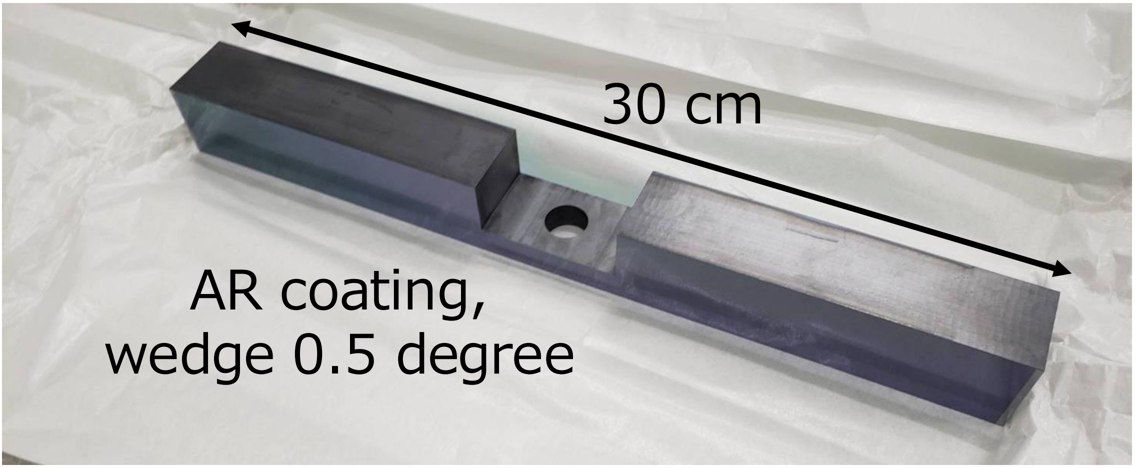
- Above 4 Hz, sensor noise is dominant
  → Sensitivity can be improved
  by replacing cavities for detection
- Significant correlation with vertical seismic noise in 0.1-4 Hz
  → Reduction of test mass tilt /
  lower resonant frequency of GAS filter

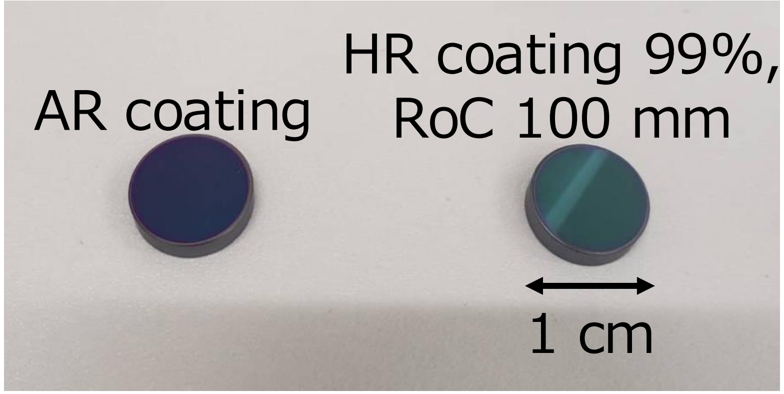




Future plans

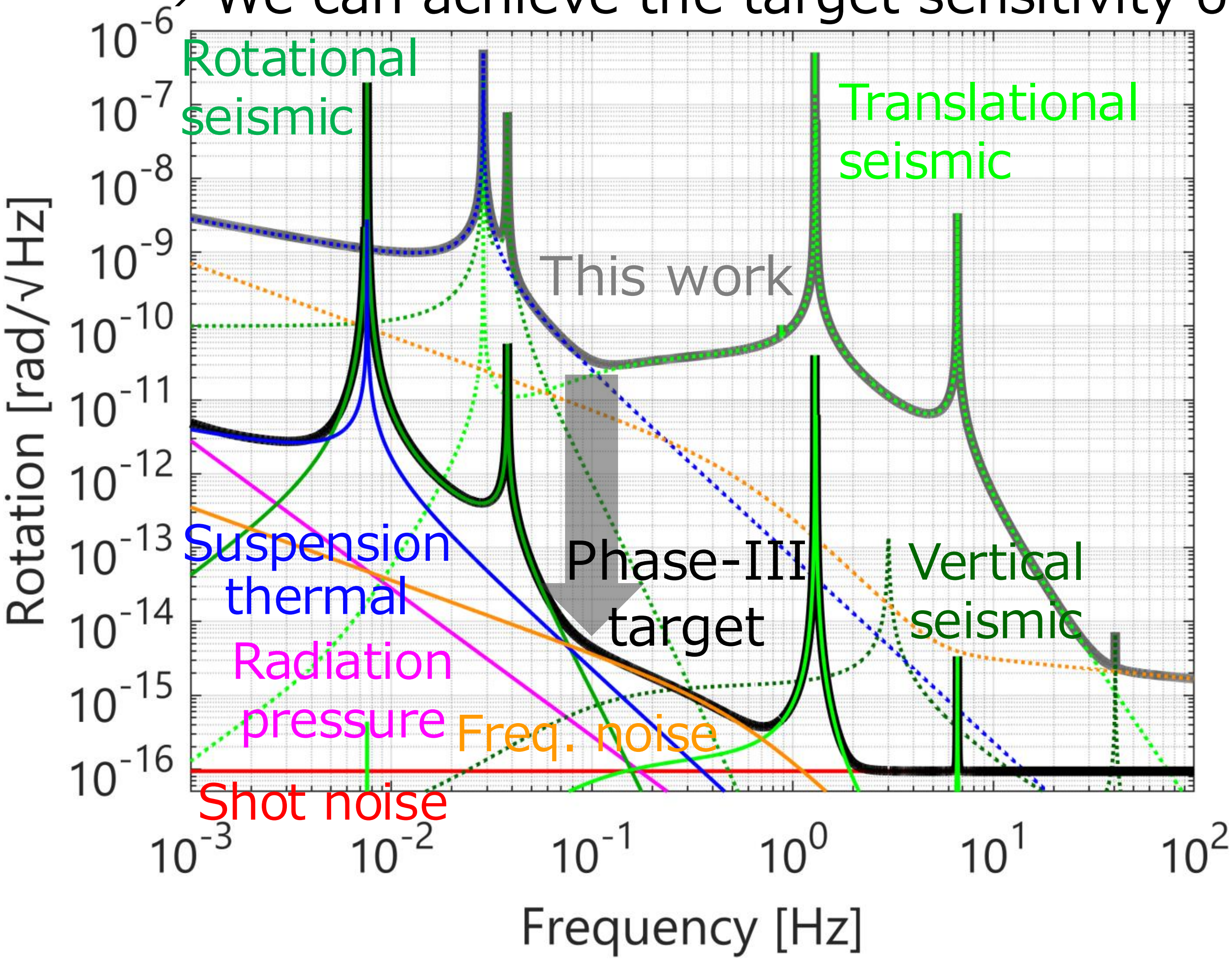
- Need to lock the cavities to measure torsional rotation
- We will replace test masses made of silicon and cool
  - Test masses with HR coating were already purchased
- I will graduate in March and Tatsuya takes over the exp.





Future plans

- Need to reduce suspension thermal noise, seismic noise, and laser freq. noise
  → We can achieve the target sensitivity of Phase-III TOBA

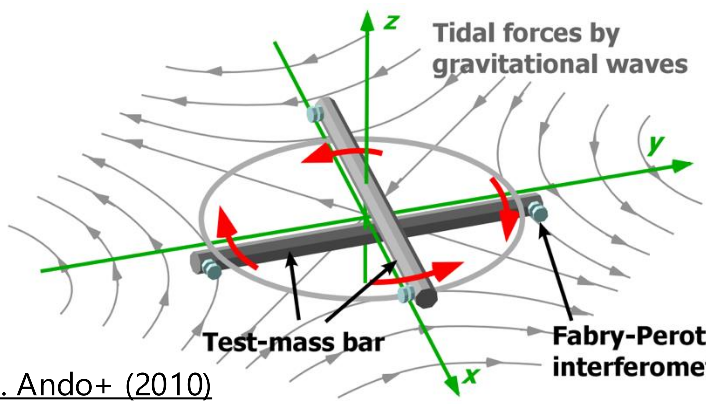


- Thermal noise
  - Temp.: 300 K → 4 K
  - Beryllium copper → silicon
  - Q factor: $10^3 \rightarrow 10^8$
- Seismic noise
  - Active isolation 1/100
  - Tilt of bars: 10^{-4} rad → 10^{-8} rad
- Freq. noise
  - Stabilization 1/1000

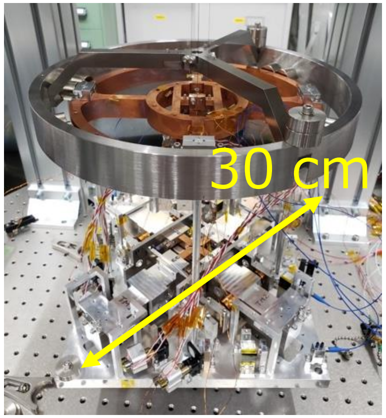
Summary

- TOBA is a GW detector for low freq. with torsion pendulums
- Phase-III TOBA with 30 cm scale bars is under development

- Element development for Phase-III TOBA
  - Cryogenic torsion pendulum
  - High-Q suspension wire at cryogenic temp.
  - Active vibration isolation
  - Cryogenic monolithic interferometer
- We are integrating optics and suspension
  to realize the target sensitivity of Phase-III TOBA



M. Ando+ (2010)



YO, PhD thesis (2024)