

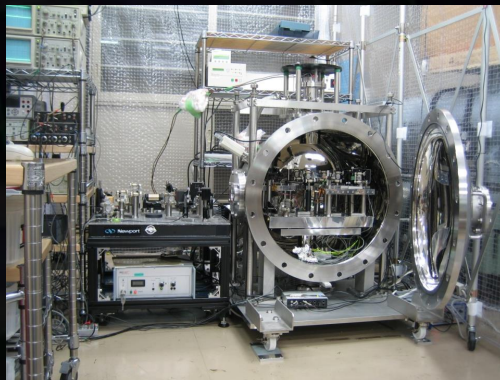
TOBA: a Low-frequency Gravitational-Wave Antenna

Masaki Ando (Univ. of Tokyo),

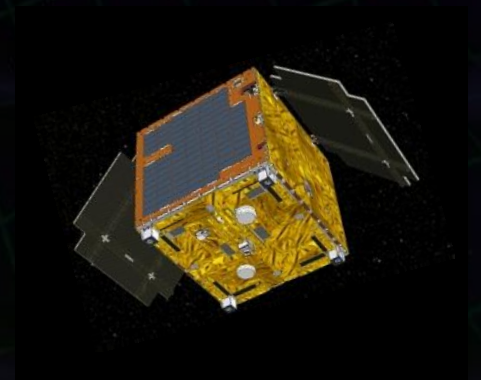
N. Aritomi, T. Shimoda, A. Shoda, Y. Kuwahara,
K. Yamamoto, Y. Aso, R. Takahashi, K. Eda, Y Itoh



Small-scale TOBA at Tokyo



Small-scale TOBA at Kyoto



SWIM on SDS-1 satellite

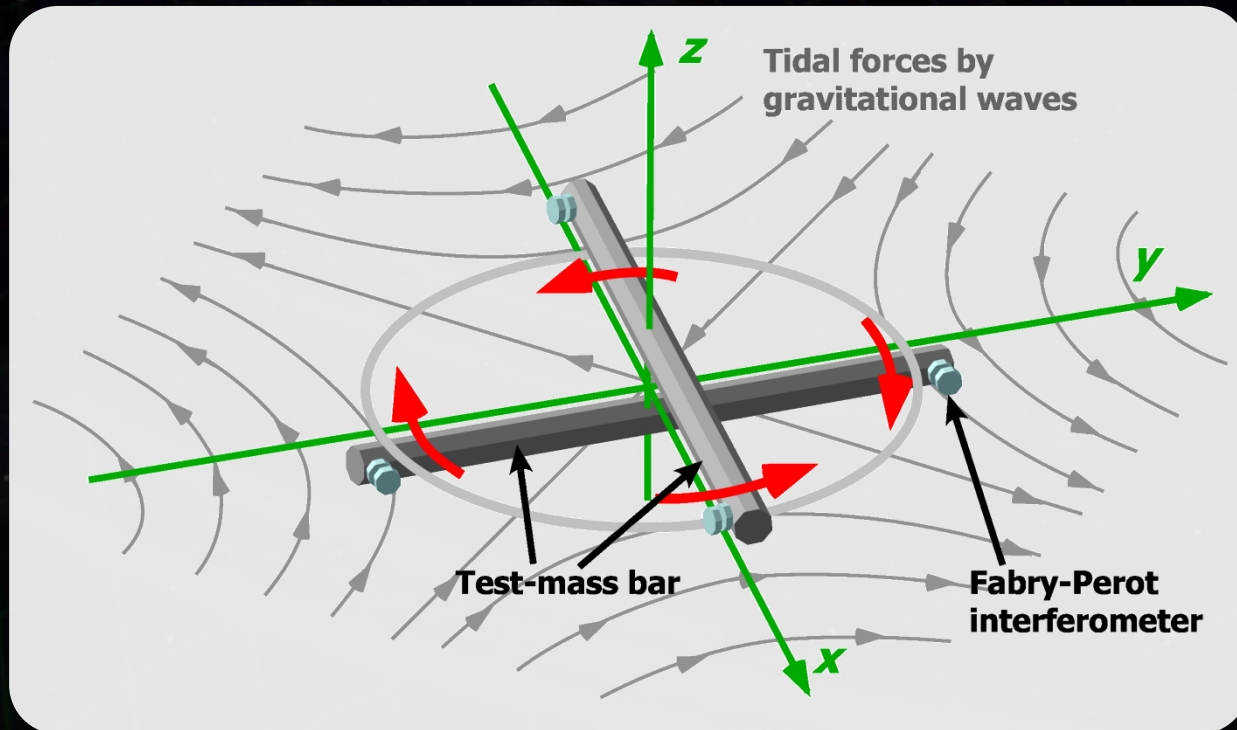
Background and Motivation

Torsion-Bar Antenna

TOBA: Torsion-Bar Antenna

Two bars suspended as torsion pendulum

⇒ Detect differential rotation by GW



M. Ando+, Phys. Rev. Lett. (2010)

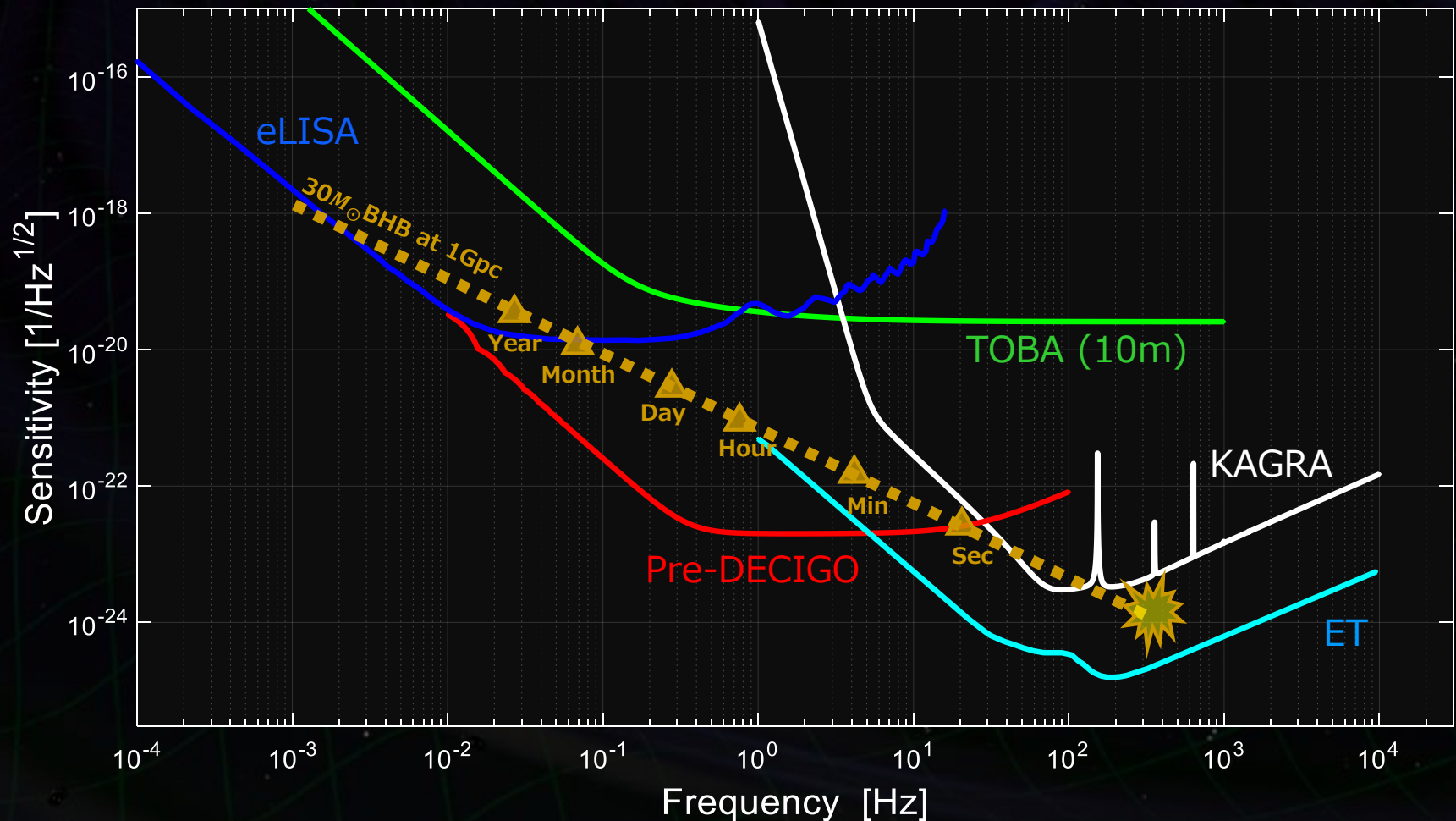
GW Science at Low Frequency

- Low-Freq. ($\sim 0.1\text{Hz}$) GW antennae will provide original sciences:
 - * Mass and orbital parameters of binaries,
 - * Intermediate-Mass Black Hole binaries,
 - * Stochastic background GW.



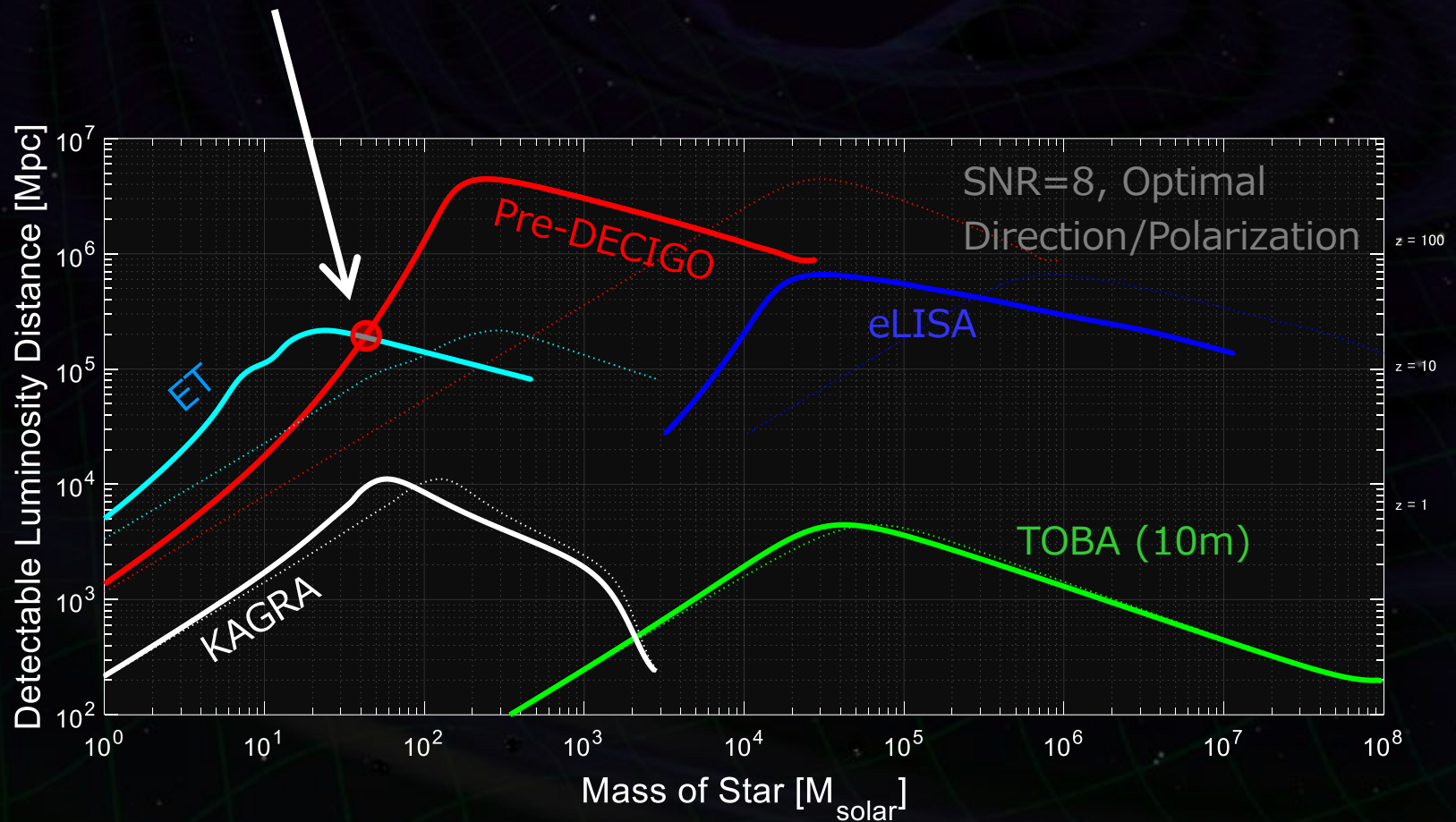
- Good sciences by ground-based antennae : $h < 10^{-19} \text{ Hz}^{-1/2}$.
- Fruitful sciences by space-borne antennae : $h < 10^{-23} \text{ Hz}^{-1/2}$.

Sensitivity Curves



Observable Range

$30M_{\odot}$ BBH Merger : 200 Gpc ($z > 10$) range.



- Low-freq. observation has significance much more than the 'detectable range'.
- With low-freq. GW telescopes, longer observation time is expected; in $30M_{\odot}$ BBH merger case, the signal is at 0.1Hz in **15days before merger**.
 - Improved parameter estimation accuracy with larger cycle number ($\sim 10^5$) :
 - * **Localization, Merger time** → Alerts for GW-EM.
 - * Mass, Distance, **Spin** → Origin and nature of BBH.

GW Science at Low Frequency

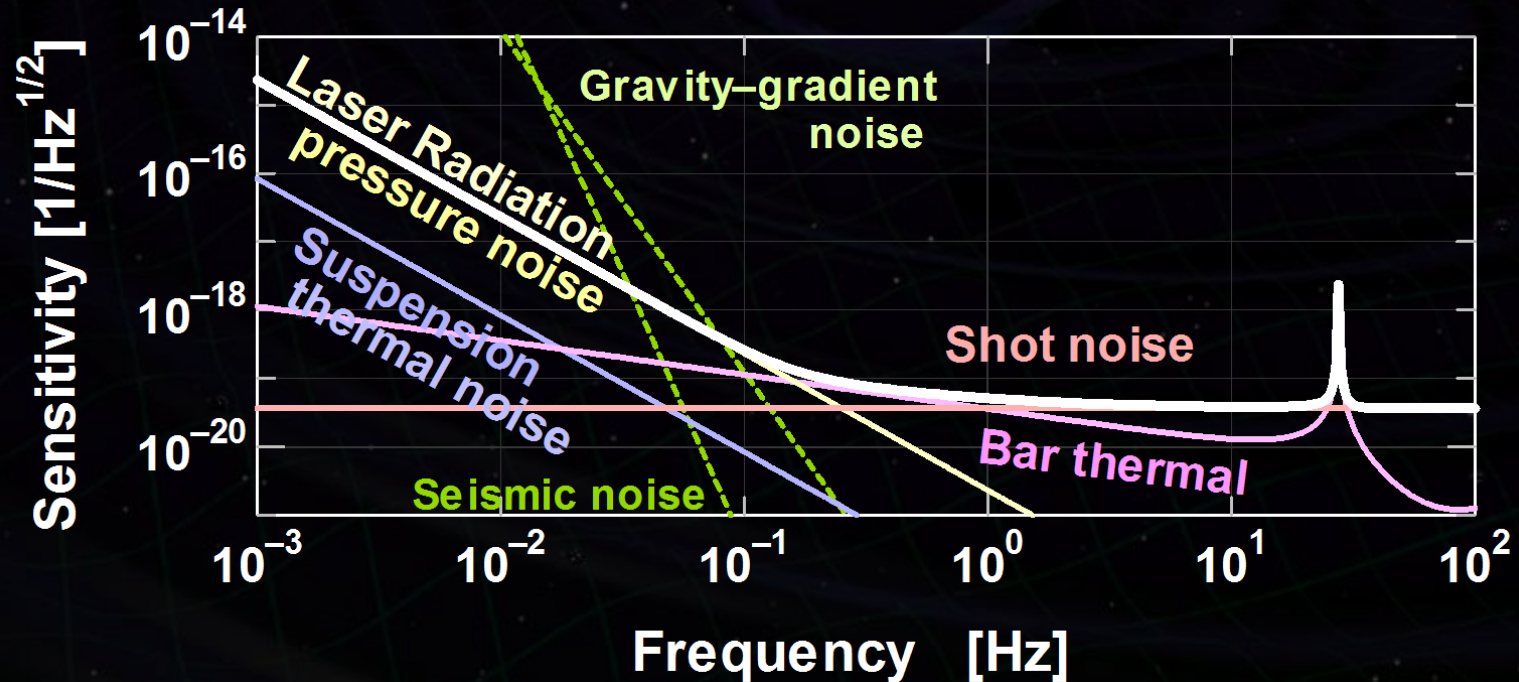
- Low-Freq. ($\sim 0.1\text{Hz}$) GW antennae will provide original sciences:
 - * Mass and orbital parameters of binaries,
 - * Intermediate-Mass Black Hole binaries,
 - * Stochastic background GW.



- Good sciences by ground-based antennae : $h < 10^{-19} \text{ Hz}^{-1/2}$.
- Fruitful sciences by space-borne antennae : $h < 10^{-23} \text{ Hz}^{-1/2}$.

Fundamental Noise Level of 10-m TOBA

Practical parameters $\Rightarrow \tilde{h} \simeq 3 \times 10^{-19} \text{ [Hz}^{-1/2}\text{]}$



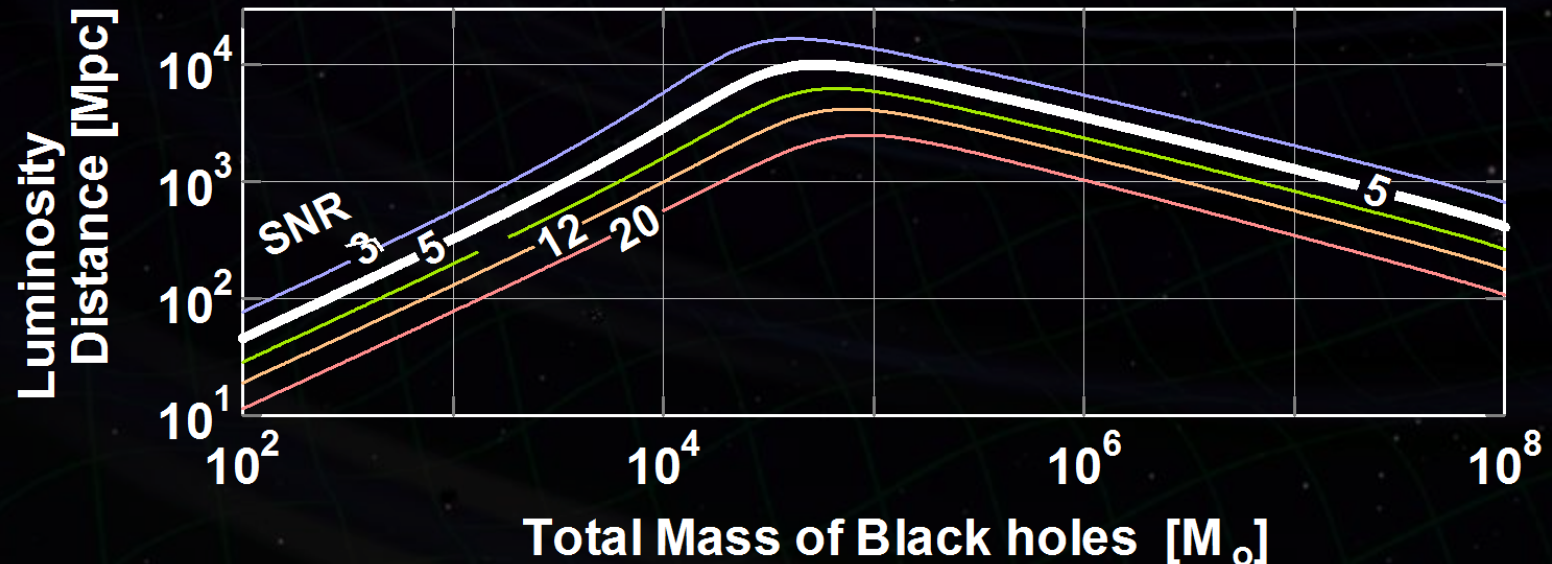
Bar length : 10m, Mass : 7600kg
Laser source : 1064nm, 10W
Cavity length : 1cm, Finesse : 100
Bar Q-value : 10⁵, Temp: 4K
Support Loss : 10⁻¹⁰

Laser Freq. noise < 10Hz/Hz^{1/2},
Freq. Noise CMRR > 100
Intensity noise < 10⁻⁷/Hz^{1/2},
Bar residual RMS motion < 10⁻¹² m

Observable Range

Inspiral range for BH-BH binaries

→ 10 Gpc ($\sim 10^5 M_{\odot}$, SNR = 5)



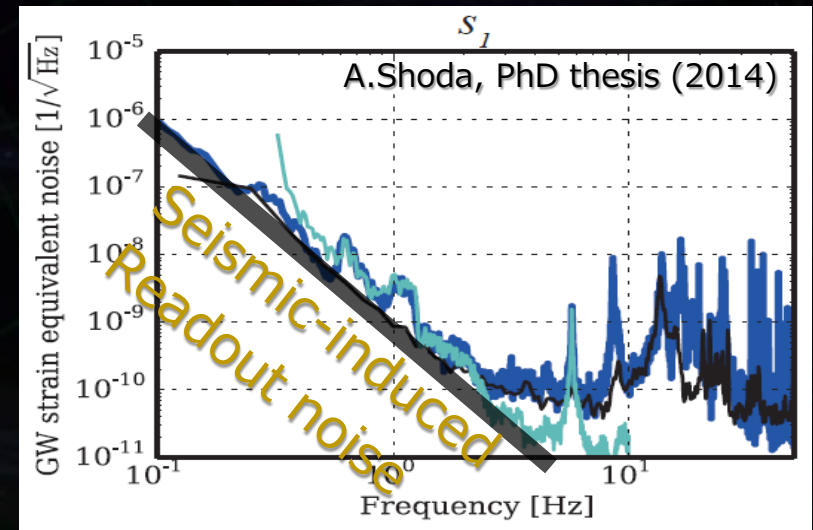
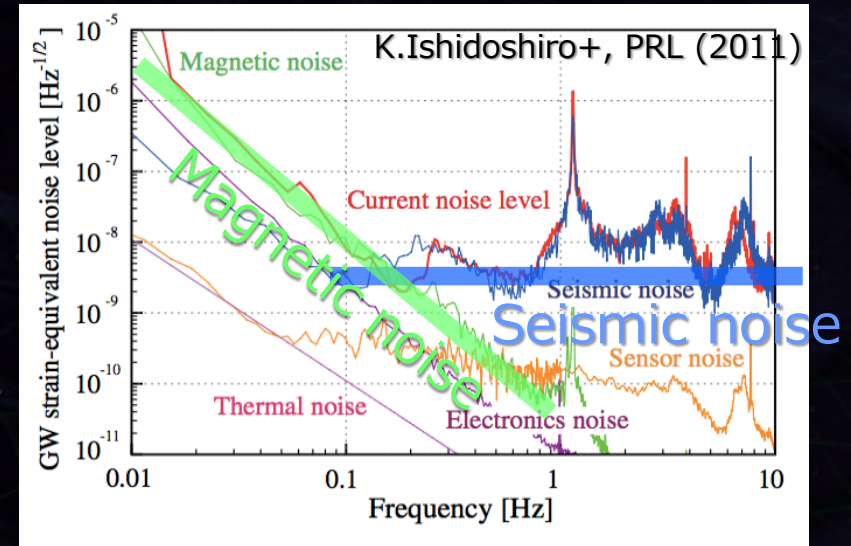
PRL105, 161101 (2010)

Prototype Developments

- **Phase-I (2005-2010, Ishidoshiro, Ando, ...)**
 - * Principle test and 0.1Hz GW observation
 - * 20cm mass, Room temp, Poor seismic isolation
 - * Two setups : Tokyo and Kyoto.
- **Phase-II (2011-2015, Shoda, Okada, ...)**
 - * Improved isolation design (Suspension + AVIT)
 - * Principle test of multiple output configuration
 - * Part of Cryogenics.
- **Space-borne TOBA (2005-2011. Kokuyama, ...)**
 - * Principle test and low-freq. GW observation.
 - * Free floating, 5cm mass, Room temp.

What We learned so far ...

- Phase-I TOBA:
 - Seismic coupling coupling from disp.
 - External magnetic fluctuation coupling
- Phase-II TOBA:
 - Seismic coupling coupling from disp.
 - Readout sensor noise



Phase-III TOBA

Possible Next Step

Strain sensitivity of $10^{-15} \text{ Hz}^{-1/2}$ at 0.1Hz.



Multiple scientific outcomes expected:

- * Observation of GWs,
- * Direct measurement of Gravity-gradient noises → Test bench for cancellation.
- * Earthquake early alert.
- * Tiny force measurements for Quantum noise, Space missions, Fund. physics,...

Conceptual Design of Phase-III TOBA

- Test Mass:

Copper (?), Length 30cm, Mass 7.6kg, Temp. 4K.

- Suspension:

Silicon, Resonant Freq. ~ 2 mHz,

Temp. 4K, Q-value $> 3 \times 10^7$

- Optical Readout :

$$\theta < 1 \times 10^{-15} \text{ rad/Hz}^{1/2}$$

Laser power > 0.1 W

- Seismic isolation :

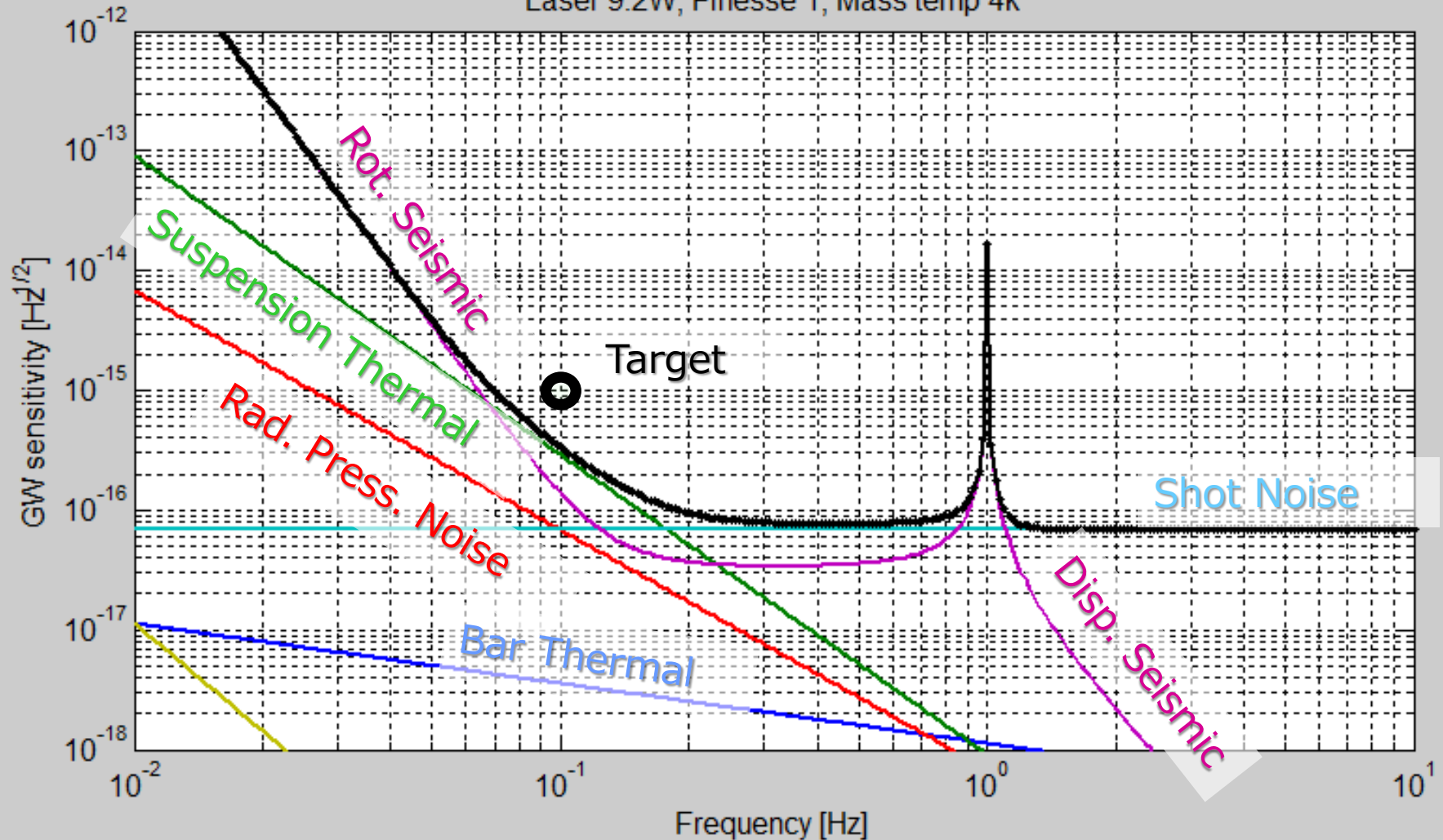
Active isolation

+ Passive suspension
(3 stages)

	@0.1 Hz	Rotation [rad/Hz ^{1/2}]	Displacement [m/Hz ^{1/2}]
Active Isolation		$< 3 \times 10^{-7}$	1×10^{-8}
Damping Mass		6.3×10^{-9}	1×10^{-8}
Upper mass		2.5×10^{-12}	1×10^{-8}
Test mass		1×10^{-15}	$< 1 \times 10^{-11}$

Sensitivity of 30cm Cryogenic TOBA

Length 0.3m, Radius 0.03m, Mass 7.6001kg, α 0.99626
Laser 9.2W, Finesse 1, Mass temp 4k



Phase-III TOBA Configuration

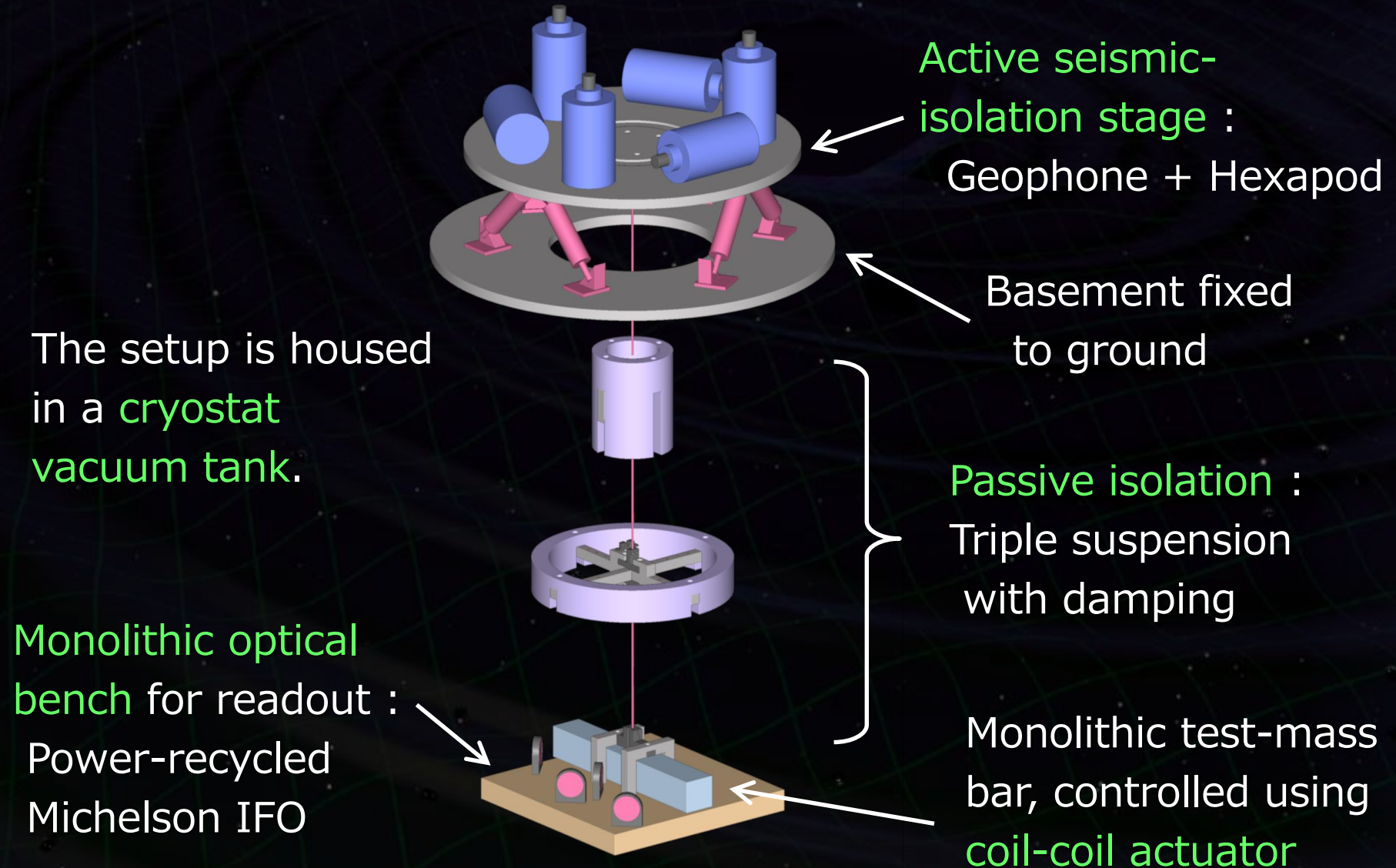


Figure: Tomofumi SHIMODA

Current Phase-III TOBA Setup

The setup is housed in a **cryostat vacuum tank**.

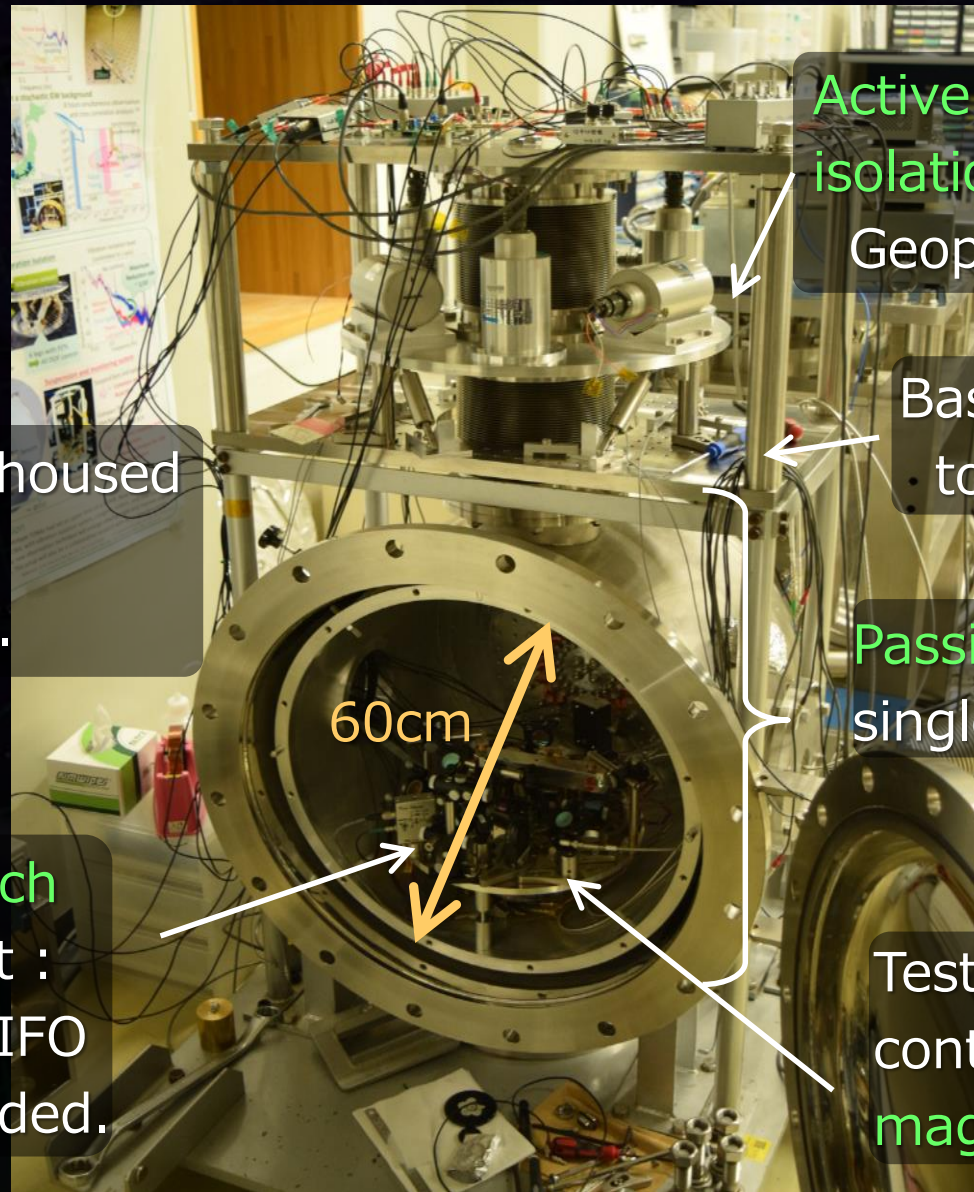
Active seismic-isolation stage :
Geophone + Hexapod

Basement fixed to ground

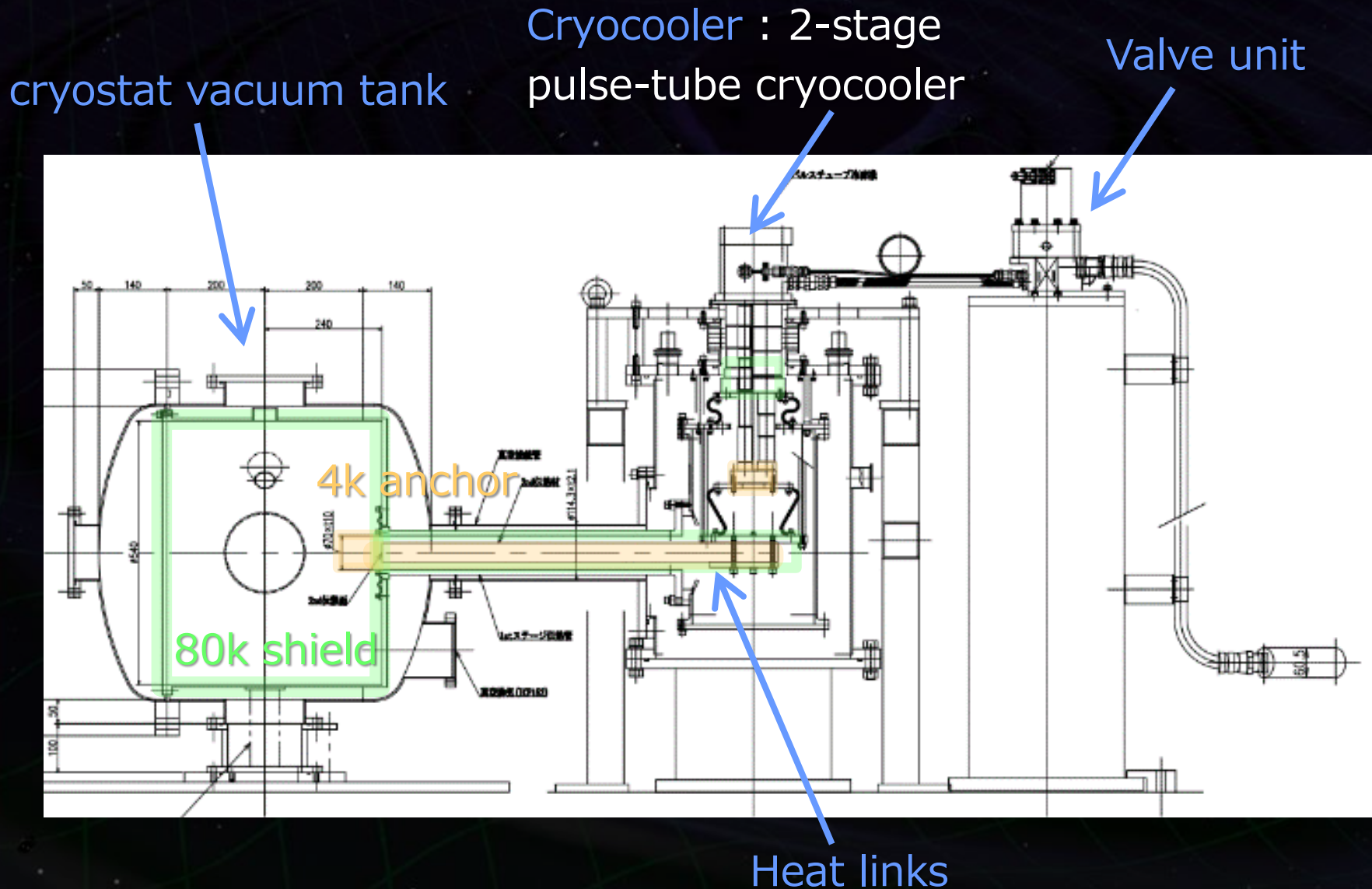
Passive isolation :
single suspension

Optical bench
for readout :
Michelson IFO
Not suspended.

Test-mass bar,
controlled using **coil-magnet actuator**



Cryostat and Cryo-cooler



Cryostat and Cryo-cooler

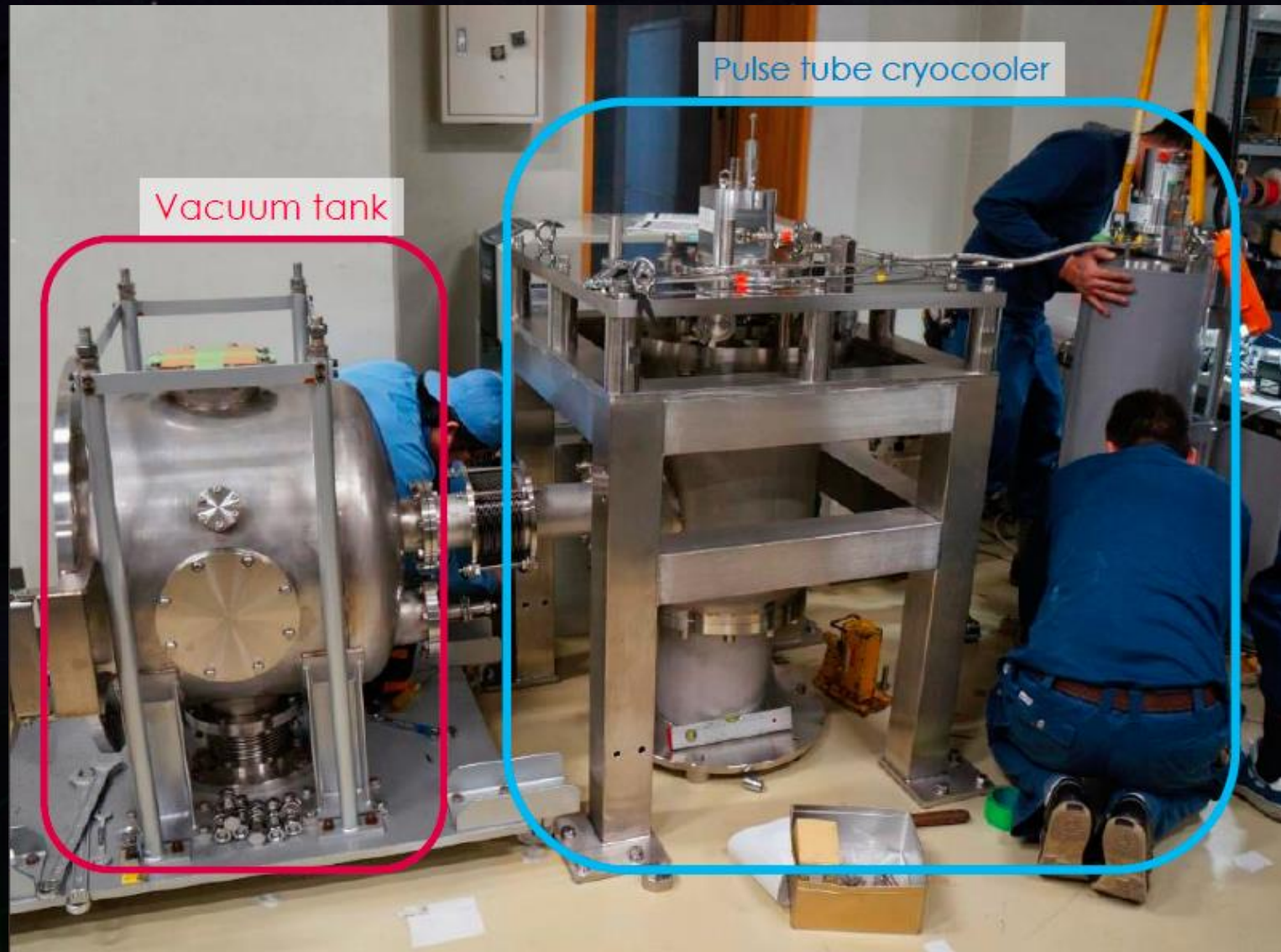


Figure: A. Shoda

Inside the Cryostat

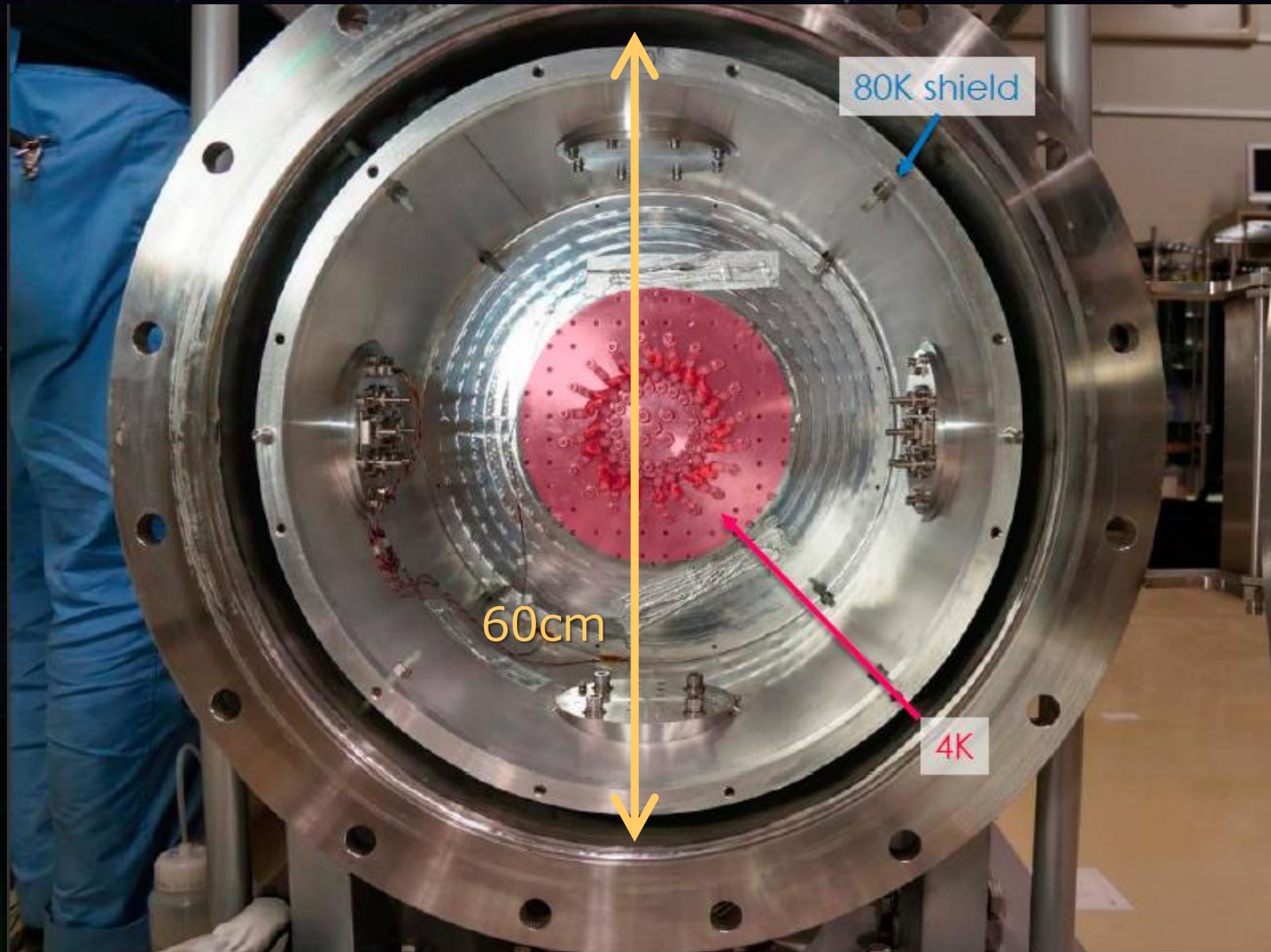


Figure: A. Shoda

Technical Challenges

- Suspension thermal noise:

$Q\text{-value} > 3 \times 10^7$, Temp. 4K .

- ⇒ • Seismic noise:

Rotational DoF, Coupling from displacement.

- ⇒ • Magnetic noise coupling:

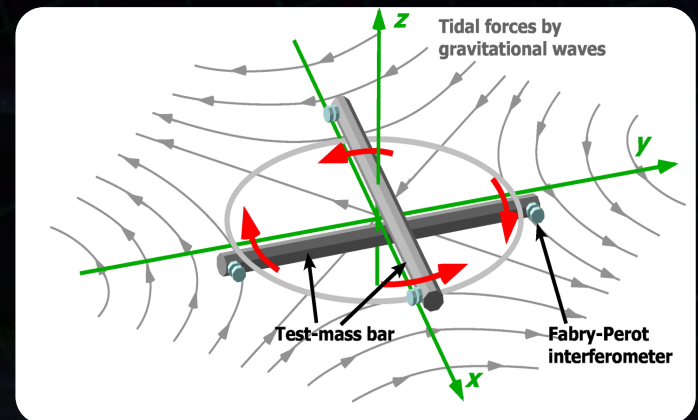
Torque by external magnetic fluctuations.

- ⇒ • Optical readout:

$\delta x < 1 \times 10^{-16} \text{ m/Hz}^{1/2}$

at 0.1Hz band.

- Cryogenic compatibilities.



Seismic Coupling Noise

- Tomofumi SHIMODA has made systematic survey of the **seismic coupling noises**, mitigation ideas, and quantitative estimation on the requirements.

Please take a look at his poster presentation.

Reduction of Seismic Coupling Noise for TOBA

GWADW2016
#11th, Italy

Tomofumi Shimoda, Naoki Arimoto, Yuji Kuwahara, Yuta Michimura, Ayaka Shoda*, Yoichi Aso*, Ryutaro Takahashi*, Kazuhiro Yamamoto*, Masaki Ando (University of Tokyo, National Astronomical Observatory of Japan, Institute for Cosmic Ray Research)

Abstract

TOBA (Torsion Bar Antenna) is a gravitational wave detector using a torsion pendulum. The resonant frequency of torsional motion is ~ 1 MHz, therefore it is sensitive to GWs at lower frequency band (0.1 – 10 Hz) and it will enable us to detect IMBH (intermediate mass black hole) binary mergers etc. Two prototypes were developed and they achieved $h \sim 10^{-8}$ / $\sqrt{\text{Hz}}$ @ 0.1 Hz $\sim 10^{-10}$ / $\sqrt{\text{Hz}}$ @ 5 Hz. One of the dominant noise sources was **seismic coupling noise**. We have to reduce this noise for the next step. Here we show the specified coupling routes and reduction methods for them.

TOBA

= "Torsion Bar Antenna" [1]

Horizontally suspended bar(s)
Rotation by tidal forces from GWs

• Low resonant frequency (~ 1 MHz)
 \Rightarrow sensitive to GWs at 0.1 – 10 Hz

final TOBA configuration

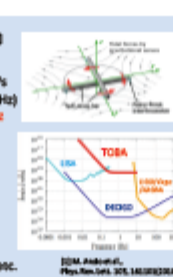
• 10m test mass

• 10W input power

• 4K cooling

$\Rightarrow h \sim 10^{-10}$ / $\sqrt{\text{Hz}}$ @ 5 Hz

• IMBH binary merger, stochastic GW background, etc.



Phase-I [2]

• magnetic levitation

• proof of principle

[2] K. Yamamoto et al., Phys. Rev. Lett. 106, 141101 (2011)

$h \sim 10^{-8}$ / $\sqrt{\text{Hz}}$ @ 0.1 Hz

Phase-II [3]

• wire suspension system

• active vibration isolation

[3] A. Shoda Ph.D thesis (2007)

$h \sim 10^{-10}$ / $\sqrt{\text{Hz}}$ @ 5 Hz

Phase-III

★ noise reduction demonstration

• Seismic noise (this topic)

• Sensor noise • Magnetic noise

• Thermal noise

target sensitivity

$h \sim 10^{-15}$ / $\sqrt{\text{Hz}}$ @ 0.1 Hz

step to final TOBA

✓ GW observation

✓ measure Newtonian noise

✓ apply to other small-force measurement experiments

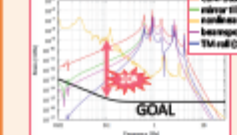
Seismic noise reduction

= rotational seismic motion

+ coupling from translational seismic motion via 5 routes

\Rightarrow adjustment is necessary for each route

without any adjustment...



coupling from seismic X

Mirror tilt (TM) tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

TM tilt (RoI)

dominant!

Active vibration isolation table (gyroscopes + bearings)

rotation on horizontal axis \Rightarrow 1st component

rotation on vertical axis \Rightarrow 2nd component

rotation on horizontal axis \Rightarrow 3rd component

rotation on vertical axis \Rightarrow 4th component

rotation on horizontal axis \Rightarrow 5th component

rotation on vertical axis \Rightarrow 6th component

rotation on horizontal axis \Rightarrow 7th component

rotation on vertical axis \Rightarrow 8th component

rotation on horizontal axis \Rightarrow 9th component

rotation on vertical axis \Rightarrow 10th component

rotation on horizontal axis \Rightarrow 11th component

rotation on vertical axis \Rightarrow 12th component

rotation on horizontal axis \Rightarrow 13th component

rotation on vertical axis \Rightarrow 14th component

rotation on horizontal axis \Rightarrow 15th component

rotation on vertical axis \Rightarrow 16th component

rotation on horizontal axis \Rightarrow 17th component

rotation on vertical axis \Rightarrow 18th component

rotation on horizontal axis \Rightarrow 19th component

rotation on vertical axis \Rightarrow 20th component

rotation on horizontal axis \Rightarrow 21st component

rotation on vertical axis \Rightarrow 22nd component

rotation on horizontal axis \Rightarrow 23rd component

rotation on vertical axis \Rightarrow 24th component

coupling from seismic Y

Center of Mass – Suspension Point offset

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 1st torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 2nd component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 3rd torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 4th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 5th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 6th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 7th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 8th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 9th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 10th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 11th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 12th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 13th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 14th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 15th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 16th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 17th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 18th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 19th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 20th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 21th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 22th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 23th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 24th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 25th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 26th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 27th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 28th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 29th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 30th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 31th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 32th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 33th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 34th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 35th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 36th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 37th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 38th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 39th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 40th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 41th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 42th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 43th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 44th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 45th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 46th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 47th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 48th component

adjust CM offset by counterweight

$\Delta x < 10$ mm

\Rightarrow reduce 49th torque

adjust TM tilt by actuation

$\Delta \theta < 10$ mrad

\Rightarrow reduce 50th component

adjust CM offset by counterweight

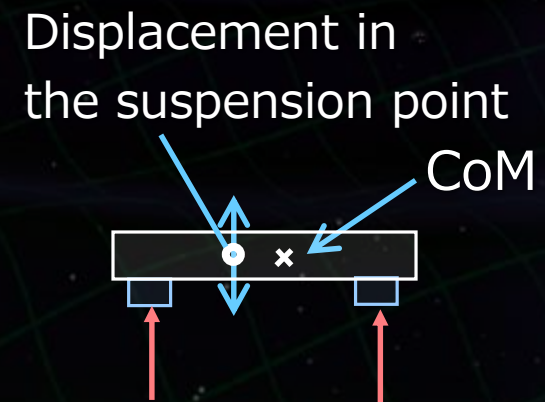
$\Delta x < 10$ mm

\Rightarrow reduce 51th torque

Displacement-to-Rotation Coupling

One example: Displacement seismic noise coupling to rotation caused by the **mismatch between the suspension point and CoM** of the test mass.

- Required Accuracy : $\Delta x < 10\text{nm}$
(Adjustment of 100mg mass position sub-mm accuracy)
- Possible to be adjusted by intentional small tilt of the mass.



Magnetic Noise Coupling

- Naoki Aritomi is developing a new-type of actuator, so as to abandon permanent magnet from the test mass. → **Inductive actuator with coils.**
- Please take a look at his poster presentation.

Gravitational Wave Advanced Detector Workshop 2016 (Elba, May 24, 2016)

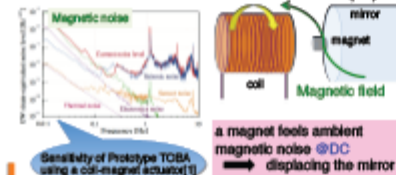
Coil-Coil Actuator for reduction of magnetic noise

N. Aritomi¹, T. Shimoda¹, K. Komori¹, Y. Kuwahara¹, Y. Michimaru¹, A. Shoda², Y. Asa³, R. Takahashi³, K. Yamamoto³, M. Ando³
¹Department of Physics, University of Tokyo ²National Astronomical Observatory of Japan ³Institute of Cosmic Ray Research, University of Tokyo
 Email: aritomi@particle.phys.u-tokyo.ac.jp

Abstract:
 For reduction of magnetic noise of coil-magnet actuators, we developed a new type of actuator: **coil-coil actuator**. It consists of only coils instead of magnet and current applied to the coils is modulated. We can choose any modulation frequency to reduce ambient magnetic noise coupling, while keeping actuation force sufficiently strong. In this poster, we show our experimental results for evaluation and reduction of the magnetic noise of a coil-coil actuator.

1. Motivation

- coil-magnet actuator is affected by ambient magnetic noise



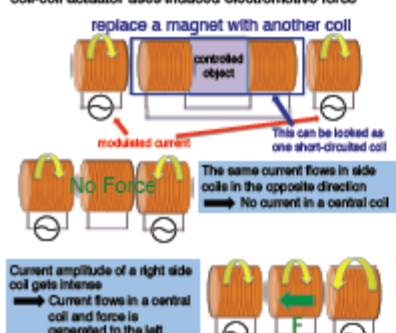
a magnet feels ambient magnetic noise @DC
 → displacing the mirror

We developed a new type of actuator consisting of only coils: **Coil-Coil Actuator**

2. Principle

- coil-coil actuator uses induced electromotive force

replace a magnet with another coil



This can be looked as one short-circuited coil

The same current flows in side coils in the opposite direction
 → No current in a central coil

Current amplitude of a right side coil gets intense
 → Current flows in a central coil and force is generated to the left

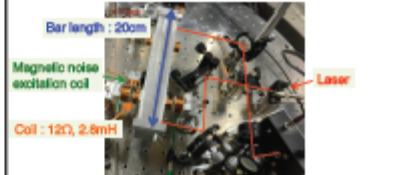
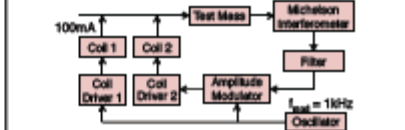
✓ Actuation force is proportional to a difference square of amplitude of current in two coils $F \propto i_1^2 - i_2^2$

- ambient magnetic noise @ modulation frequency couples
 → we can choose any modulation frequency to reduce ambient magnetic noise coupling!

3. Experimental Setup

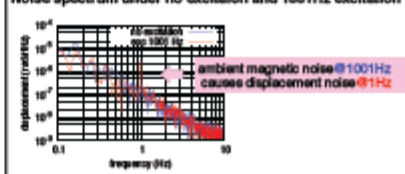
- control a torsion pendulum by using a **coil-coil actuator**
- actuator force 2×10^{-8} N/A

Bar length: 20cm
 Magnetic noise excitation coil
 Coil: 12Q, 2.9mH

4. Result

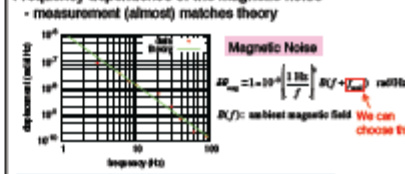
Noise spectrum under no excitation and 1001Hz excitation



ambient magnetic noise @1001Hz causes displacement noise @1Hz

Frequency dependence of the magnetic noise

- measurement (almost) matches theory



Magnetic Noise
 $\Delta F_{me} = 1 - 10^{-6} \left(\frac{1 \text{ Hz}}{f} \right) \frac{B(f)}{f}$
 $B(f) = \text{ambient magnetic field}$
 We can choose trial

References

[1] K. Ichikawa et al., 'Upper Limit on Gravitational Wave Backgrounds at 0.2 Hz with a Torsion-Bar Antenna' PRL 100 101101 (2011)

5. Summary

- We controlled a torsion pendulum by using a **coil-coil actuator**
- We evaluated the magnetic noise of a coil-coil actuator and showed it matches theory

	electrostatic	coil-magnet	coil-coil
force	small	large	large
linearity	bad	good	good
magnetic noise	none	large	small

Magnetic Noise Coupling

- Operation of small TOBA with coil-coil actuator.
- Evaluation of external magnetic coupling.

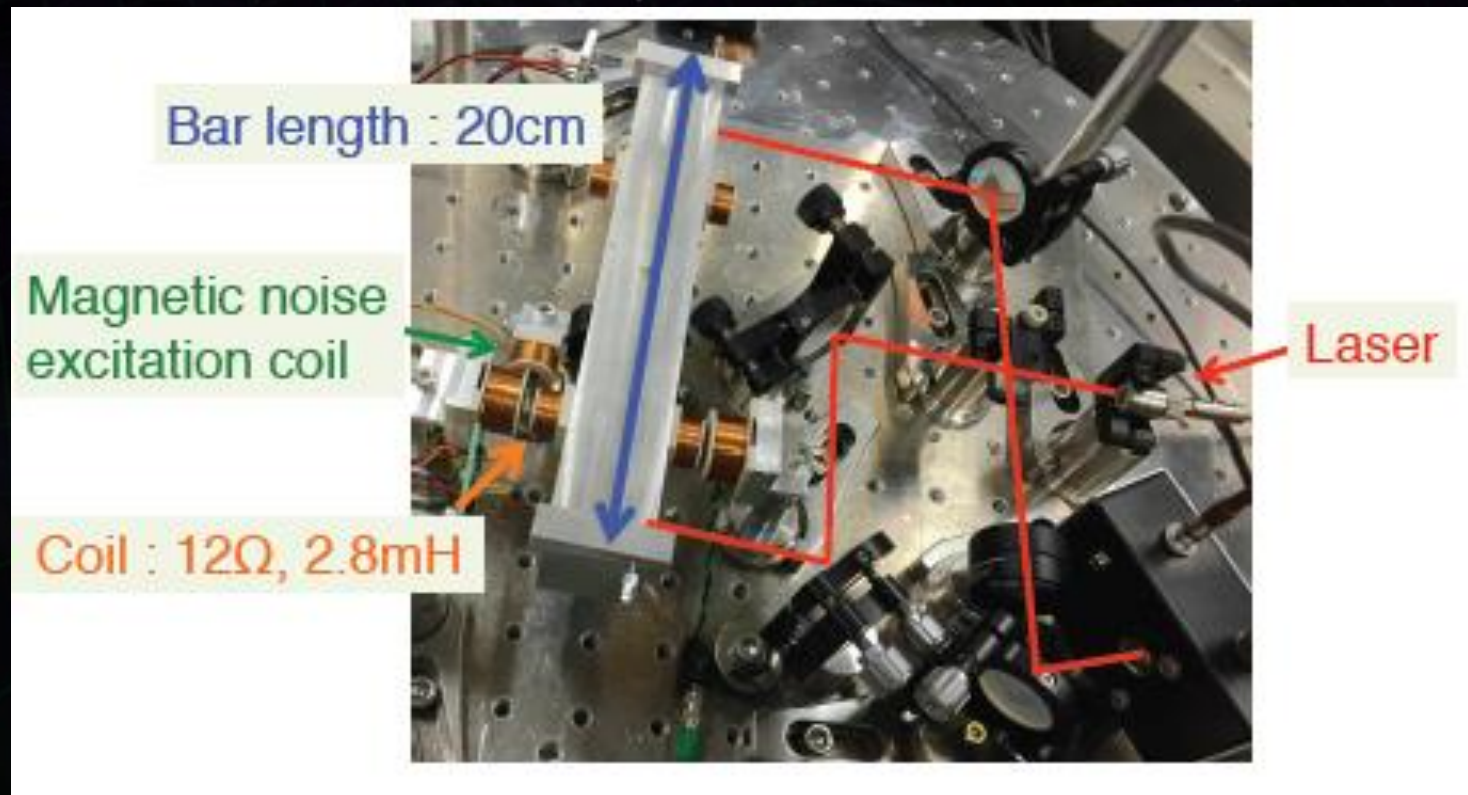


Figure: Naoki ARITOMI

Monolithic Optical Bench

- Monolithic test mass and optical bench.

Power-recycled Michelson IFO in this case.

- Silica test mass, 20cm length, $\lambda/10$ polished.
- Silica optical bench, optics will be glued.

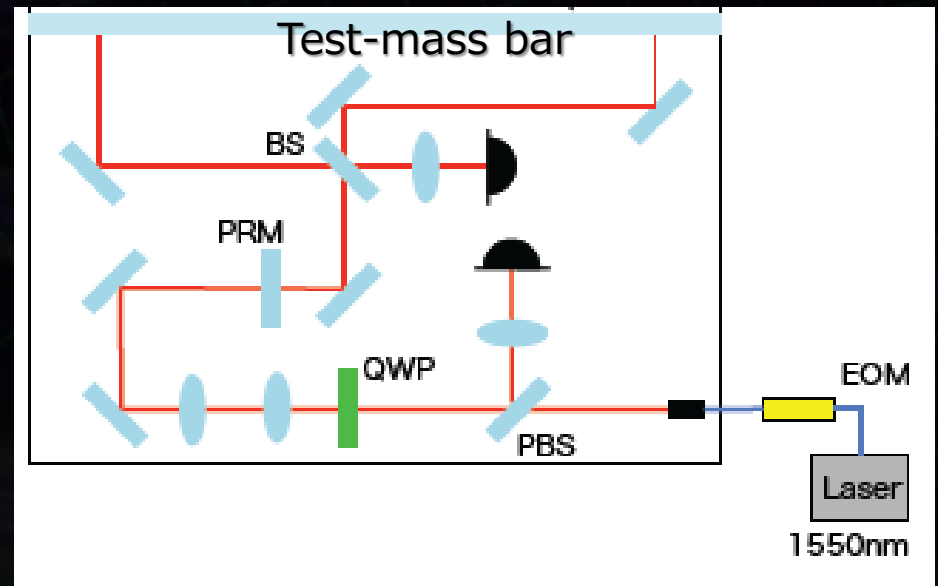
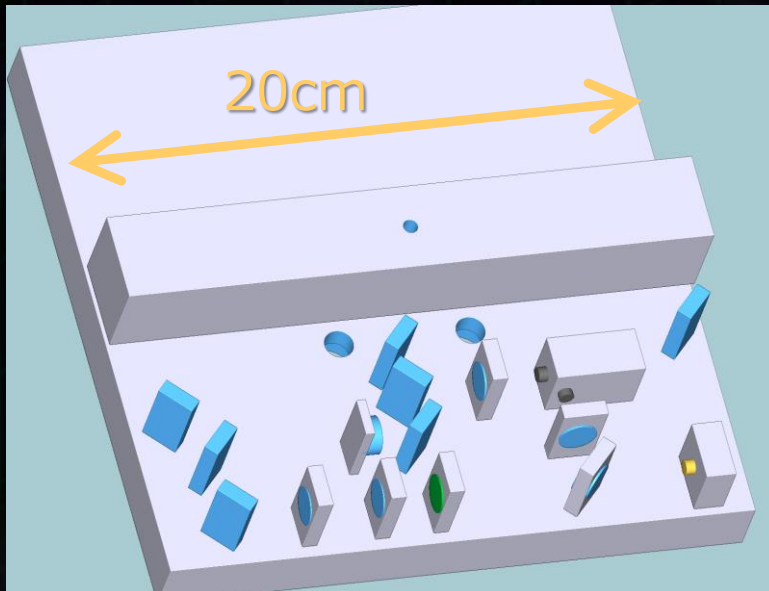
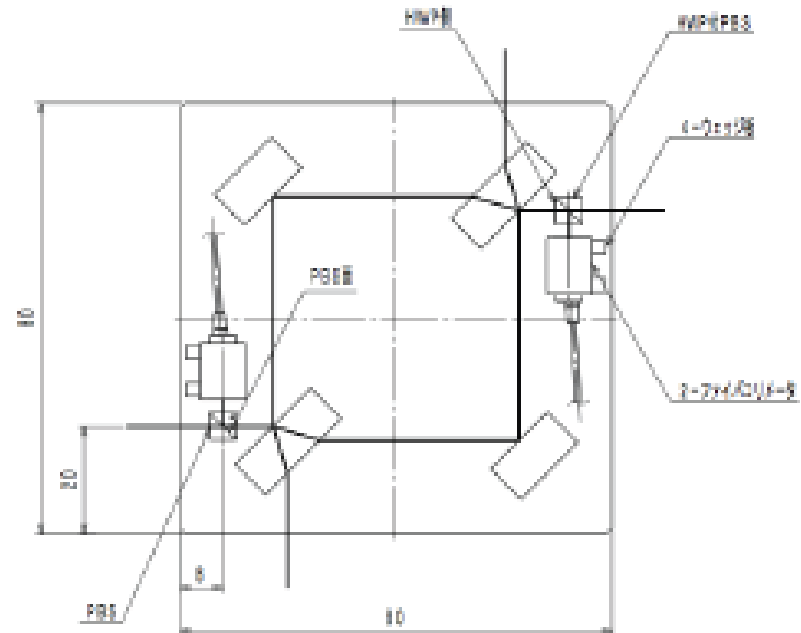
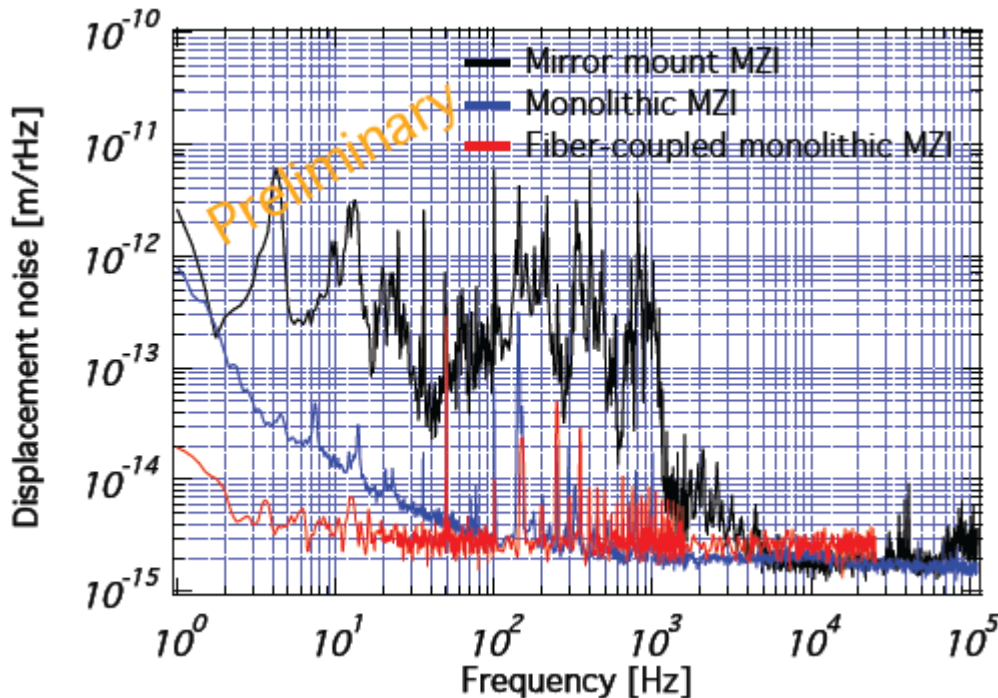


Figure: Naoki ARITOMI

Previous Result

- S.Sato's Mach-Zehnder IFO experiment
→ Monolithic optical bench is promising to realize shot-noise-limited sensitivity at low-frequency below 1Hz.



S.Sato (2013)

Monolithic Optical Bench

- Fused Silica components have been delivered.
 - Test mass: Polished and Mirror-coated.
 - Optical bench: Polished and shaped for sus.



Fused Silica Test Mass
(Not unpacked yet)



Fused Silica Optical Bench

Summary

Schedule (prediction)

- Tests at room temp. (~2016.12)
 - Investigation and experimental tests on seismic noise coupling noise.
 - Tests of Coil-Coil actuator
 - Operation and noise evaluation with monolithic optical bench.
- Cryogenic operation (~2018.12)
 - Tuning of active isolation stage.
 - High-quality wire for suspension.
 - Cryogenic operation to reach sensitivity

$$h < 1 \times 10^{-15} \text{ Hz}^{-1/2}$$

Summary

- In U-Tokyo, we are in a design phase of the next TOBA experiments
 - * Sensitivity of $h \sim 10^{-15} \text{ Hz}^{-1/2}$ is a good target.
 - Best GW antenna in this band.
 - Scalable up to the 10-m TOBA.
 - Open several possibilities in application.
 - * 30-cm scale cryogenic torsion pendulum.

Any suggestion in this workshop are welcome!



End