TOBA: a Low-frequency Gravitational-Wave Antenna

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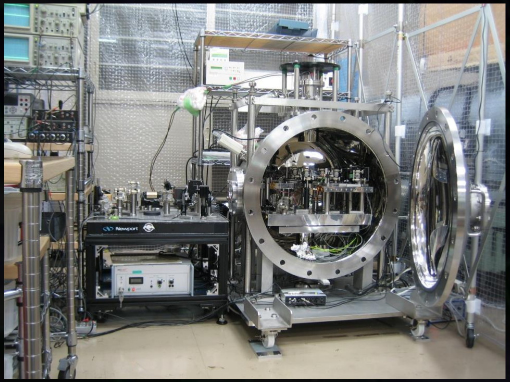
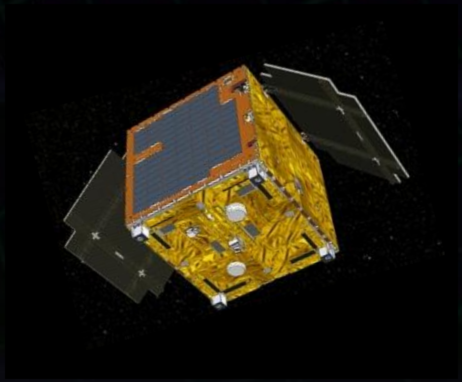
Small-scale TOBA at Tokyo



Small-scale TOBA at Kyoto



SWIM on SDS-1 satellite

GWADW2016 (May 24th, 2016, Elba Island, Italy)

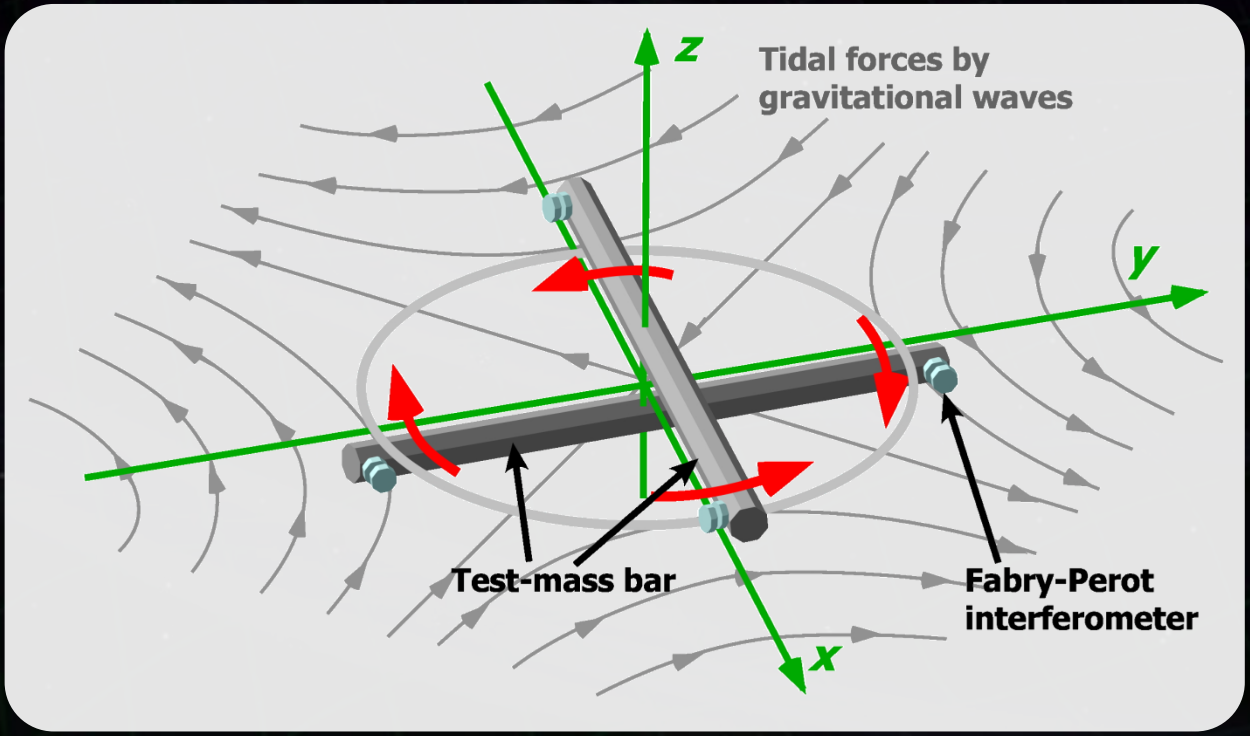
Background and Motivation

Torsion-Bar Antenna

TOBA: Torsion-Bar Antenna

Two bars suspended as torsion pendulum

⇨ Detect differential rotation by GW



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

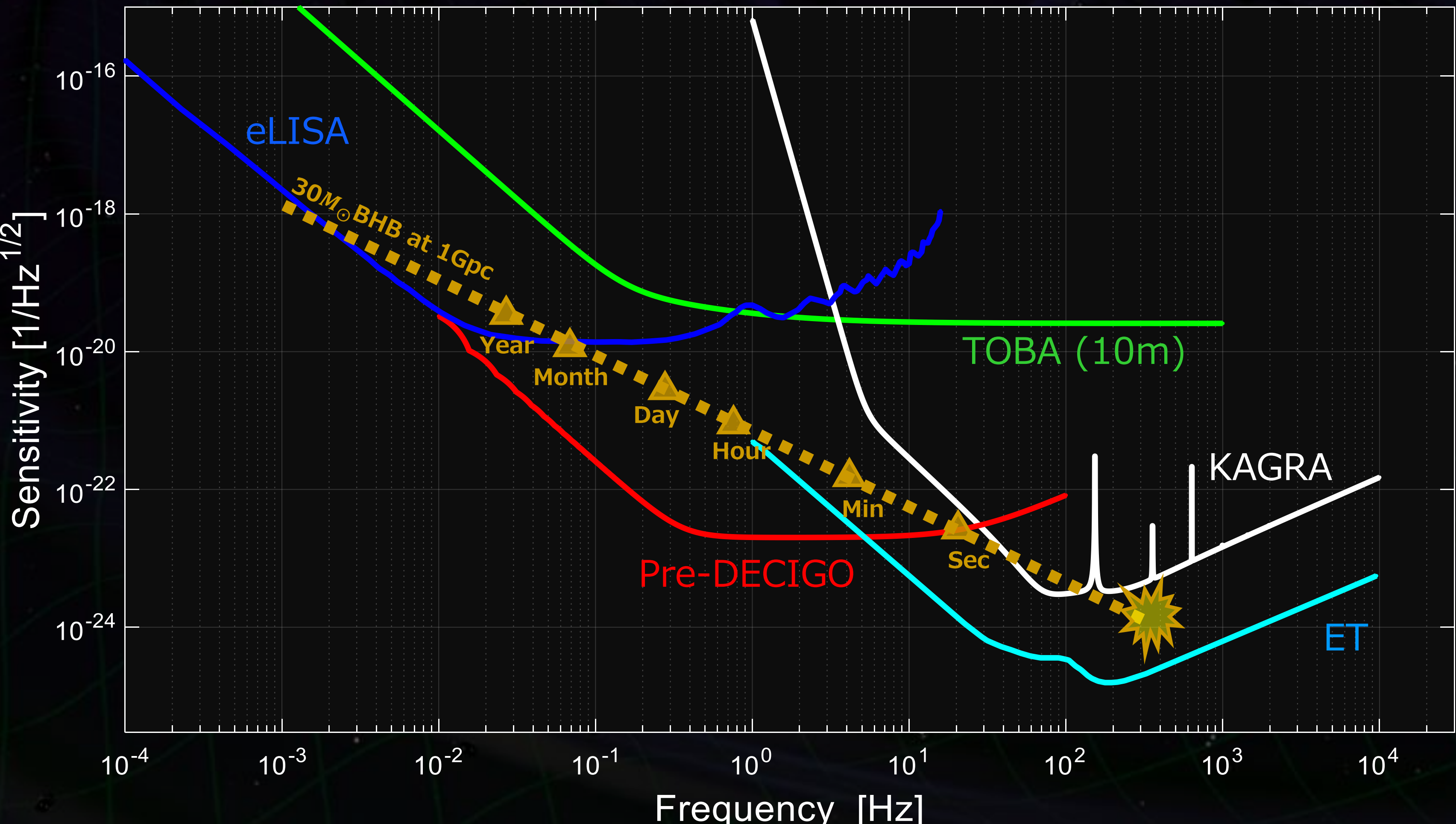
GW Science at Low Frequency

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

⇩

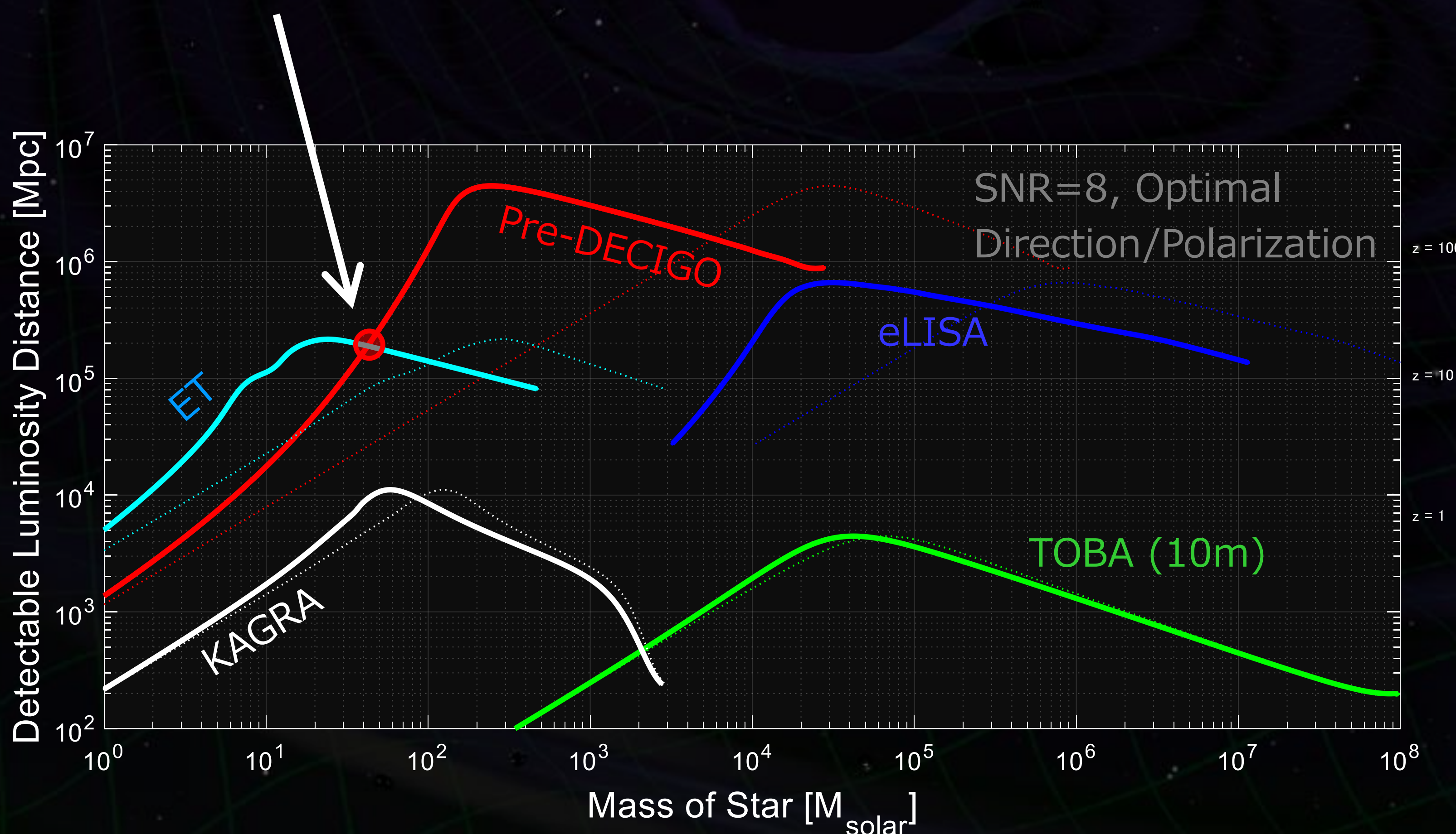
- Good sciences by ground-based antennae : $h < 10^{-19}\ \mathrm{Hz}^{-1/2}$.
- Fruitful sciences by space-borne antennae : $h < 10^{-23}\ \mathrm{Hz}^{-1/2}$.

Sensitivity Curves



Observable Range

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



Low-Frequency Observations

DECIGO

- 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 lager cycle number ($\sim10^5$) :

  * Localization, Merger time → Alerts for GW-EM.

  * Mass, Distance, Spin → Origin and nature of BBH.

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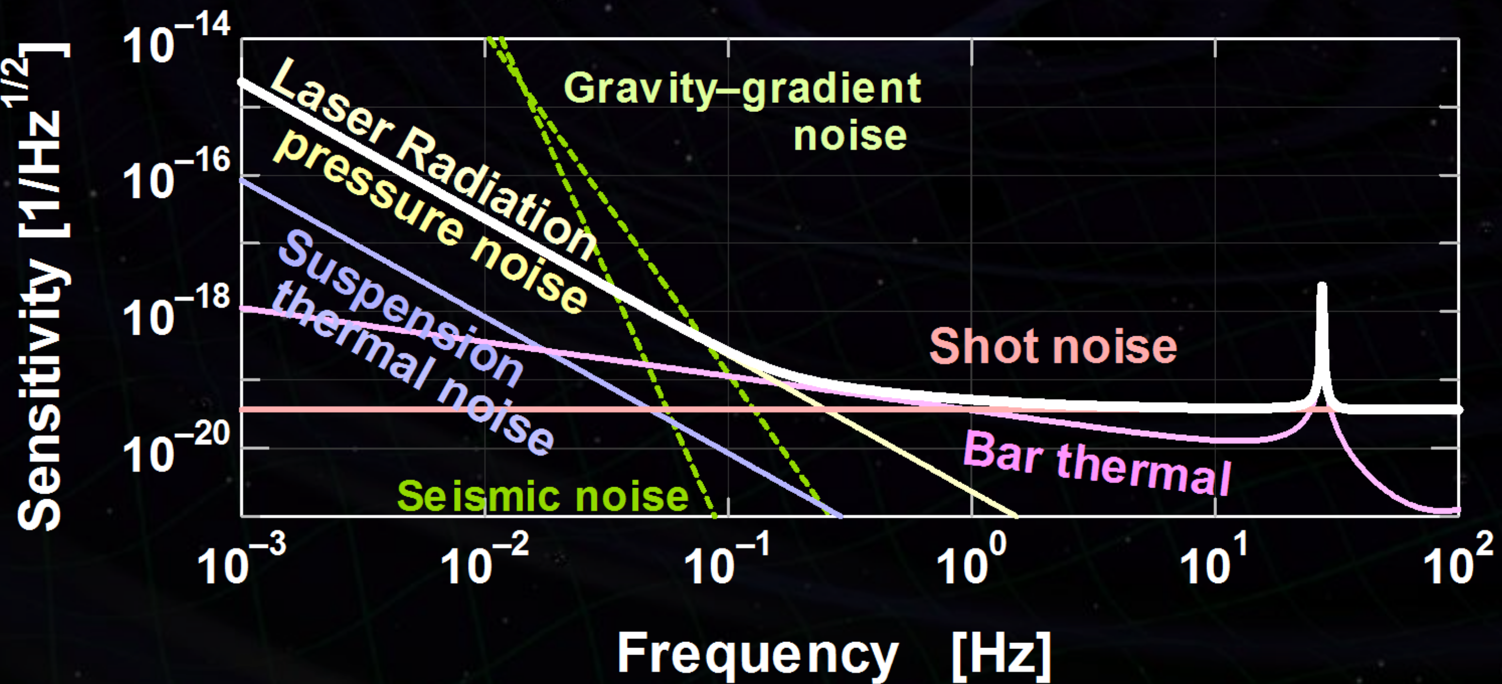
Fundamental Noise Level of 10-m TOBA

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



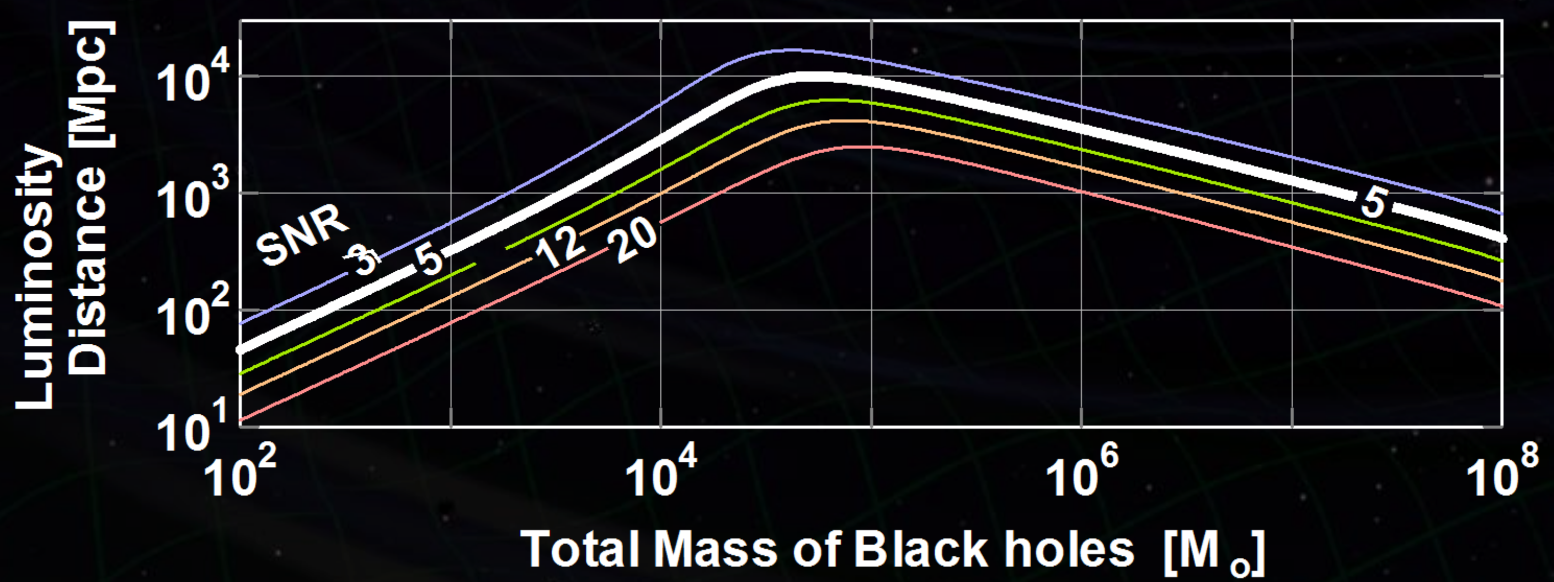
Bar length : 10m, Mass : 7600kg
Laser source : 1064nm, 10W
Cavity length : 1cm, Finesse : 100
Bar Q-value : 10^5 , Temp: 4K
Support Loss : 10^{-10}

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)



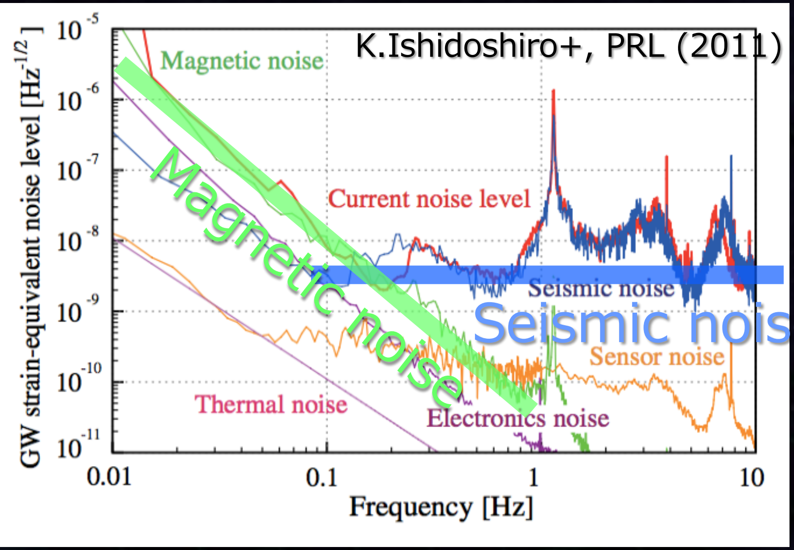
PRL105, 161101 (2010)

Prototype Developments

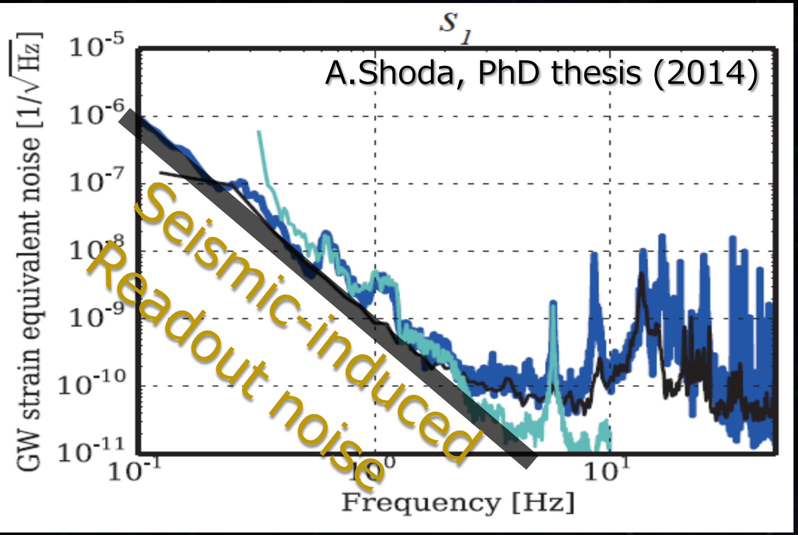
- Phase-I (2005-2010, Ishidoshiro, Ando, ⋯)
  * Principle test and 0.1Hz GW observation
  * 20cm mass, Room temp, Poor seismic isolation
  * Two setups : Tokyo and Kyoto.
- Phase-II (2011-2015, Shoda, Okada, ⋯)
  * Improved isolation design (Suspension + AVIT)
  * Principle test of multiple output configuration
  * 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} $Hz^{-1/2}$ at 0.1Hz.

⇩

Multiple scientific outcomes expected:

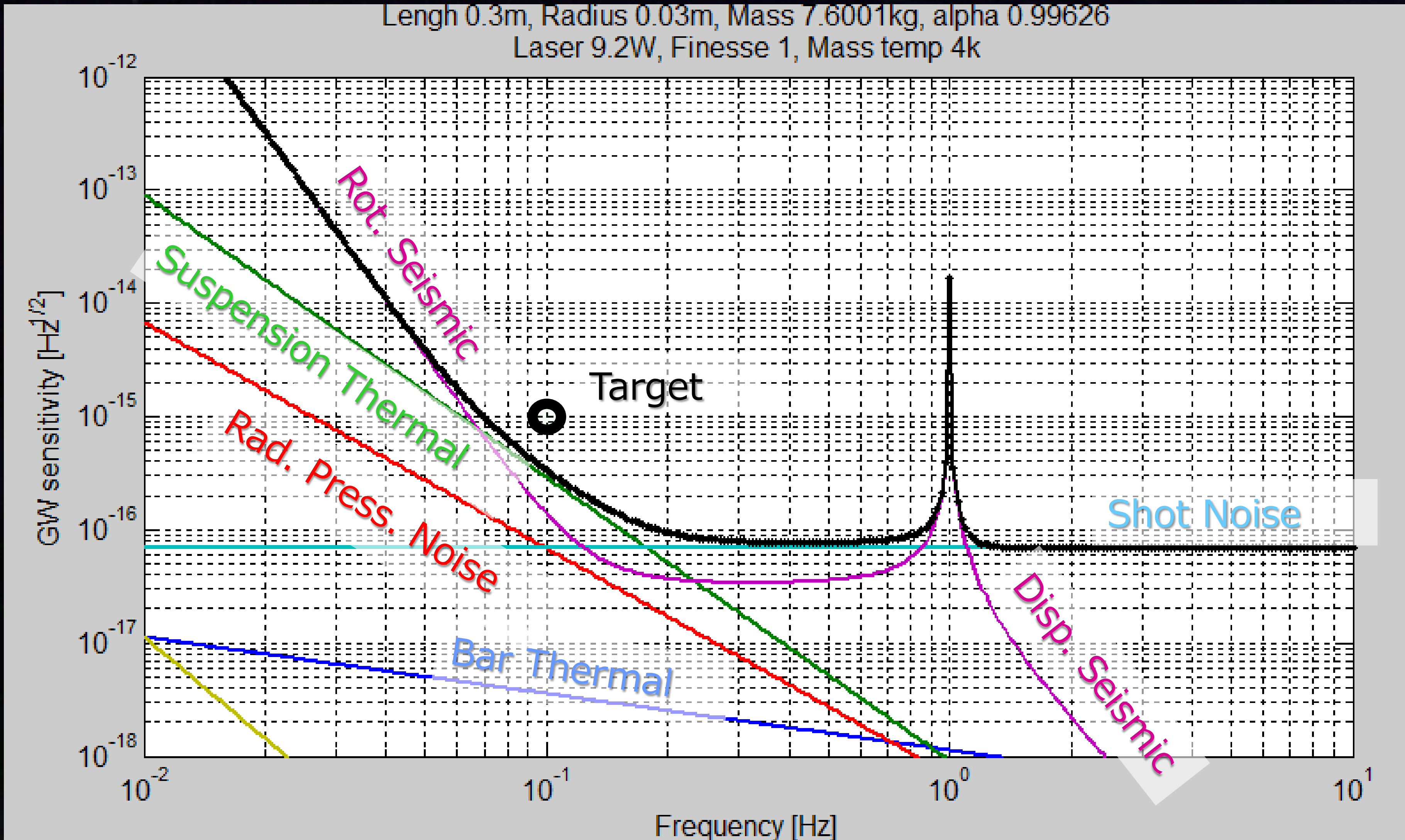
* Observation of GWs,
* Direct measurement of Gravity-gradient noises → Test bench for cancellation.
* Earthquake early alert.
* Tiny force measurements for Quantum noise, Space missions, Fund. physics,…

Conceptual Design of Phase-III TOBA

- Test Mass:
  Cupper (?), Length 30cm, Mass 7.6kg, Temp. 4K.
- Suspension:
  Silicon, Resonant Freq. ~2 mHz,
  Temp. 4K, Q-value $> 3 \times 10^{7}$
- Optical Readout :
  $\theta < 1 \times 10^{-15}\ \mathrm{rad/Hz}^{1/2}$
  Laser power > 0.1W
- Seismic isolation :
  Active isolation
  + Passive suspension
  (3 stages)

@0.1 Hz	Rotation $[\mathrm{rad/Hz}^{1/2}]$	Displacement $[\mathrm{m/Hz}^{1/2}]$
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



Phase-III TOBA Configuration

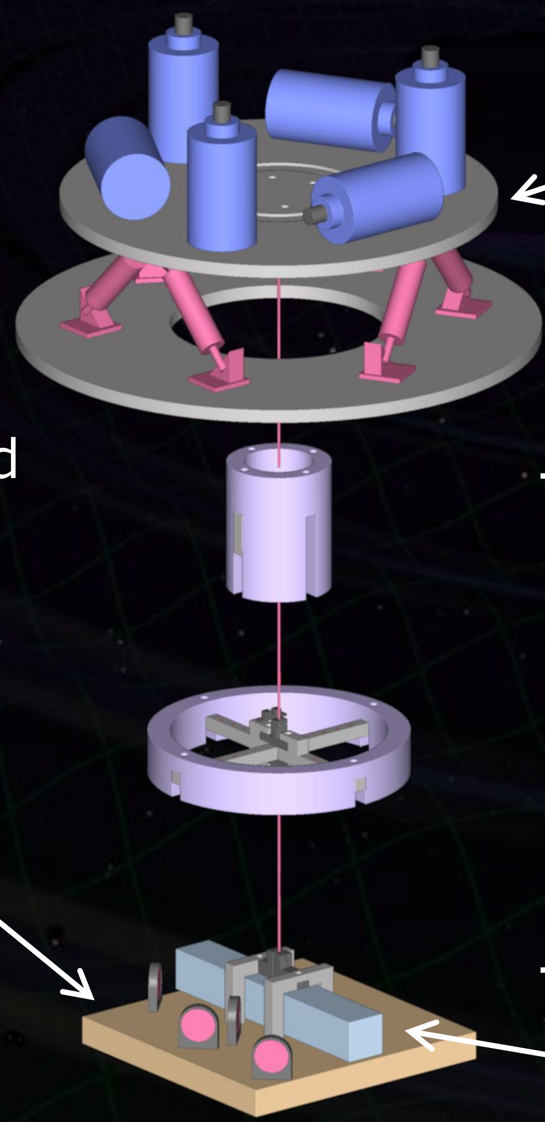


Figure: Tomofumi SHIMODA

Active seismic-isolation stage : Geophone + Hexapod

Basement fixed to ground

The setup is housed in a cryostat vacuum tank.

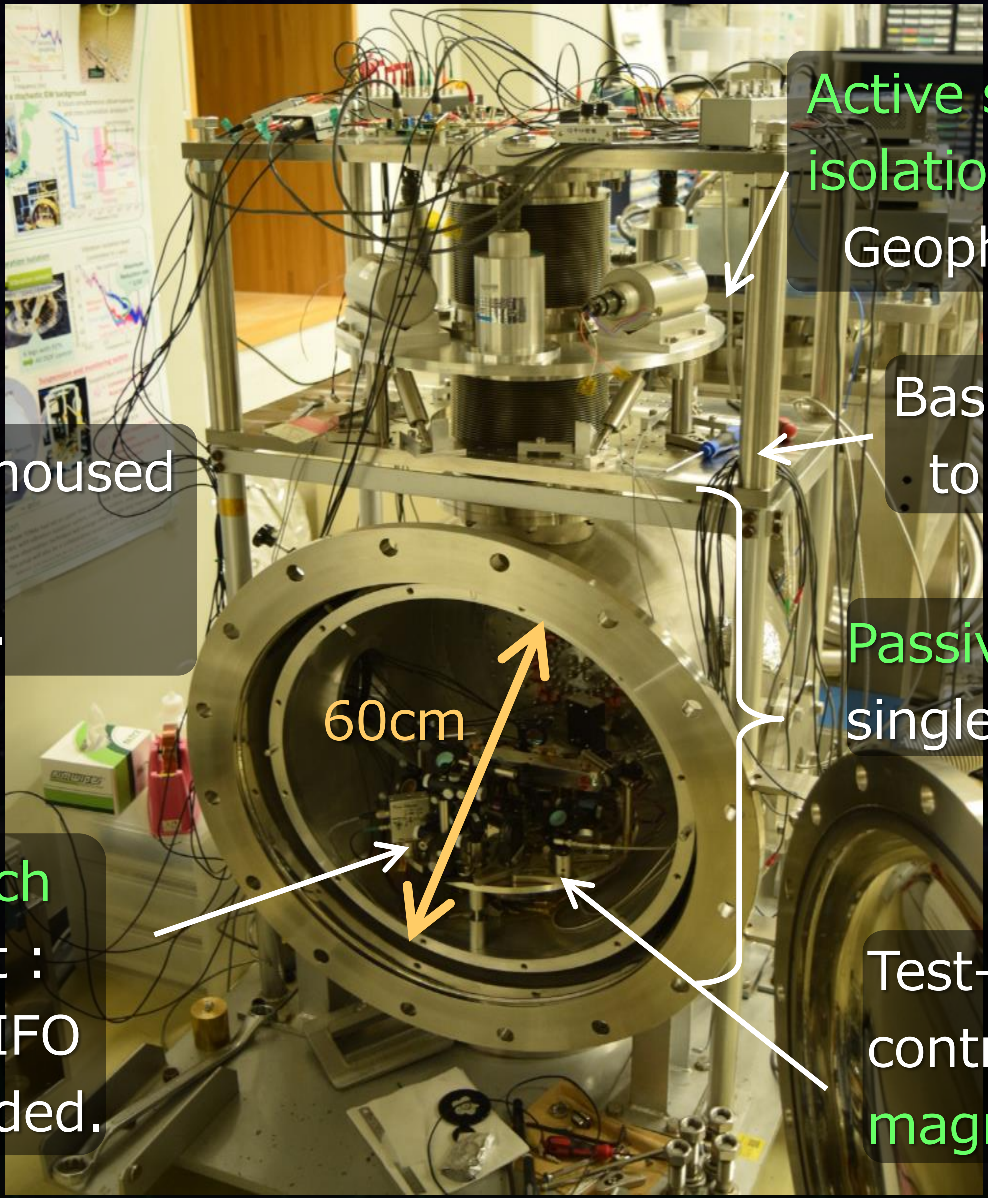
Passive isolation : Triple suspension with damping

Monolithic optical bench for readout : Power-recycled Michelson IFO

Monolithic test-mass bar, controlled using coil-coil actuator

Current Phase-III TOBA Setup

The setup is housed in a cryostat vacuum tank.



Active seismic-isolation stage : Geophone + Hexapod

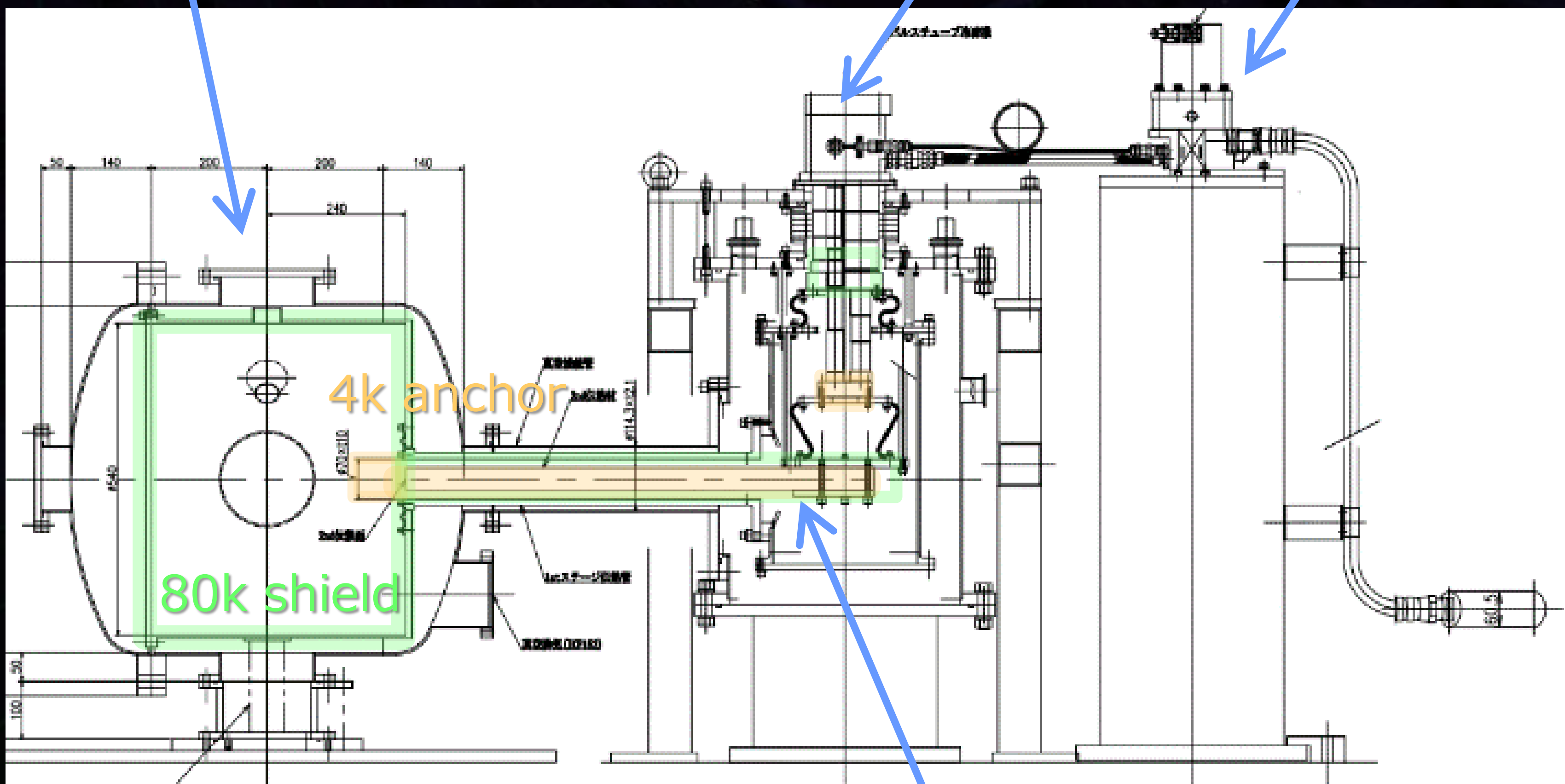
Basement fixed to ground

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

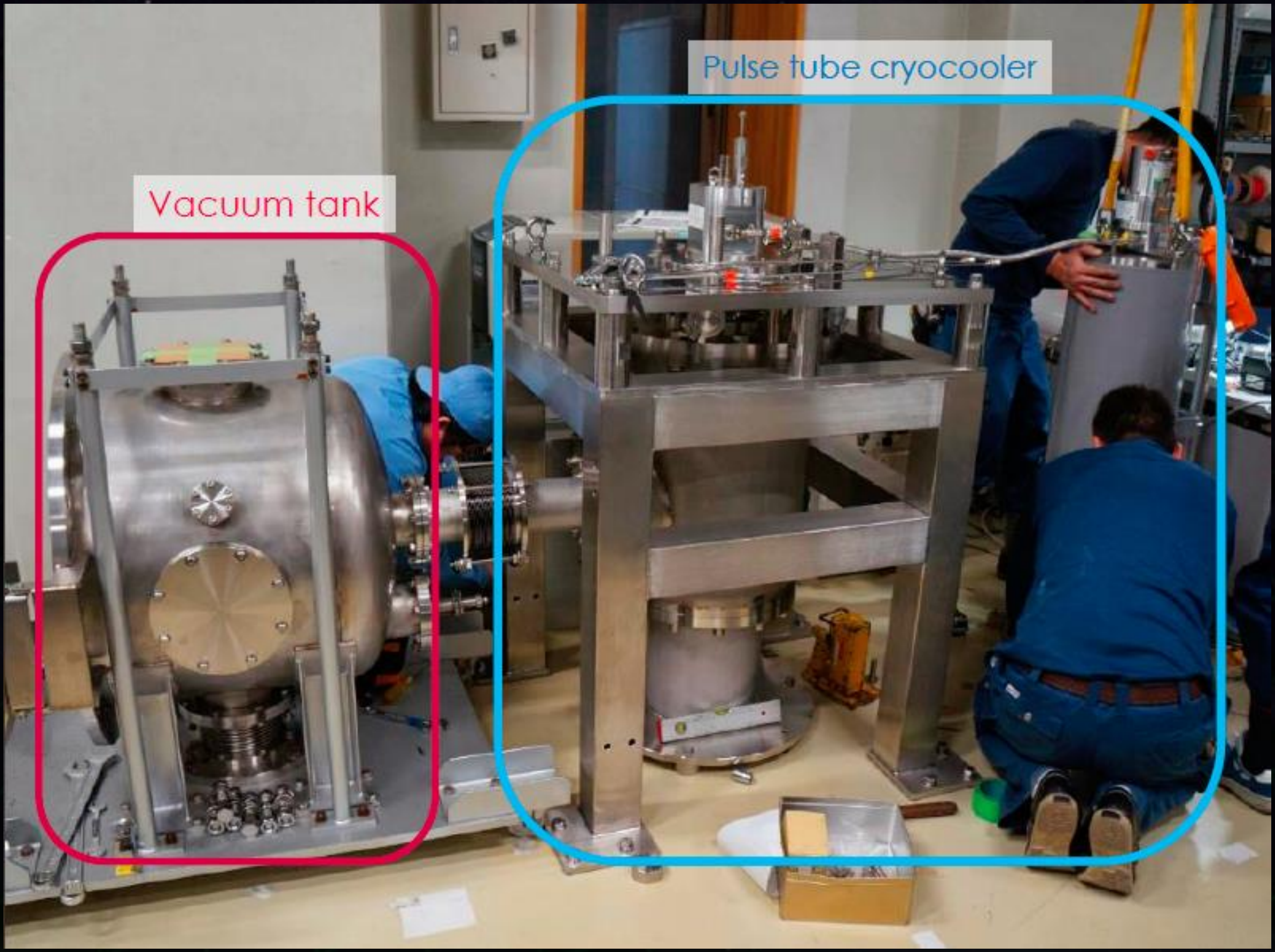


Figure: A. Shoda

Inside the Cryostat

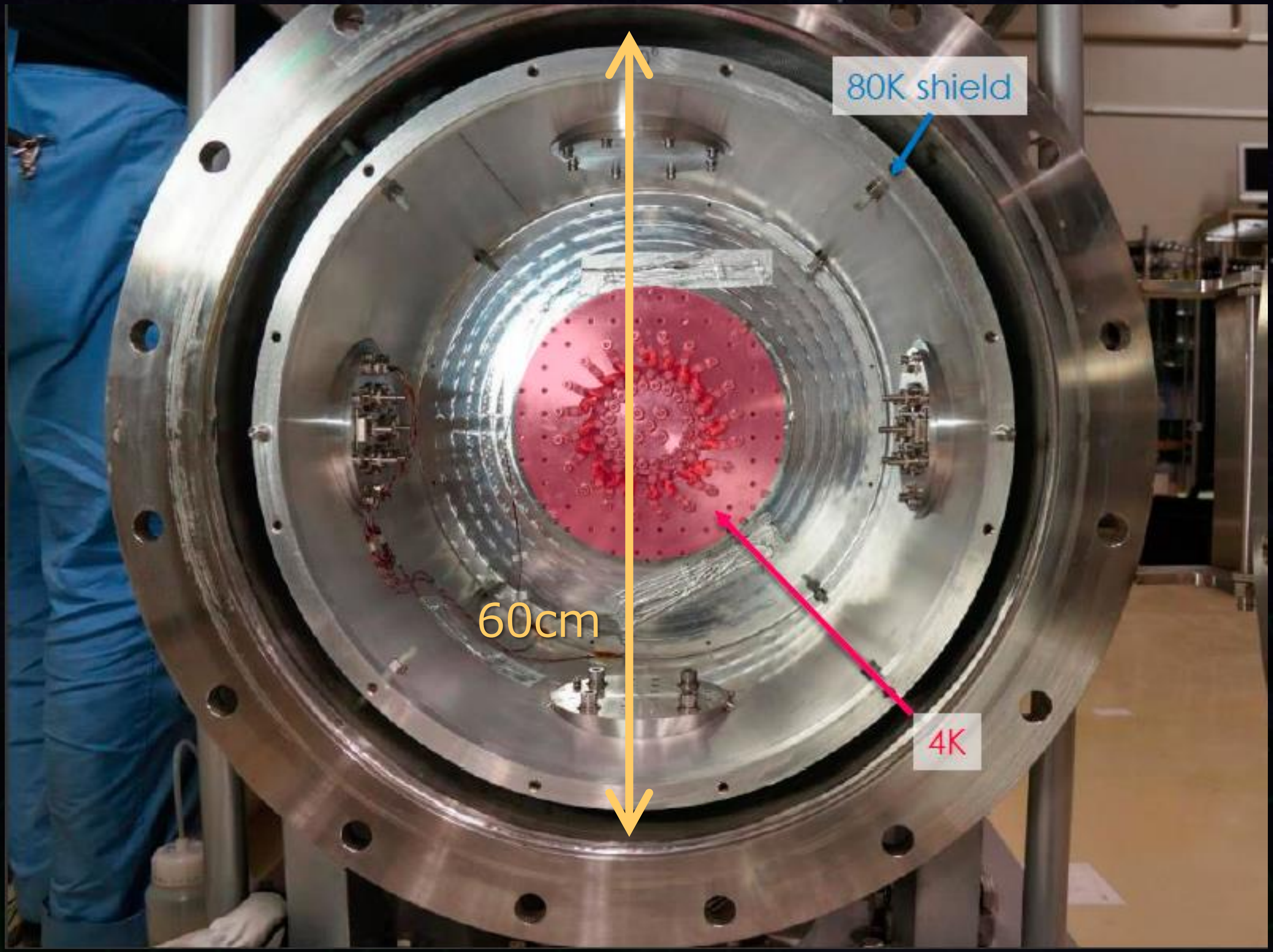


Figure: A. Shoda

Technical Challenges

- Suspension thermal noise:

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

- Seismic noise:

  Rotational DoF, Coupling from displacement.

- Magnetic noise coupling:

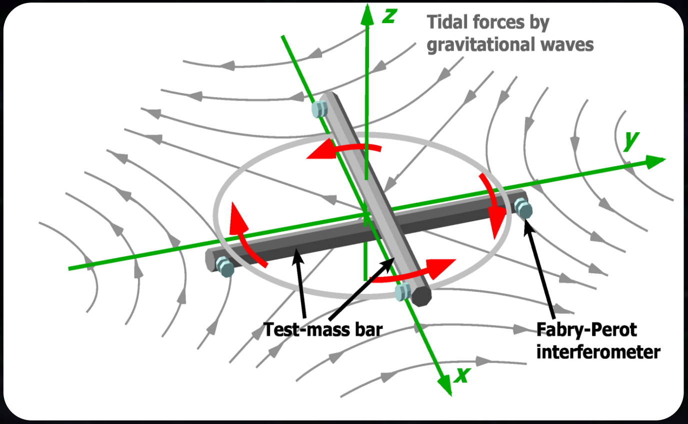
  Torque by external magnetic fluctuations.

- Optical readout:

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

  at 0.1Hz band.

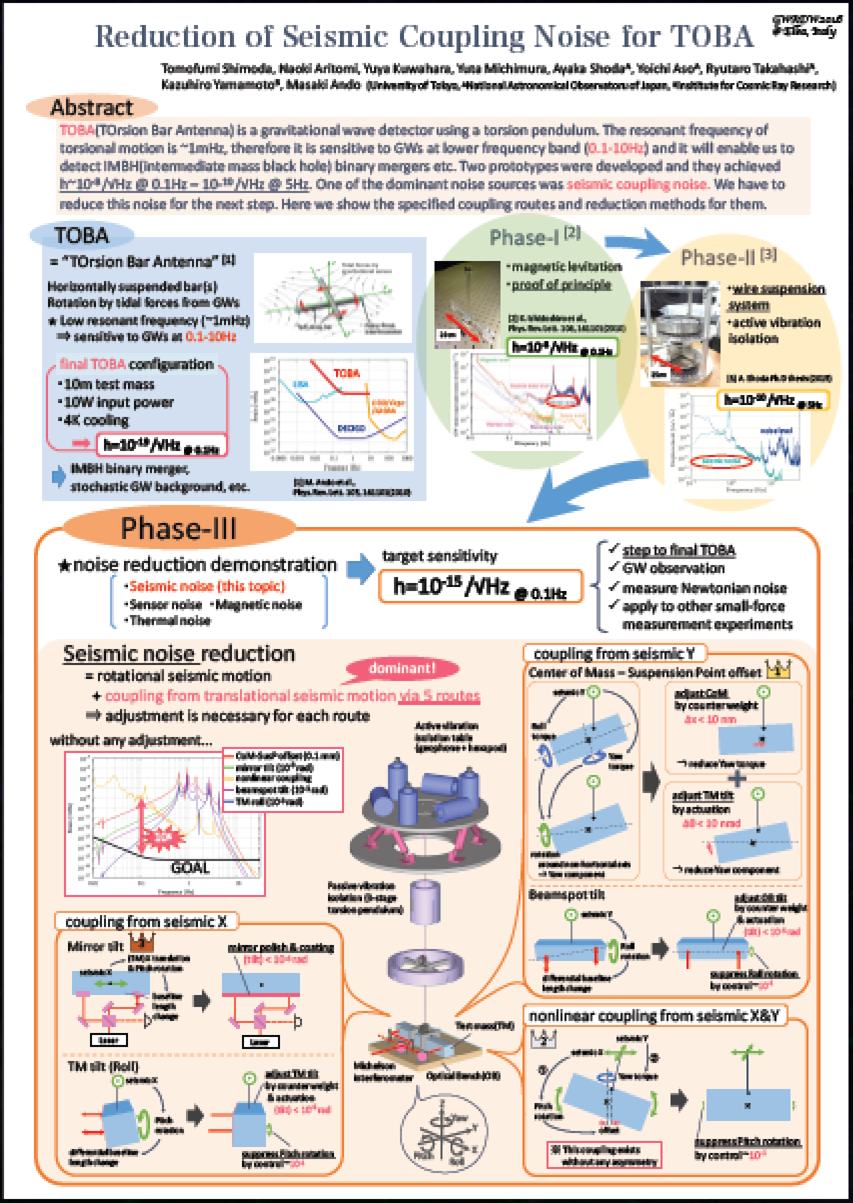
- Cryogenic compatibilities.



Seismic Coupling Noise

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

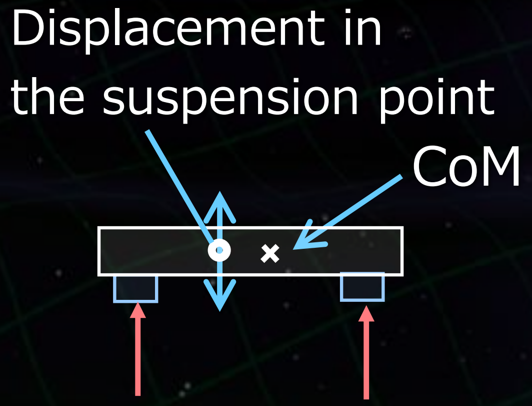
Please take a look at his poster presentation.



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.

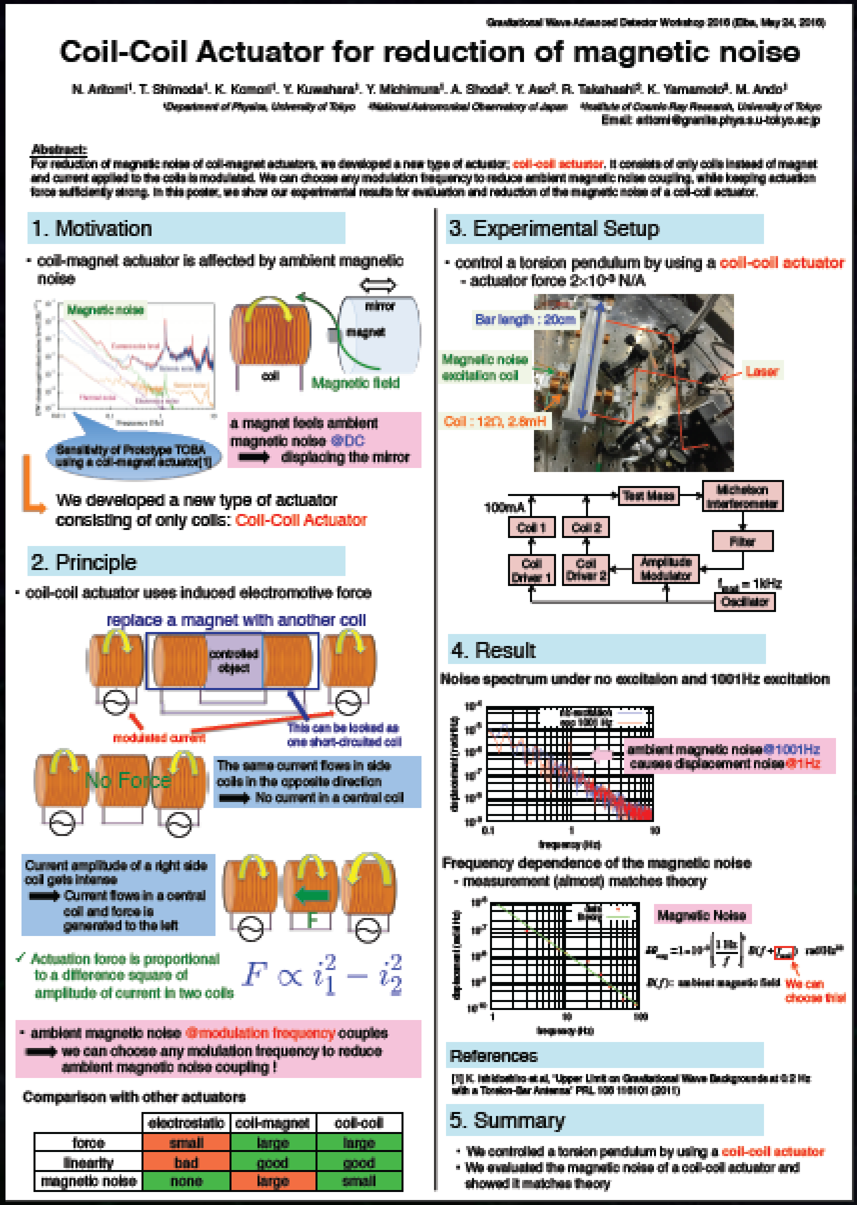
- Required Accuracy : Δx<10nm (Adjustment of 100mg mass position sub-mm accuracy)
- Possible to be adjusted by intentional small tilt of the mass.



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.



Magnetic Noise Coupling

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

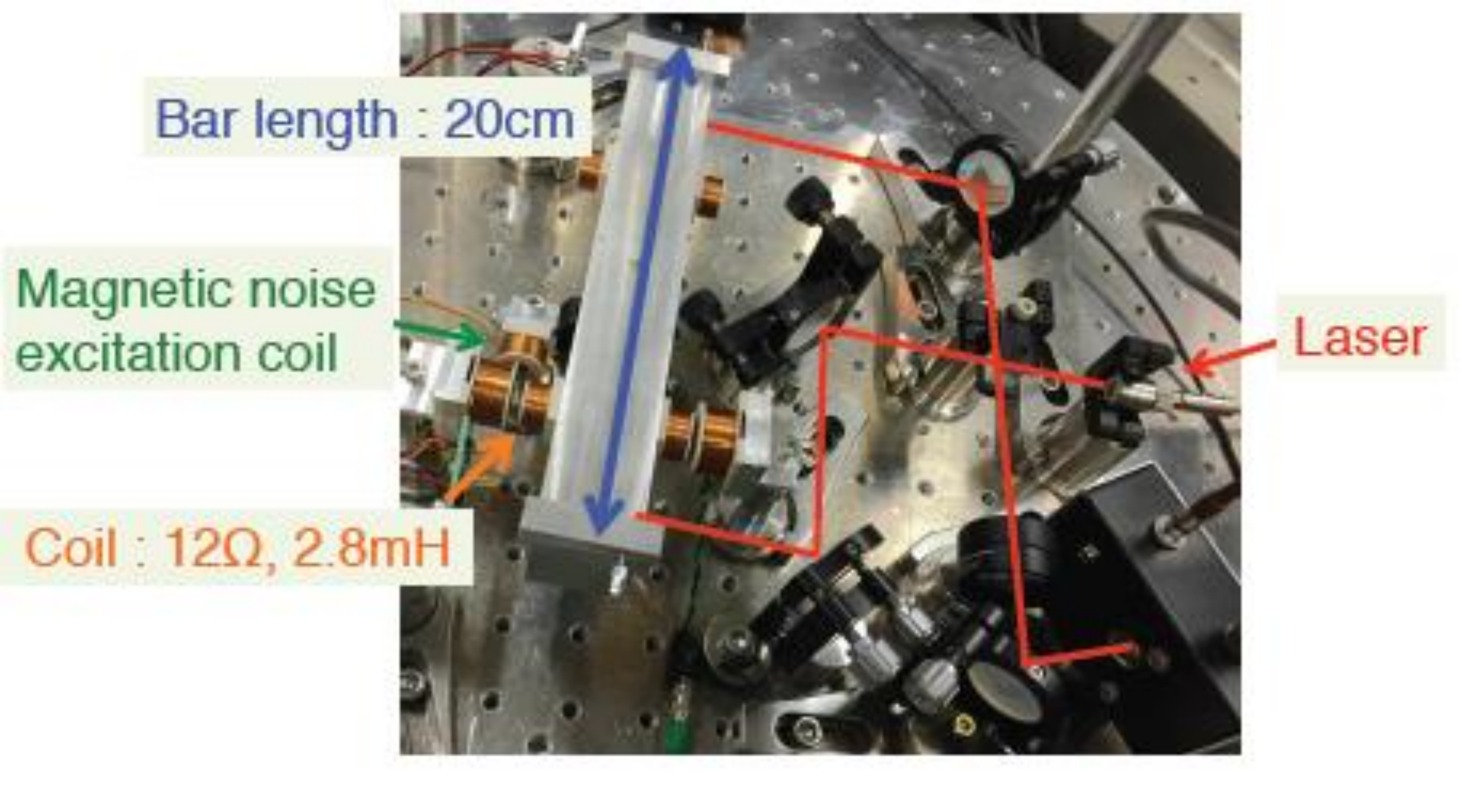
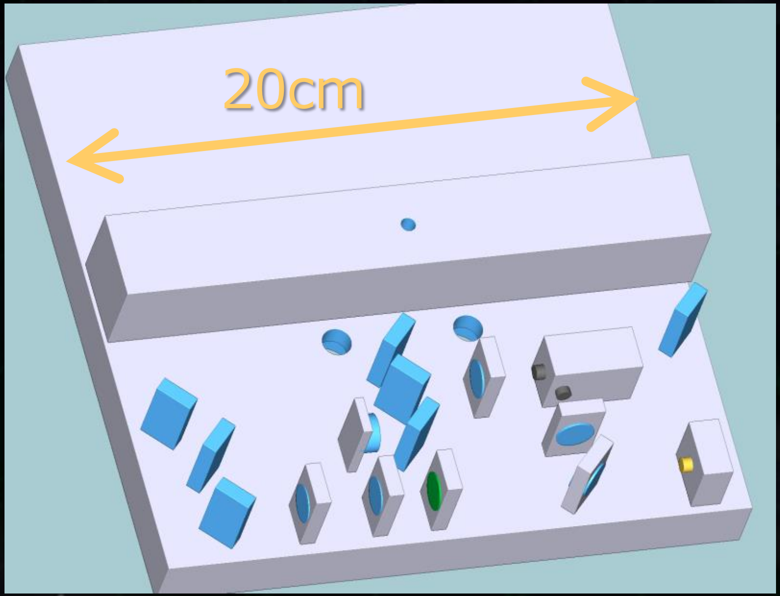


Figure: Naoki ARITOMI

Monolithic Optical Bench

- Monolithic test mass and optical bench.
  Power-recycled Michelson IFO in this case.
  - Silica test mass, 20cm length, λ/10 polished.
  - Silica optical bench, optics will be glued.



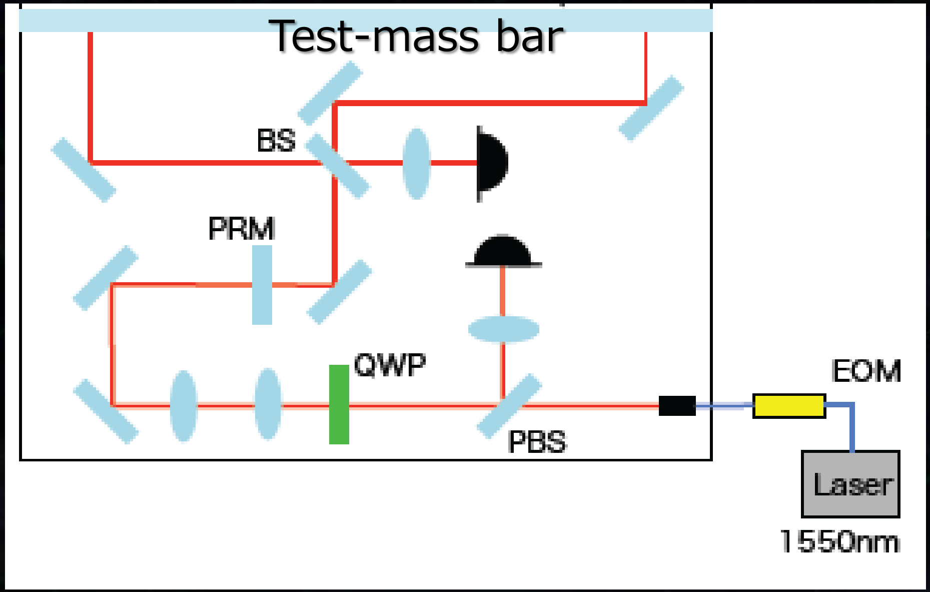
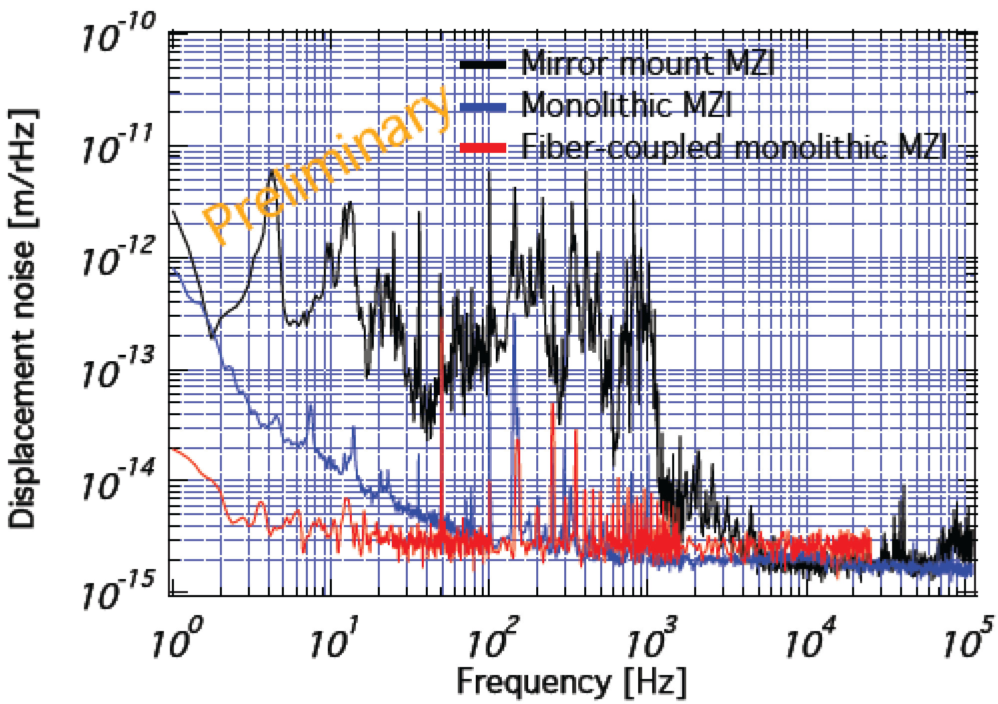


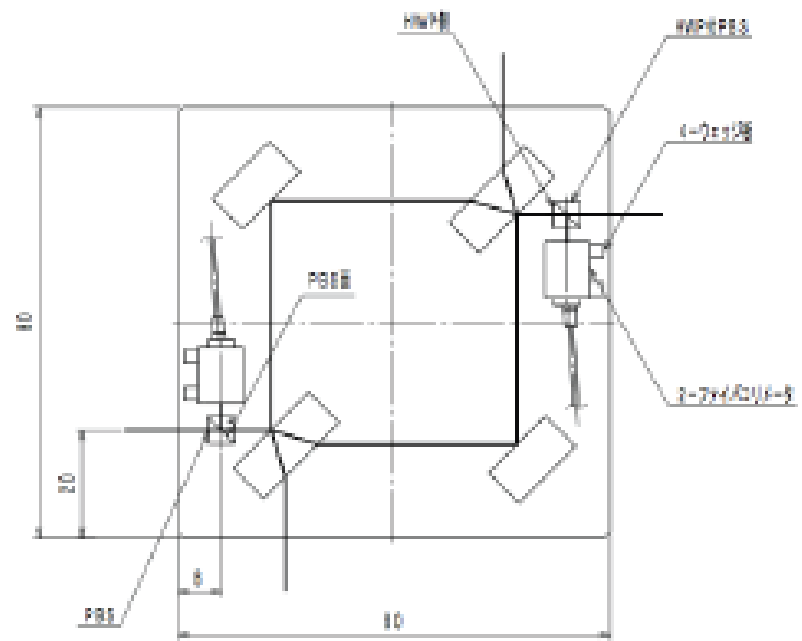
Figure: Naoki ARITOMI

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

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

Summary

- In U-Tokyo, we are in a design phase of the next TOBA experiments

  * Sensitivity of $h \sim 10^{-15}\,\mathrm{Hz}^{-1/2}$ 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