A cryogenic torsion-bar antenna (TOBA) as a local gravity gradient sensor

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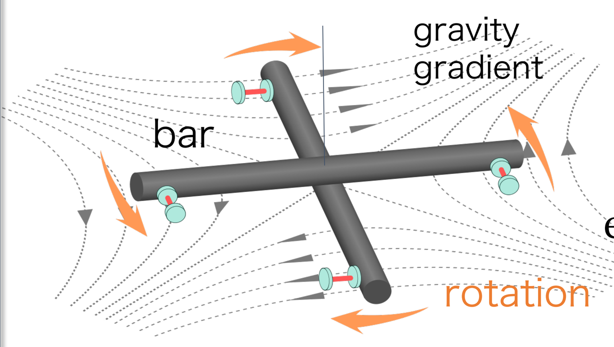
Abstract

TOBA (TOrsion-Bar Antenna) is a low-frequency gravity gradiometer using a torsion pendulum. Its low torsional resonant frequency (few mHz) enables the suspended bar to behave as a free mass at low frequencies, hence the bar can respond to **fluctuation of local gravity gradient around 0.1 Hz.** Such a detector can be used as a local gravitational field sensor to measure Newtonian noise and to detect early warning signals from earthquakes. 35 cm scale TOBA is currently under development for such purposes. One of the key feature is a cryogenic system to reduce the thermal noise of the pendulum. Here we report on the performance of the **cryogenic system** and on the investigations of relevant environmental noises.

1. TOBA and gravity gradient measurement

= low-frequency gravity gradiometer using a torsion pendulum [1-3]

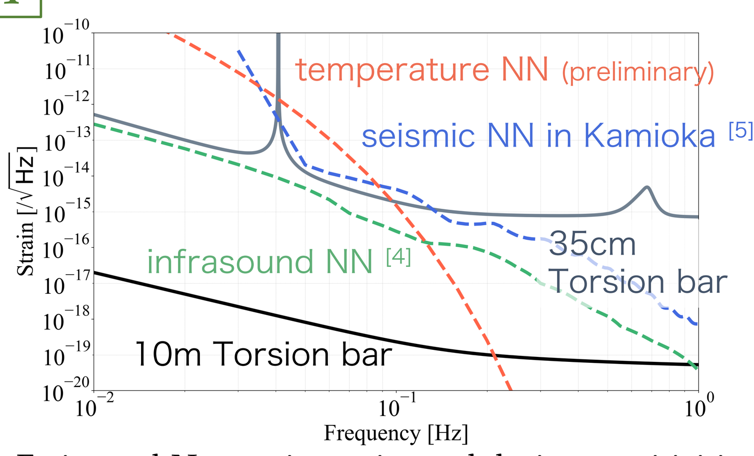


- Tidal force from graity gradient induces rotation of bar(s)
- Low resonant frequency of torsional mode (few mHz) enables free-mass like behavior around 0.1 Hz
  ⇒ **sensitive to fluctuation of gravity gradient around 0.1 Hz**

Geophysical observation with ~35 cm TOBA

・Newtonian noise (NN)
(local fluctuation of gravitational field caused by density perturbation of ground, atmosphere, etc.)

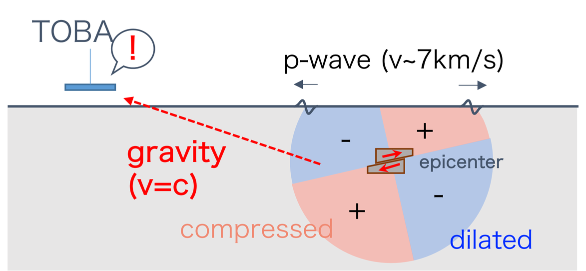
direct detection of NN with TOBA
⇒ R&D of NN for future GW detectors



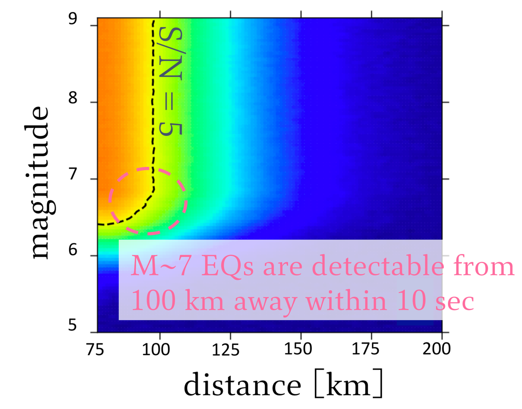
Estiamted Newtonian noise and design sensitivities

・Earthquake early warning
Density perturbation caused by fault rupture generate gravitational signals preceeding seismic waves [6]

detectable with 35cm TOBA
⇒ earlier detection of earthquakes than using p-waves



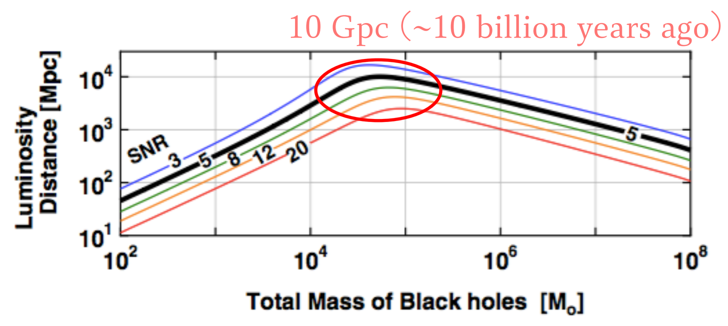
Gravity perturbation from earthquakes



S/N at 10 s after onset with ~30cm scale detector (~10^{-15} /rtHz) [7]

Astrophysical targets with ~10 m TOBA

・Intermediate mass black hole (IMBH) binary
Binaries of $10^{3\text{-}6}$ M_{sun} black holes are detectable with TOBA
⇒ provide information about the formation process of supermassive black holes (SMBHs)



Detectable range of binary IMBHs with 10m TOBA [1]

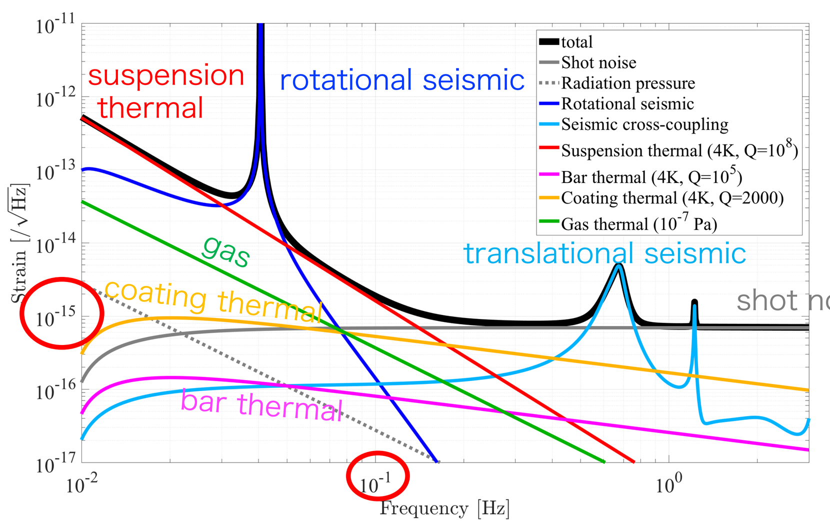
[1] M. Ando et al., Phys. Rev. L **105**, 161101(2010) [2] A. Shoda et al., Phys. Rev. D **95**, 082004(2017)
[3] T. Shimoda et al., Int. J. Mod. Phys. D **28**, 1940003 (2019) [4] D. Fiorucci et al., Phys. Rev. D **97**, 062003 (2018)
[5] K. Somiya, Class. Quantum Grav. **29**, 124007 (2012) [6] J. Harms et al., Geophys. J. Int. **201**, 1416 (2015)
[7] K. Juhel et al., J. Geophys. Res.: Solid Earth **123**, 10889 (2018)

2. Development of 35 cm TOBA

Before developing the 10 m detector, a 35 cm cryogenic prototype is under development for **geophysical observations & technical demonstration of noise reduction**

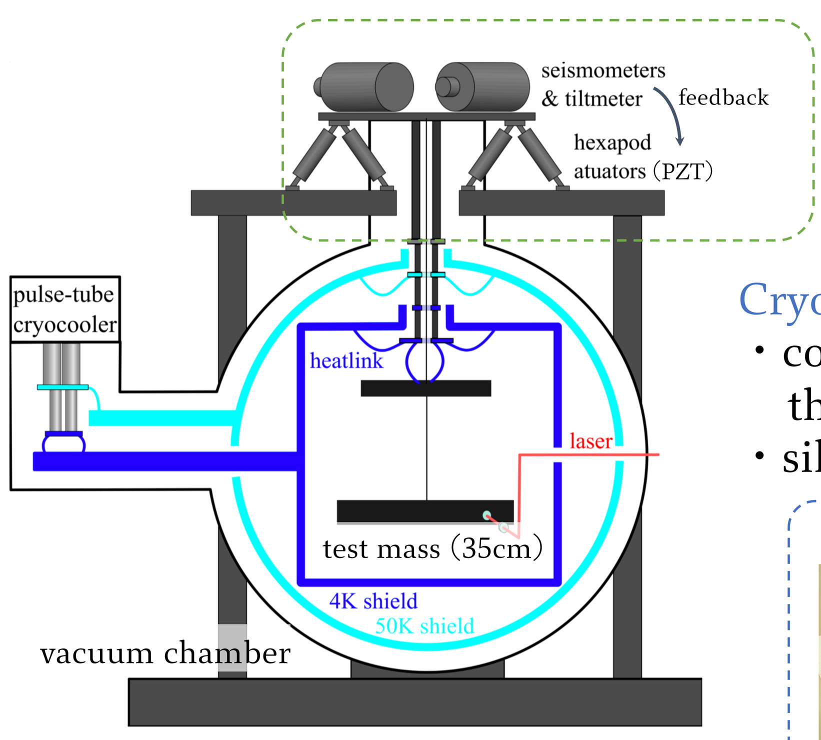
Target sensitivity :
10^{-15} /rtHz @ 0.1 Hz

★ direct measurement of NN
⇒ investigate the nature of NN
★ detection of earthquakes
★ first attempt of a large-scale cryogenic torsion pendulum



Design sensitivity of 35 cm prototype

Detector configuration

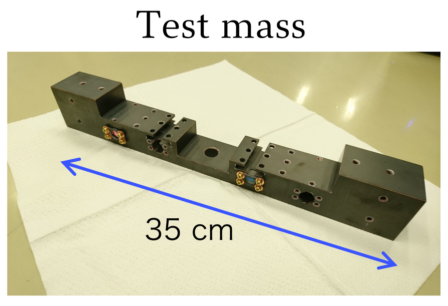


Active vibration isolation system (AVIS)
- suppress the seismic vibration down to 10^{-7} m/rtHz @ 0.1 Hz
- isolate the vibration via heatlinks

Cryogenic system
- cool the masses down to ~ 4 K to suppress thermal noise
- silicon or sapphire wire (Q_{bulk}>10^8 at low-temp.)

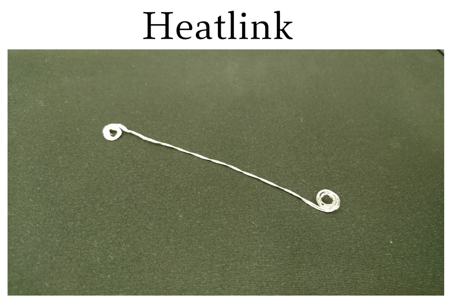
Optical system
WFS with HG_{10}-mode resonant cavity
- amplify angular signal (HG_{10}-mode) by the cavity to suppress sensing noise

Test mass



Copper mass with oxidized surface (high emissivity ~ 0.6)

Heatlink

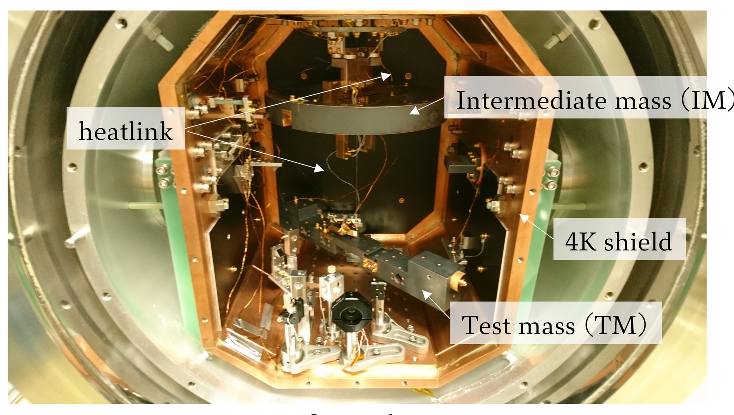


6N aluminum (high thermal conductivity)

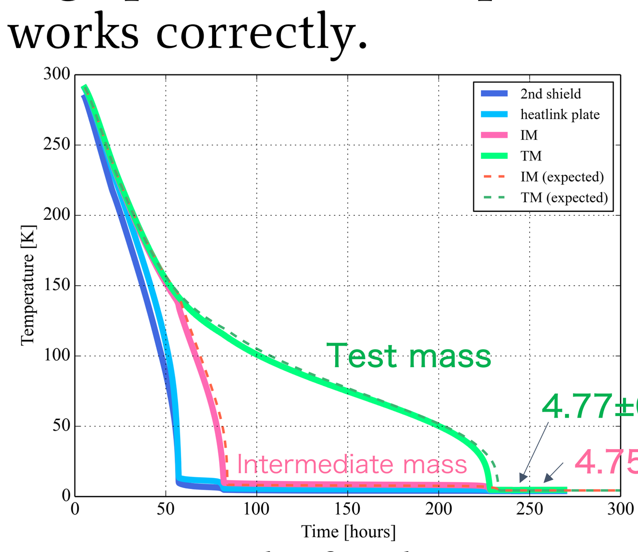
⇒ effective cooling to minimize vibration

3. Cooling test

Cooling test using a simplified double-stage pendulum was performed to check if the designed cryogenic system works correctly.



Setup of cooling test



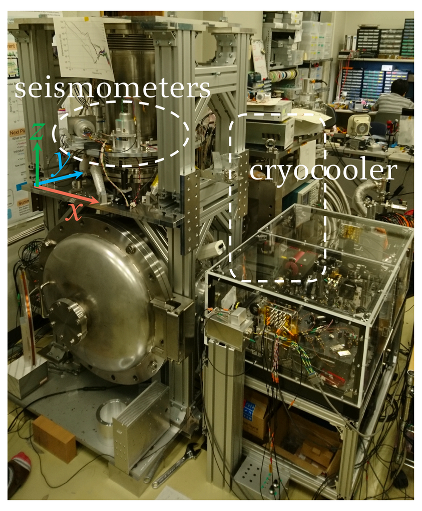
Result of cooling test

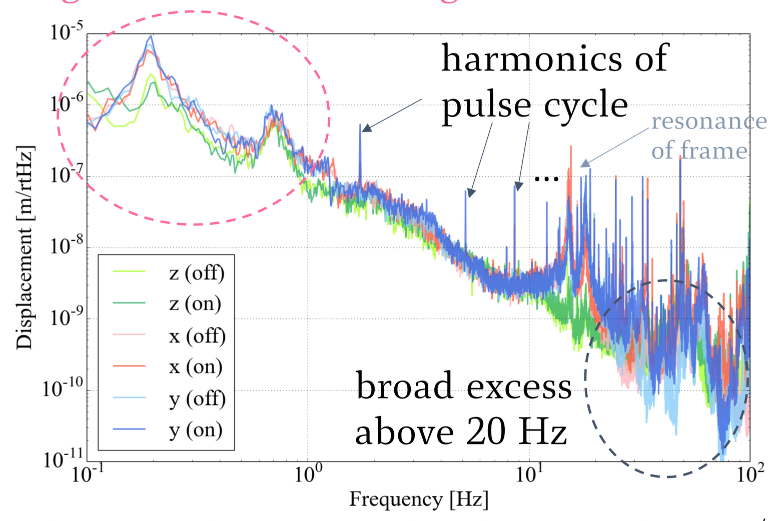
The pendulum was successfully cooled to ~4.8 K in line with the expected cooling curve

4. Investigation of environmental noise

・Vibration noise

No significant excess among main observational band





Vibration at the top stage when the cryocooler is on/off

RMS (> 0.1 Hz)

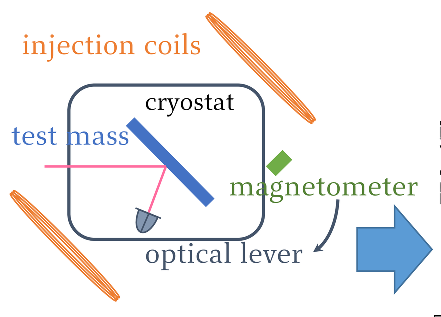
	cryocooler OFF [um]	cryocooler ON [um]
x	1.7	1.6
y	1.9	2.4
z	0.34	0.38

displacement RMS is below the actuator range of AVIS (~ 90um)

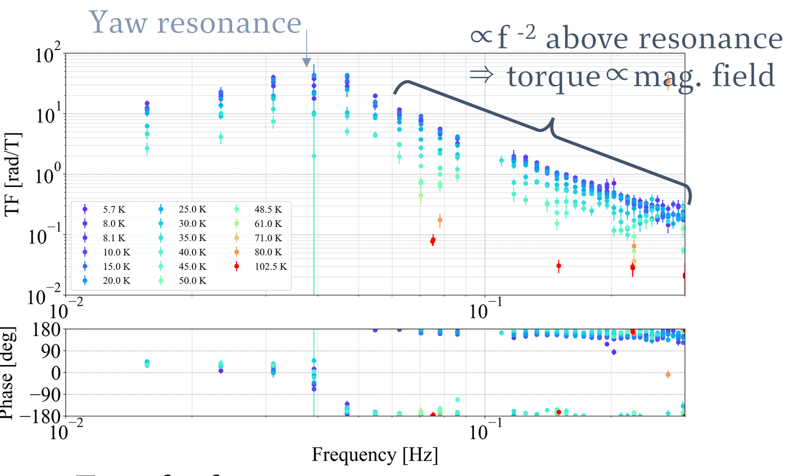
Excess of vibration due to the cryocooler will not be a problem in TOBA

・Magnetic noise

Transfer functions from magnetic field to the rotation of the bar were measured by injecting magnetic fluctuation with coils



Magnetic injection setup

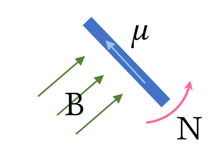


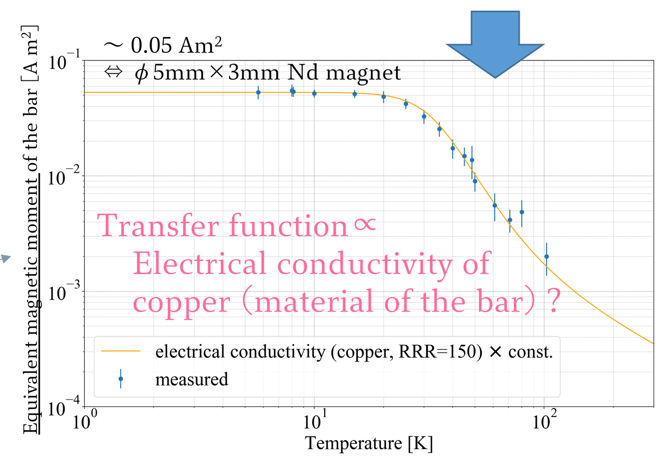
Transfer functions at various temperatures

・Transfer functions are very large at cryogenic temperatures
- like that the bar has 0.05 A m^2 of magnetic moment (≒ ϕ5×3mm Nd magnet) though no magnetic component is attached on the bar

・Temperature dependence seems to be proportional to **the electrical conductivity** of the bar, but the mechanism is unclear.

calculated by
μ = N / B
magnetic moment, torque, magnetic field

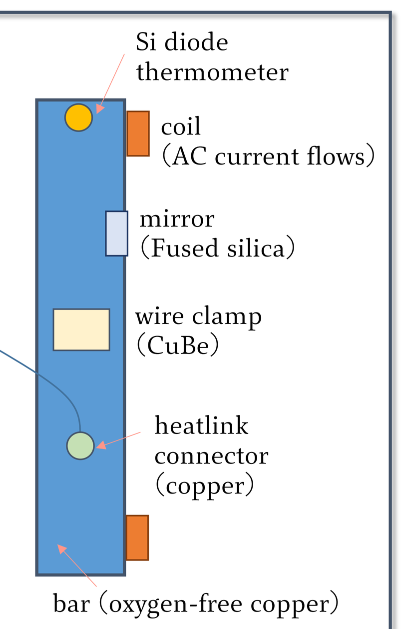




Temperature dependence of the transfer function

5. Discussion

What is the origin of large coupling with magnetic fluctuation?
- The magnetic moments of the components on the bar seem to be small
- The coupling seems to be proportional to electrical conductivity of the bar
  - an electric current is flowing in the bar?
    → the corresponding current is a few A ⇒ unrealistic
  - related to eddy current?
    → the torque should be proportional to frequency, but the measured torque was almost independent to frequency
- Or is it related to other parameters which has similar temperature dependence as electrical conductivity?



components on the bar

Further investigations (e.g. change the material of the bar to identify the key parameters) are needed

6. Conclusion

The performance of the cryogenic torsion pendulum was investigated. The cryogenic system worked as expected and the pendulum was successfully cooled to ~4.8 K without increasing the vibration of the cryostat significantly. This is an important technical milestone of TOBA for the observation of low-frequency gravity gradient fluctuation. However, coupling to magnetic field fluctuation became very large at cryogenic temperatures. From the temperature dependence, it is suggested that the coupling is related to the electrical conductivity, but the mechanism is unclear. Further investigations like changing the material of the bar remain as future tasks to identify the origin of magnetic coupling at cryogenic temperatures.