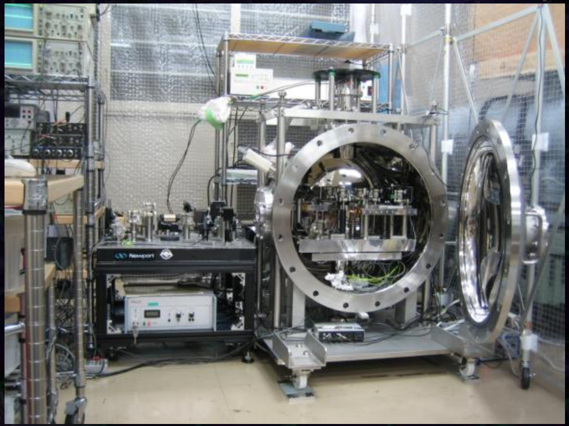
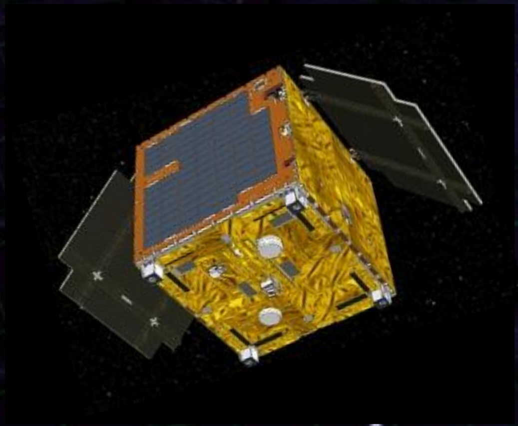
TOBA: Torsion-Bar Antenna

Small-scale TOBA at Tokyo



Small-scale TOBA at Kyoto



SWIM on SDS-1 satellite

Masaki Ando (National Astronomical Observatory)

K.Ishidoshiro, A.Shoda, K.Okada, W.Kokuyama, K.Yagi, K.Yamamoto, H.Takahashi, N.Kanda, Y.Aso, N.Matsumoto, K.Tsubono, A.Takamori, R.Gondo, R.Takahashi, and the Mango team

Gravitational Waves: New Frontier (Jan. 16-18, 2013, Seoul National University, Korea)

Motivation

Low-freq. GW observation → New sciences

- Large amplitude and/or stationary GWs radiated by sources with large masses and long time-scales.
- Difficult with ground-based detectors because of free-mass limitation and seismic disturbances.
- Space-borne detector requires large resources.

Novel approach : TOBA (Torsion-Bar Antenna)

- Low-freq. GW obs. even with ground-based config.
- Unexplored band observation with space detector.

Introduction

- Principle of TOBA
- Fundamental sensitivity
- Sciences at 0.1Hz and μHz bands

Prototype Tests

- Small-scale prototype
- GWB observation by two TOBAs
- SWIM$\mu\nu$: space demonstration
- Medium-scale TOBA

Summary

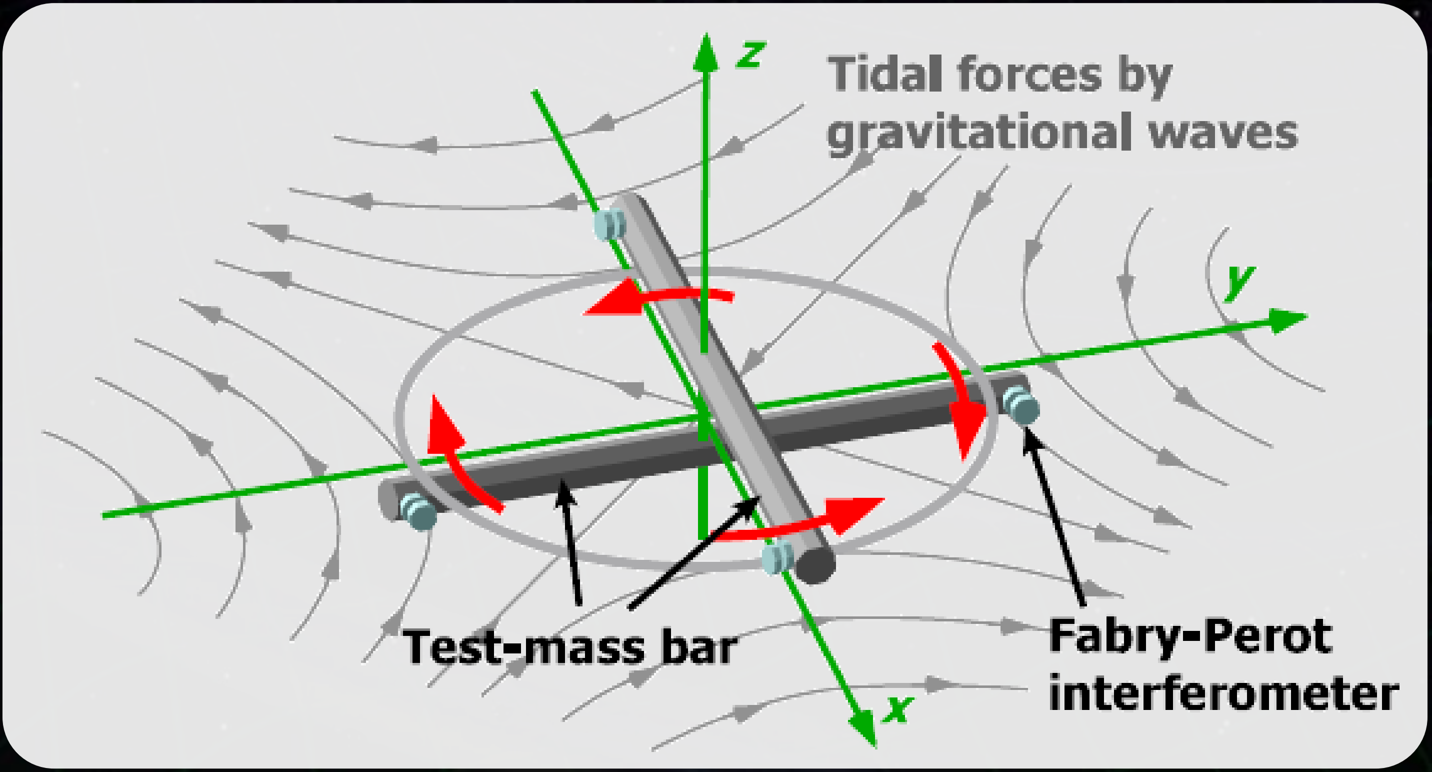
TOBA Introduction

Reference: MA+, PRL (2010)

TOBA

TOBA : Torsion-Bar Antenna

Monitors tidal-force fluctuation caused by GWs.

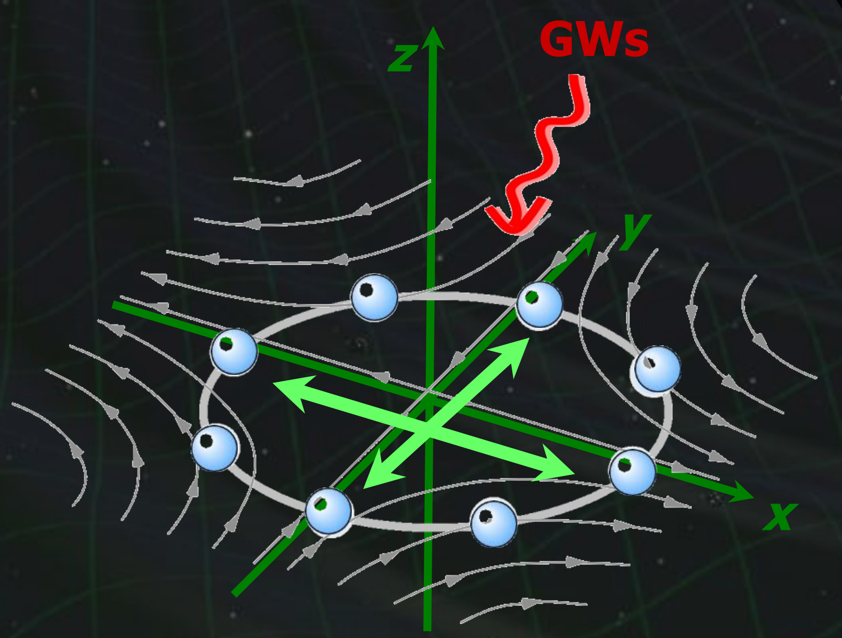


MA+, Phys. Rev. Lett. 105, 161101 (2010)

Detection Principle

Conventional IFO antenna

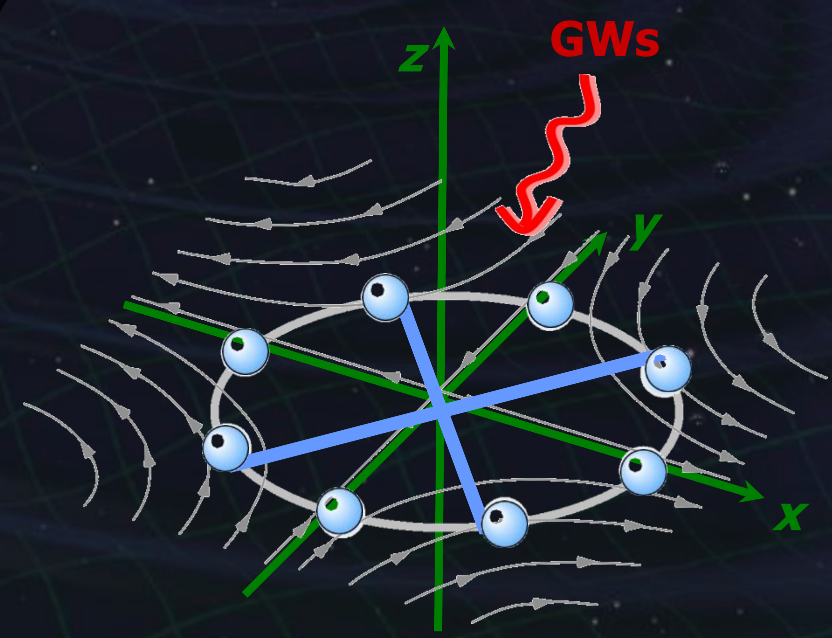
Detect differential length change



Strain $h \sim \frac{\delta L}{L}$

Torsion-bar antenna

Detect differential rotation



Angle $h \sim \delta\theta \sim \frac{\delta L}{L}$

Changes in tidal forces using free test masses

Interferometer and TOBA

Conventional IFO

Obs. band 10Hz-1kHz

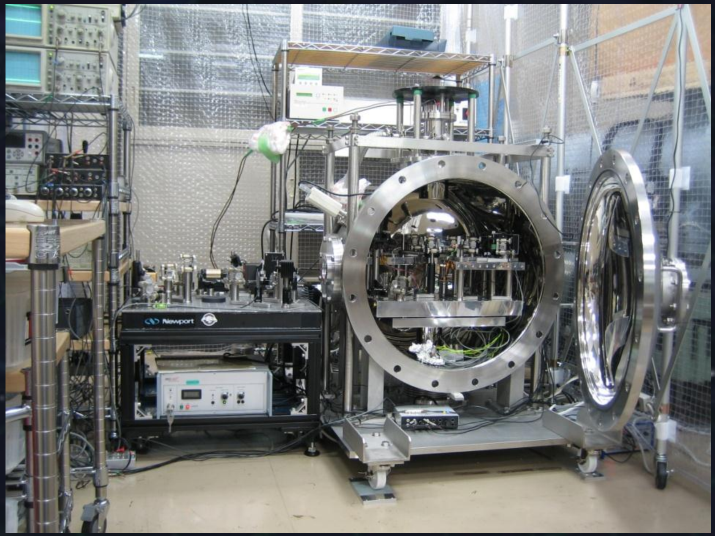
Suspended as pendulum
(Obs. band >>1Hz)

Long baseline
→ High sensitivity

$$\mathrm{SQL} \propto 1/(M \cdot L^2)^{1/2}$$

TOBA

Obs. band 10mHz-1Hz

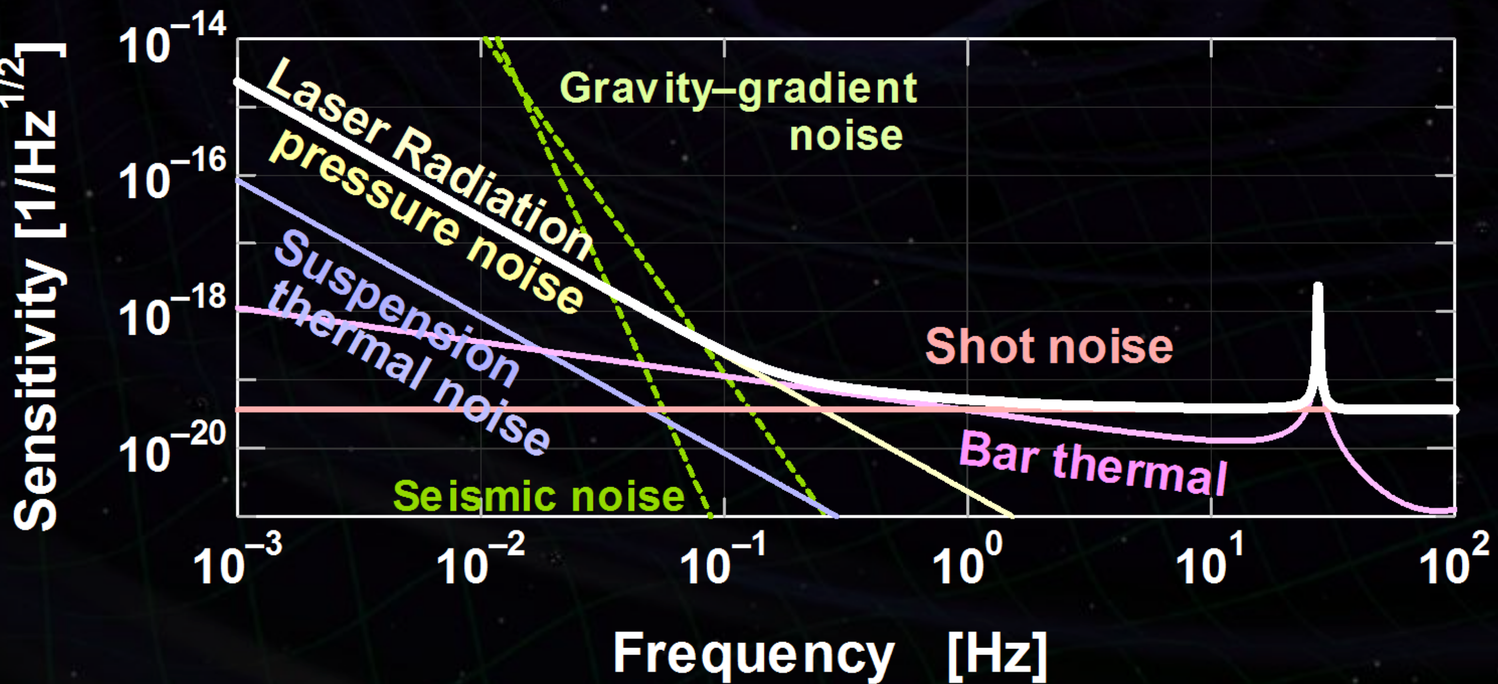


Torsion pendulum
(Obs. band >> 1mHz)

Shorter length
→ Simple config.
Common-mode rejection

Fundamental Noise Level

Practical parameters ⇨ $\tilde{h} \simeq 3 \times 10^{-19}$ $[\mathrm{Hz}^{-1/2}]$ (at 0.1 Hz)

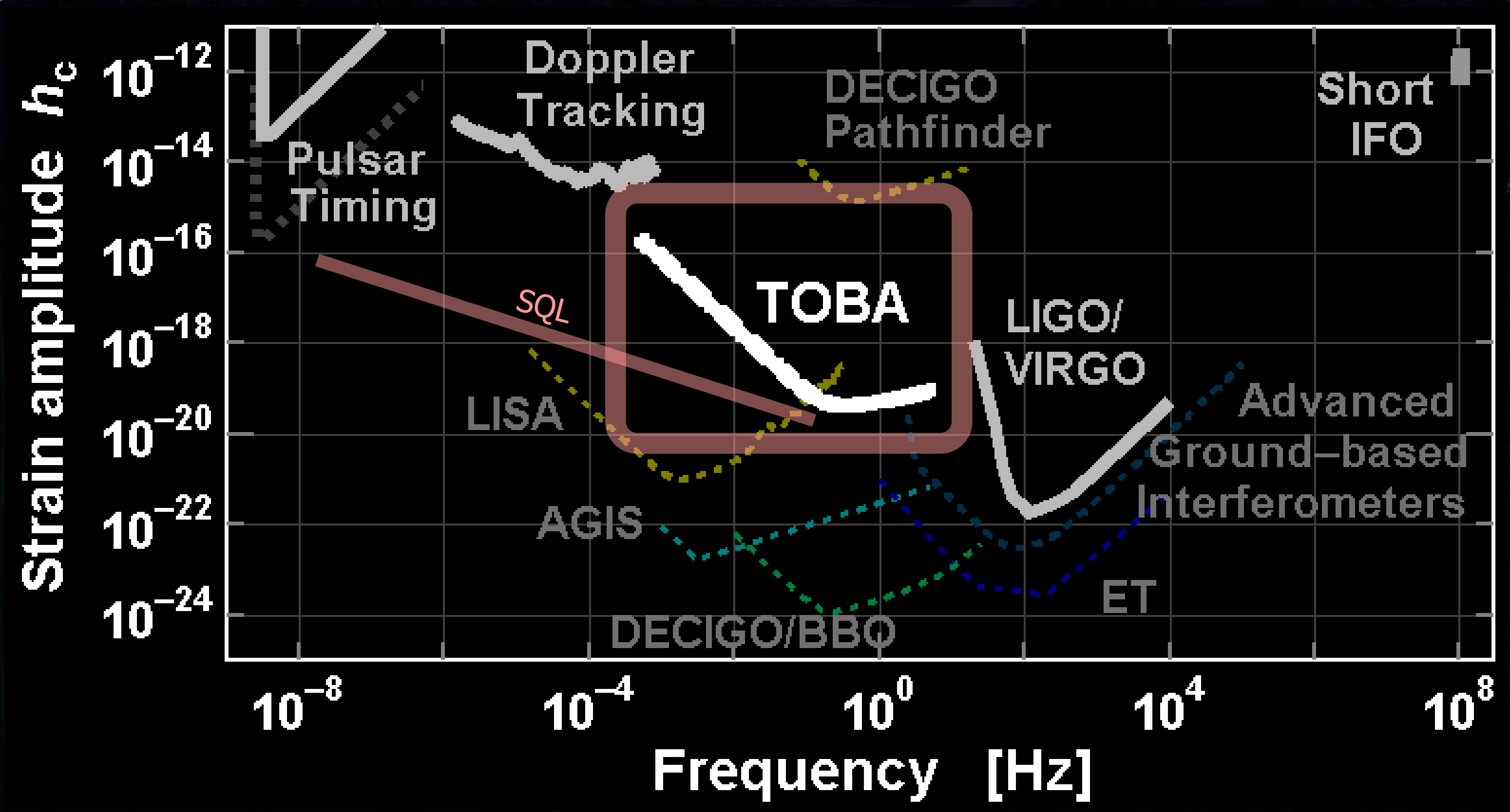


Bar length : 10m, Mass : 7600kg
Laser source : 1064nm, 10W
Cavity length : 1cm, Finesse : 100
Bar Q-value : 10^5 , Temp: 4K
Support Loss : 10^{-10}

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

TOBA Sensitivity

DECIGO/BBO band:
Between ground-based detectors and LISA bands

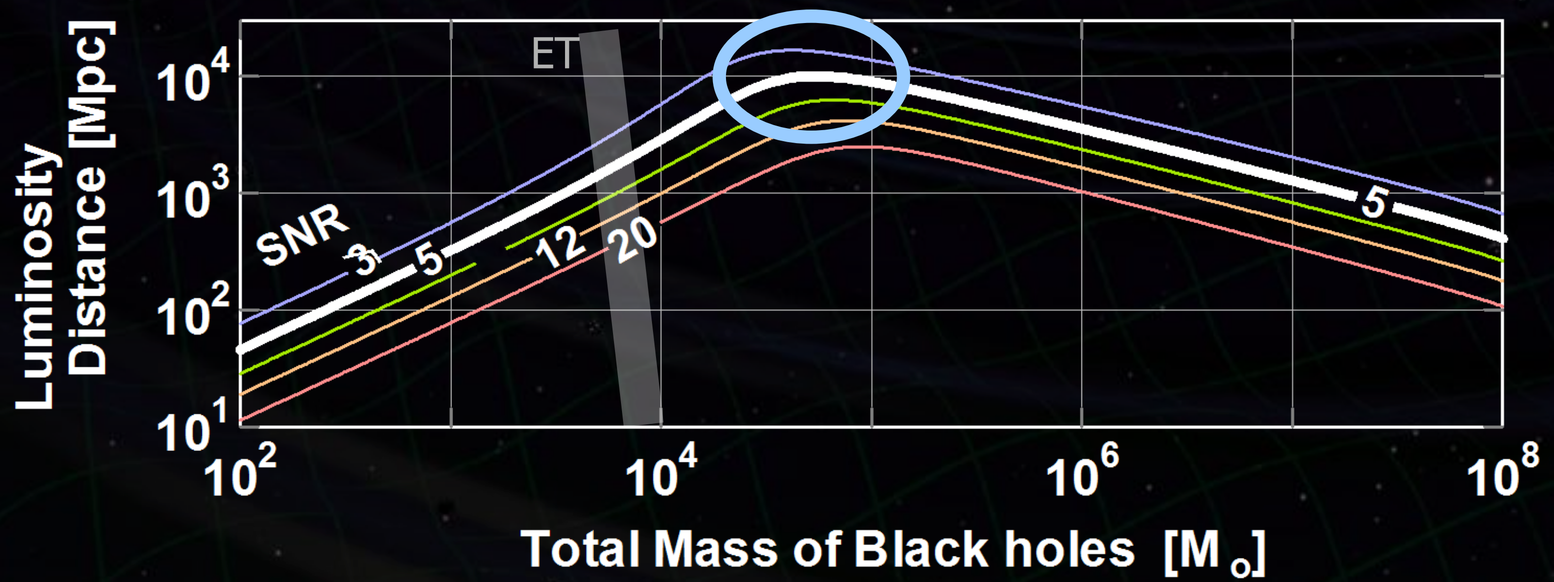


Characteristic amplitude : $h_c = \tilde{h} \times \sqrt{f_{\mathrm{center}}}$ (Dimensionless strain)

Observable Range

GWs from binary BH mergers

➡ Obs. Range ~10Gpc $(\sim 10^5 M_\odot,\ \mathrm{SNR} = 5)$



Calculation by K.Yagi : BH merger hybrid waveform, spin 0.5/0.5

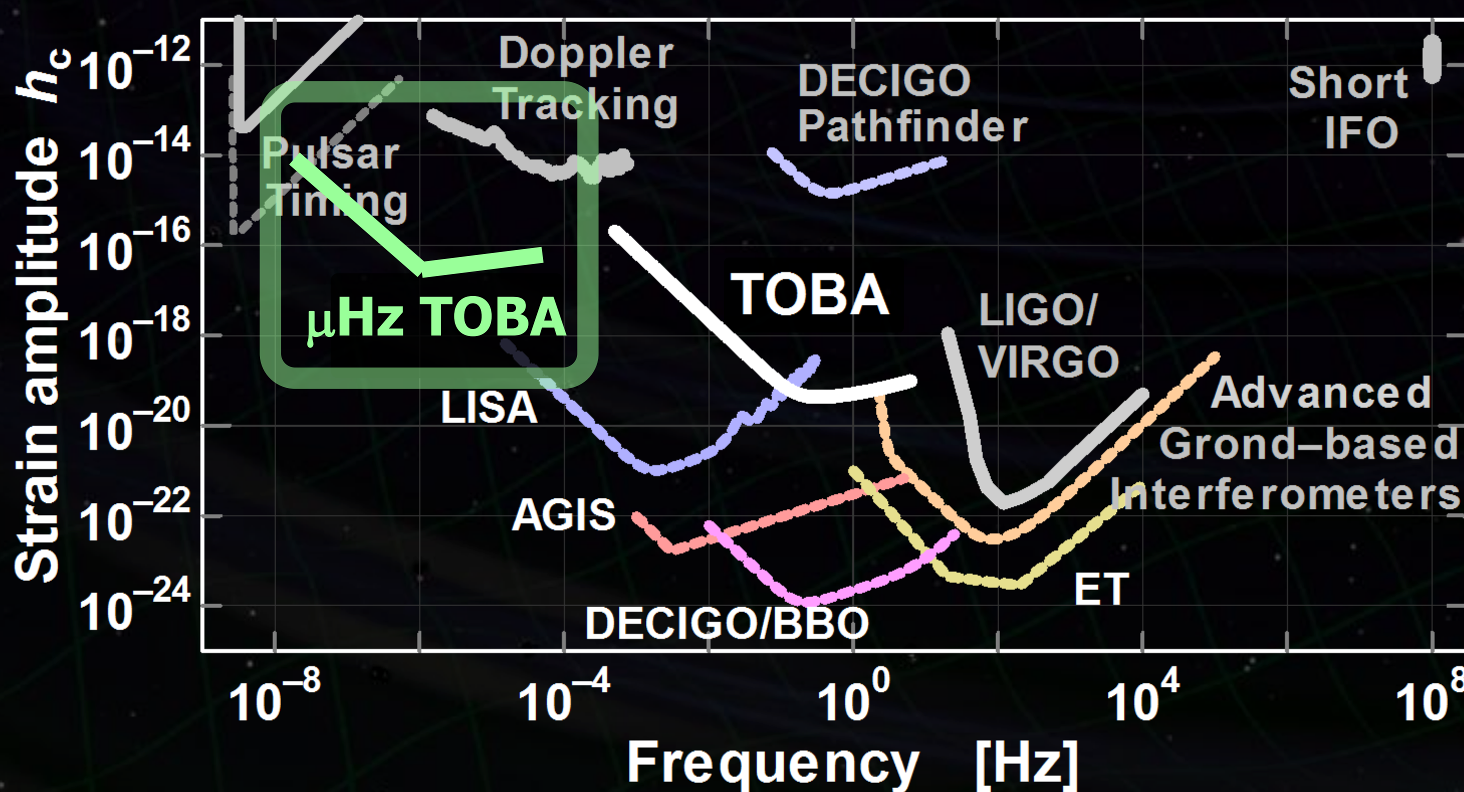
Micro-Hz TOBA

Tune center freq. to μHz

(Laser power 1mW, Rotation TOBA in space)

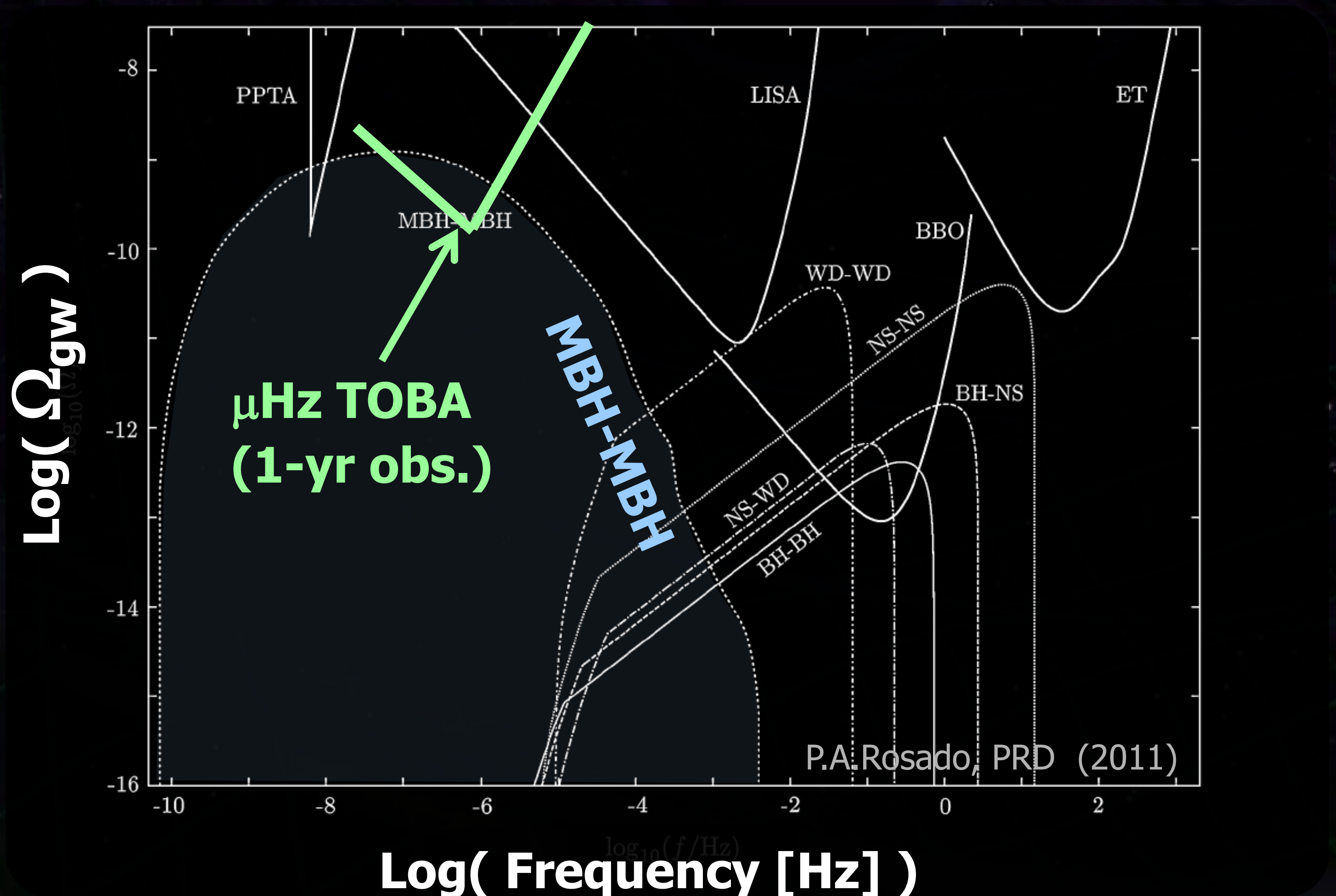
⇨ Bridge the Pulsar-timing and LISA

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



GWB Observation

GWB by MBH binaries → Galaxy (SMBH) formation scenario

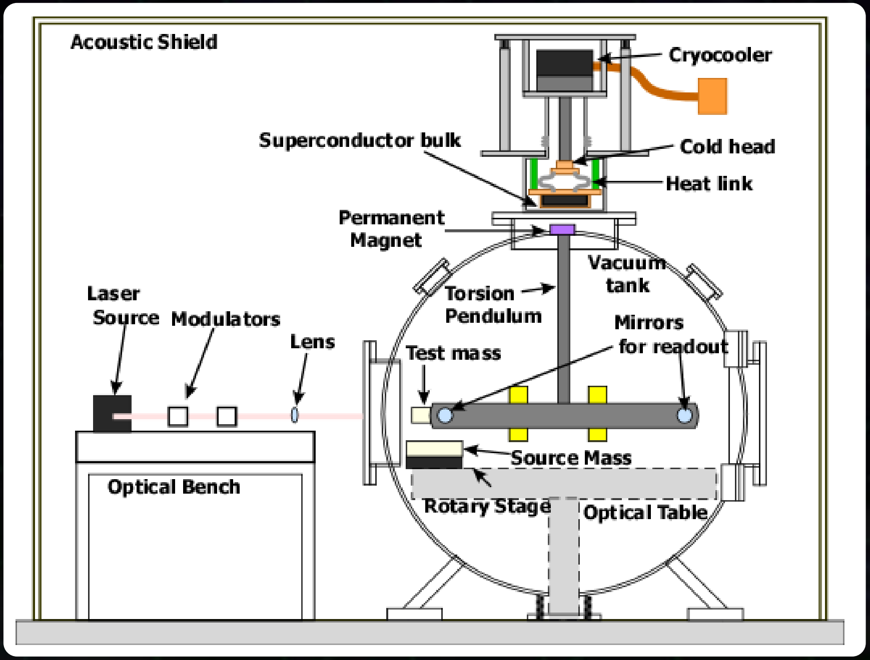


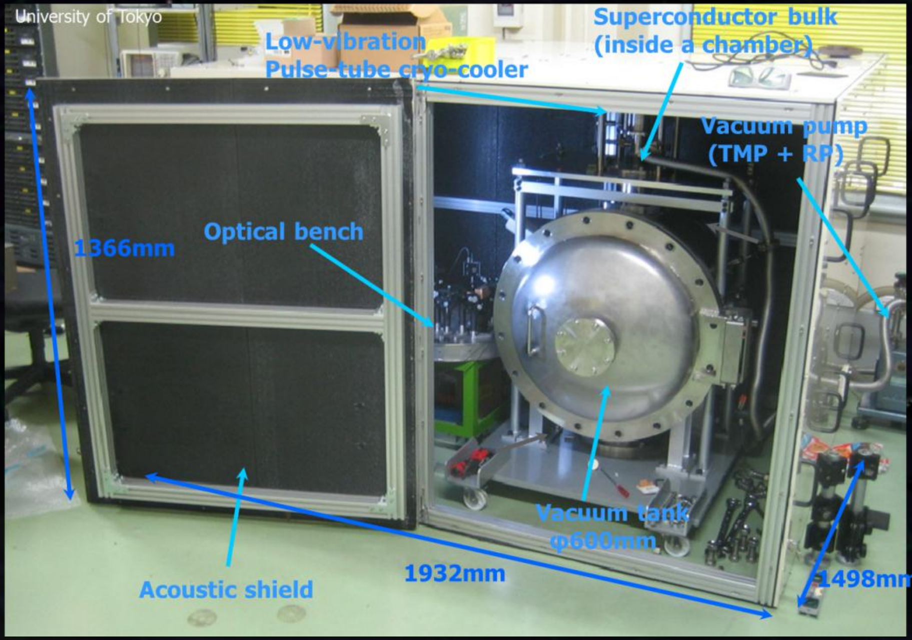
Prototype Tests

Reference:
- K.Ishidoshiro+ PRL (2011)
- A. Shoda, presentation at GWPAW2011
- W.Kokuyama, Ph.D thesis (2012)

First TOBA Prototype

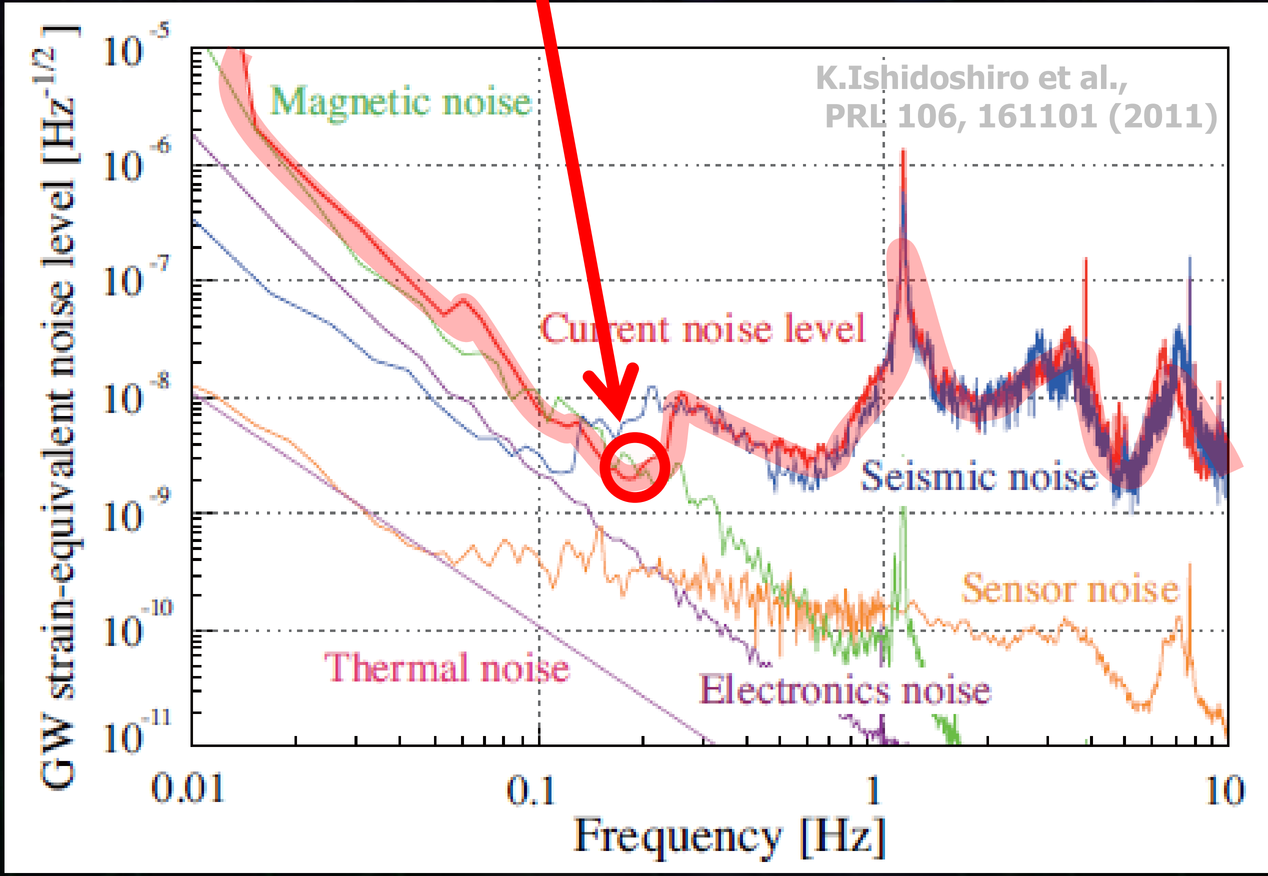
- Small-scale TOBA prototype (Univ. Tokyo, 2006 -)
  - 20cm test-mass bar at room temperature
  - Torsion pendulum by super-conductive levitation
  - Sensor : Michelson interferometer with Nd:YAG laser





Sensitivity of Small TOBA

Sensitivity $\tilde{h} \simeq 2 \times 10^{-9}$ $[\mathrm{Hz}^{-1/2}]$ at 0.2Hz

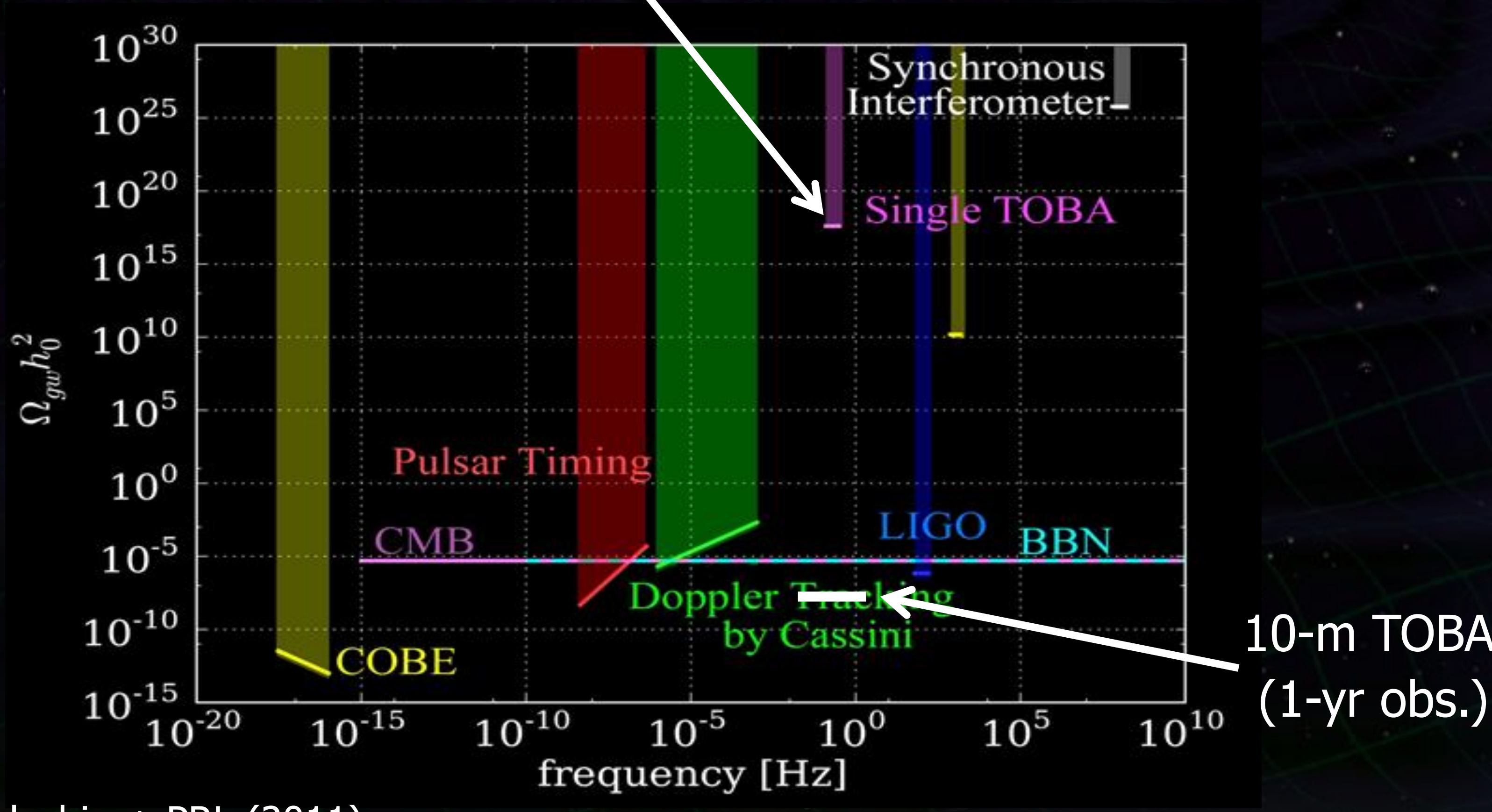


Limited by magnetic disturbances and seismic coupling

Comparison with Previous Results

New upper limit at unexplored frequency band of 0.2Hz

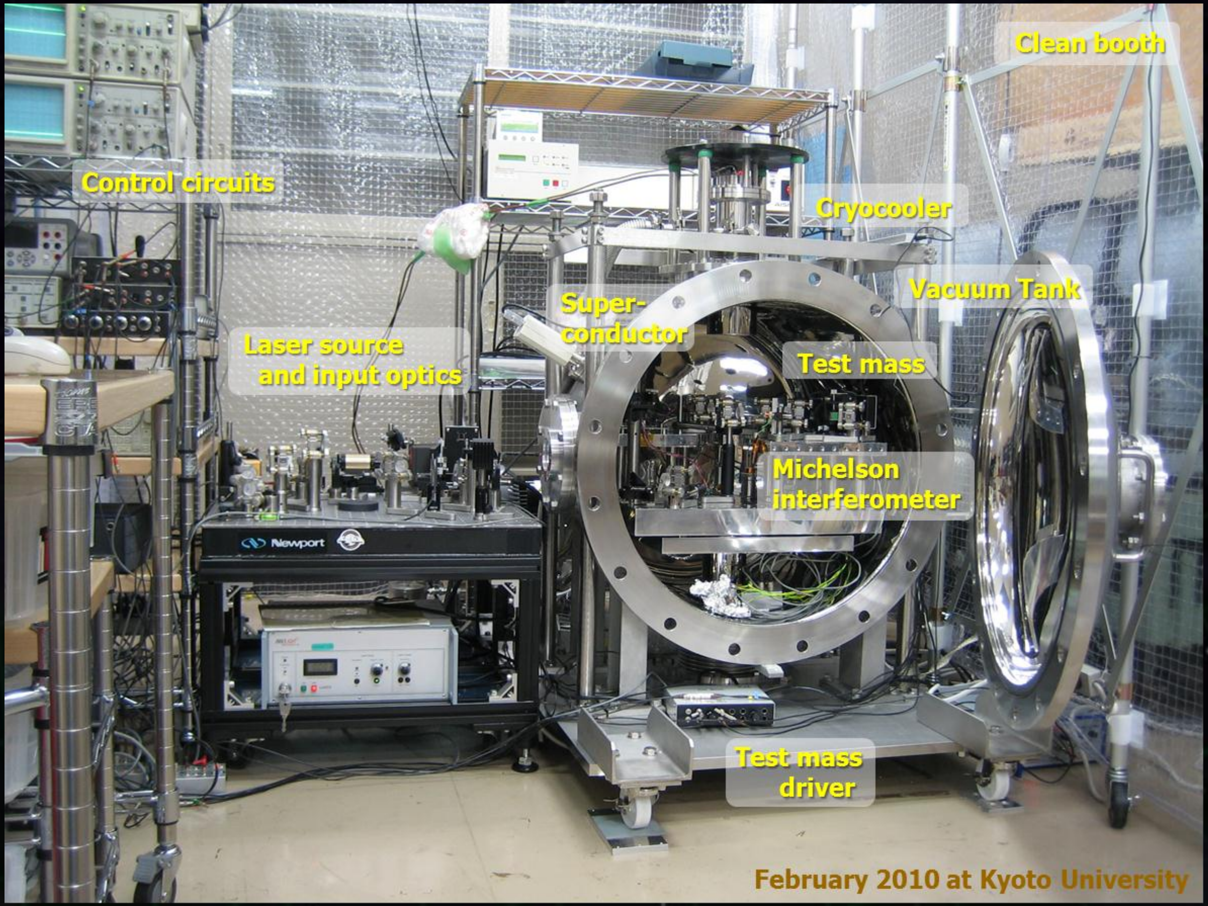
$$\Omega_{gw}^{UL} = 4.3 \times 10^{17} \quad \text{(C.L. 95\%)}$$



K.Ishidoshiro+ PRL (2011)

Second Small-scale TOBA

- Small-scale TOBA prototype (Kyoto Univ., 2009 -)
  - Almost same design as the first one
  - Small differences : Cooling system, Test mass shape

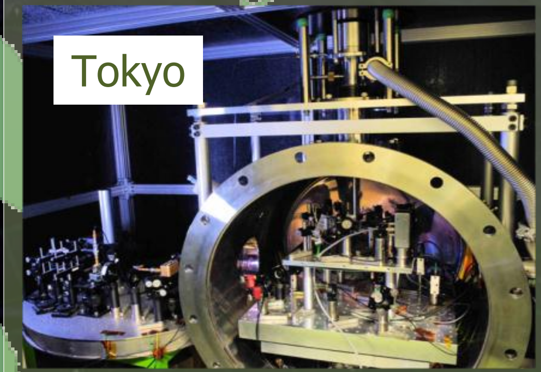


Observation with Two Detectors

Observation with two detectors

- Tokyo and Kyoto, 370km separation
- Comparable sensitivity

On-line calibration
(for monitoring the gain):
8.7 Hz signal
Monitored GPS signal:
1pps and serial signal
Temperature: ~40K



On-line calibration
(for monitoring the gain):
10 Hz signal
Monitored GPS signal:
1pps signal
Temperature: ~70K

DATE: 0:00 – 5:00, July 20, 2010
Sampling frequency: 1kHz
Direction of Test-mass bar: north-south

Original fig. by
A.Shoda
(GWPAW 2011)

Sensitivities

One-night observation runs x three times

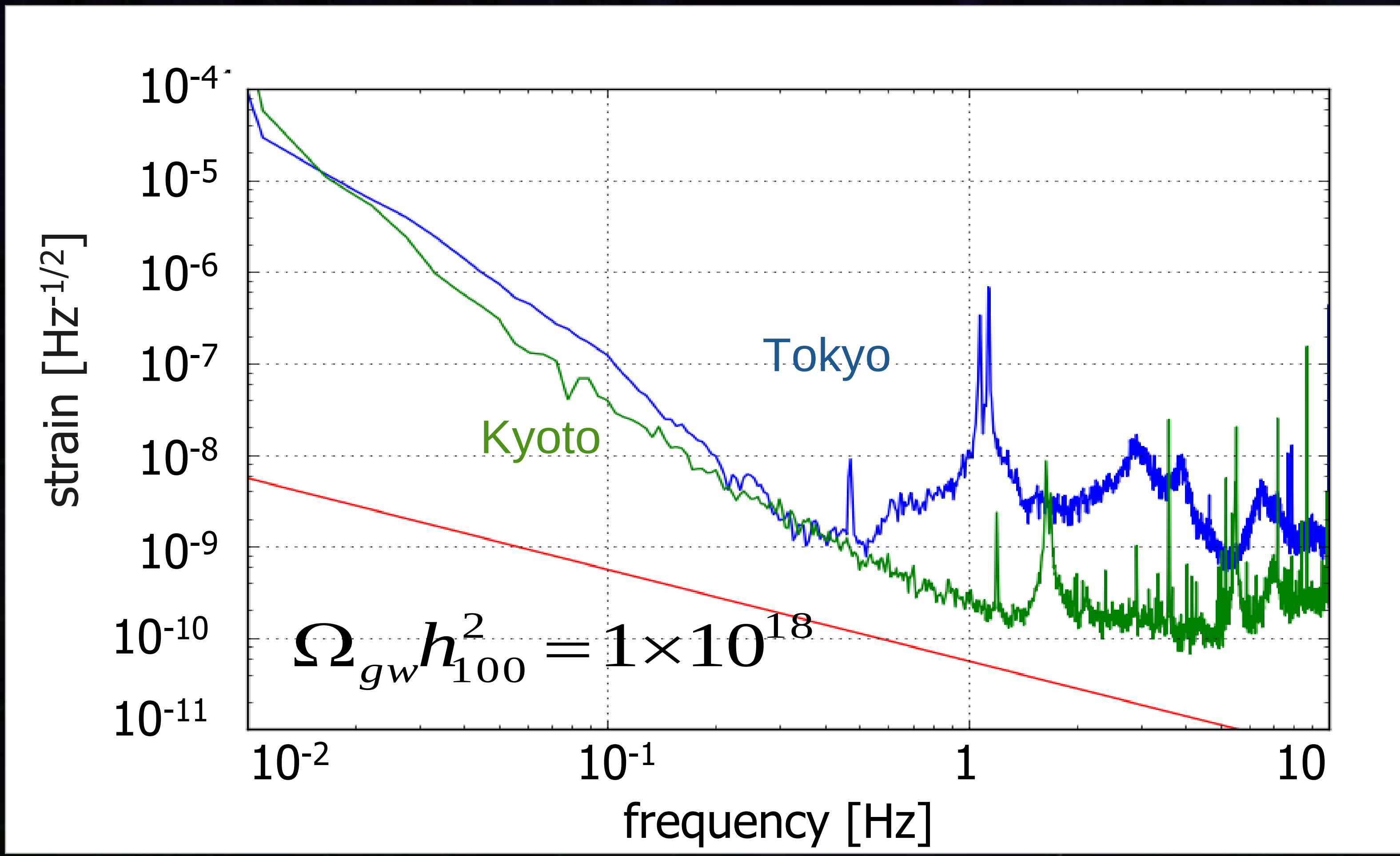


Fig. By A.Shoda

Upper Limit by Two TOBAs

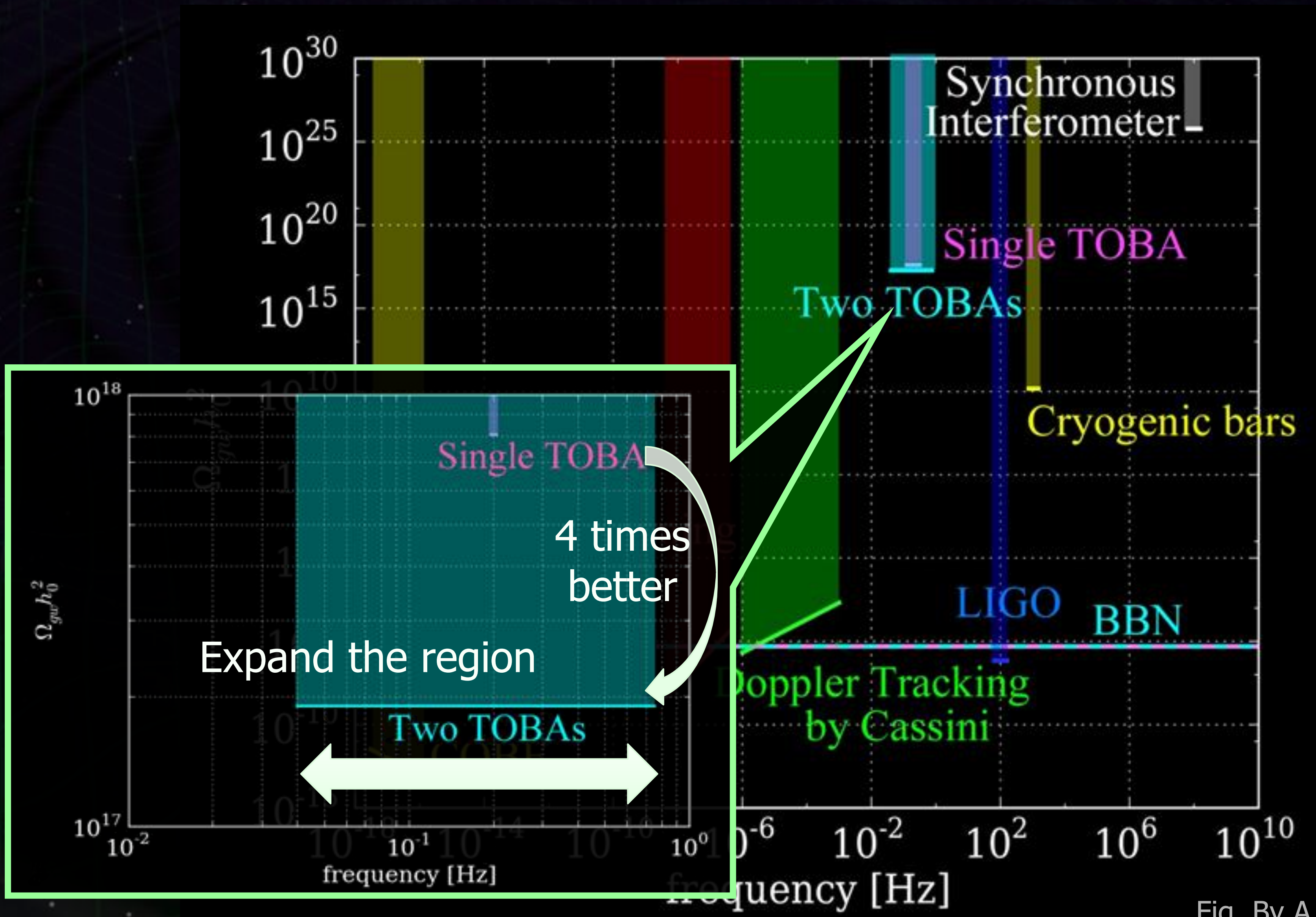
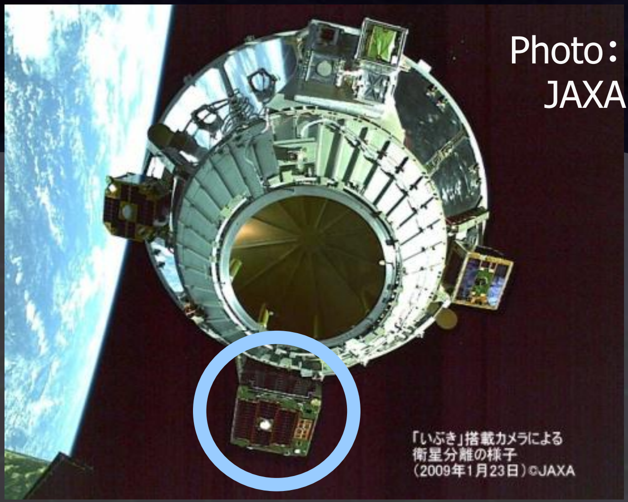


Fig. By A.Shoda

Space TOBA : SWIMμν

Small Module SWIMμν on SDS-1

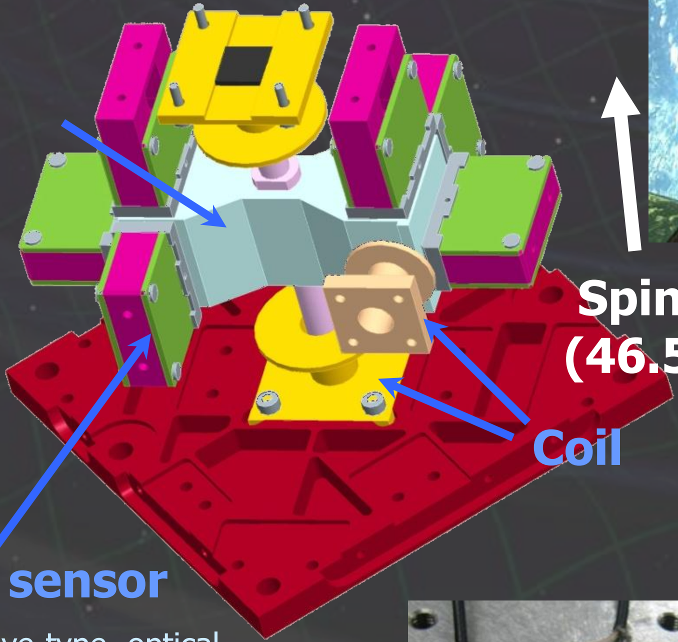
Launched Jan. 2009, Terminated Sept. 2010



TAM: Torsion Antenna Module with free-falling test mass
(Size : 80mm cube, Weight : ~500g)

Test mass

~47g Aluminum, Surface polished
Small magnets for position control

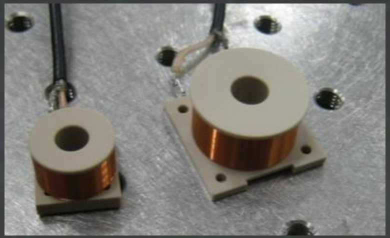


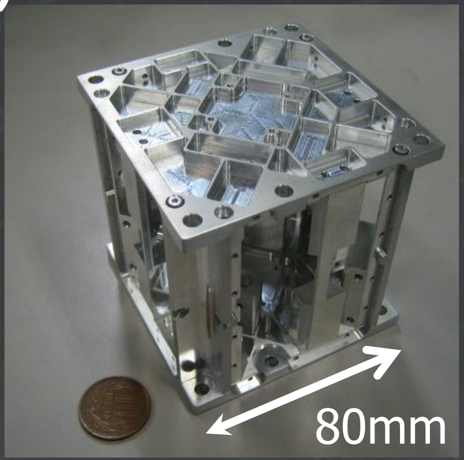
Spin Axis (46.5mHz)

Coil

Photo sensor

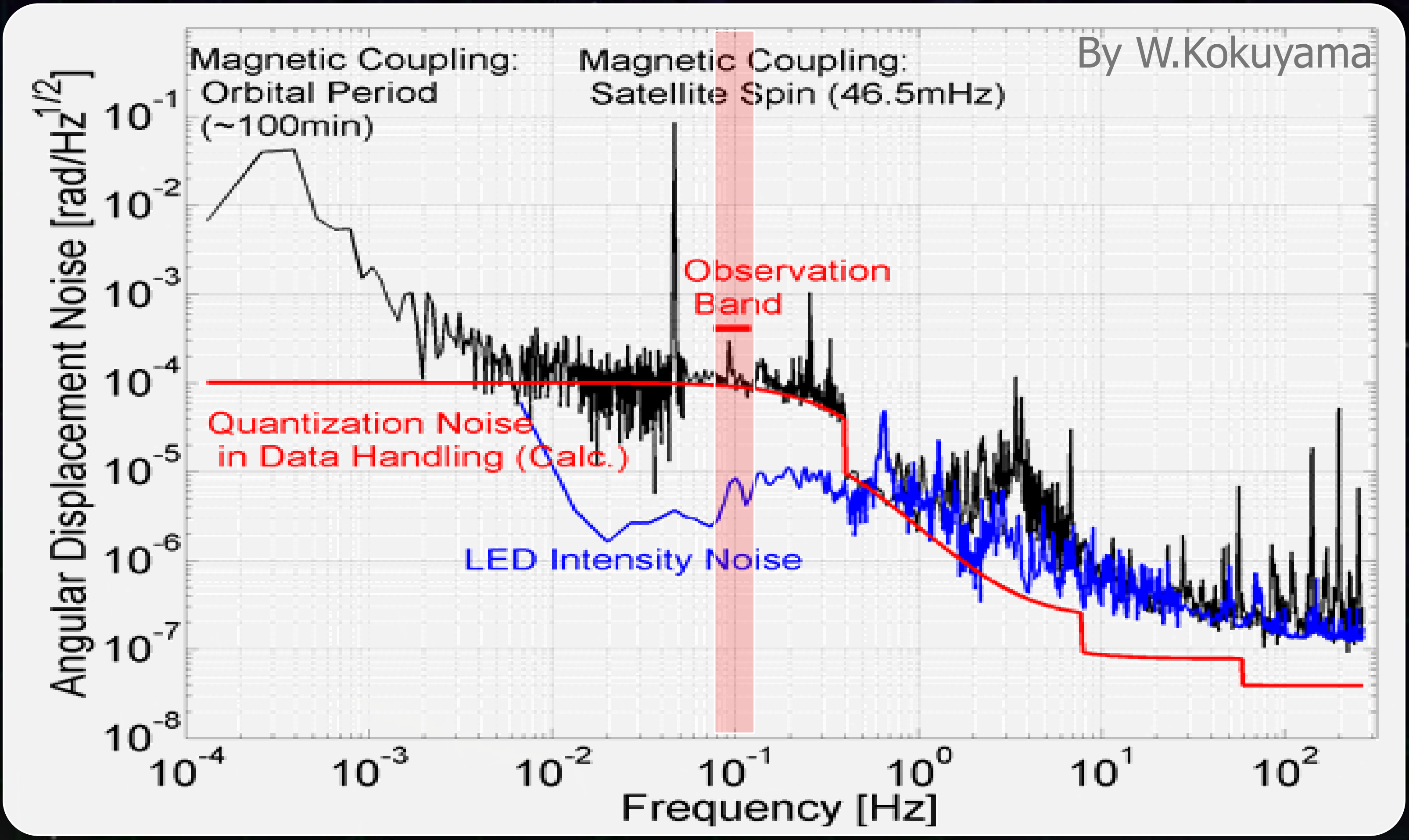
Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion





Sensitivity

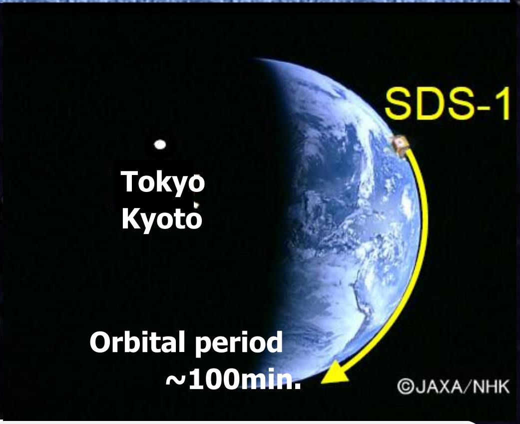
Though limited by non-fundamental noises, best as a space-borne GW detector.

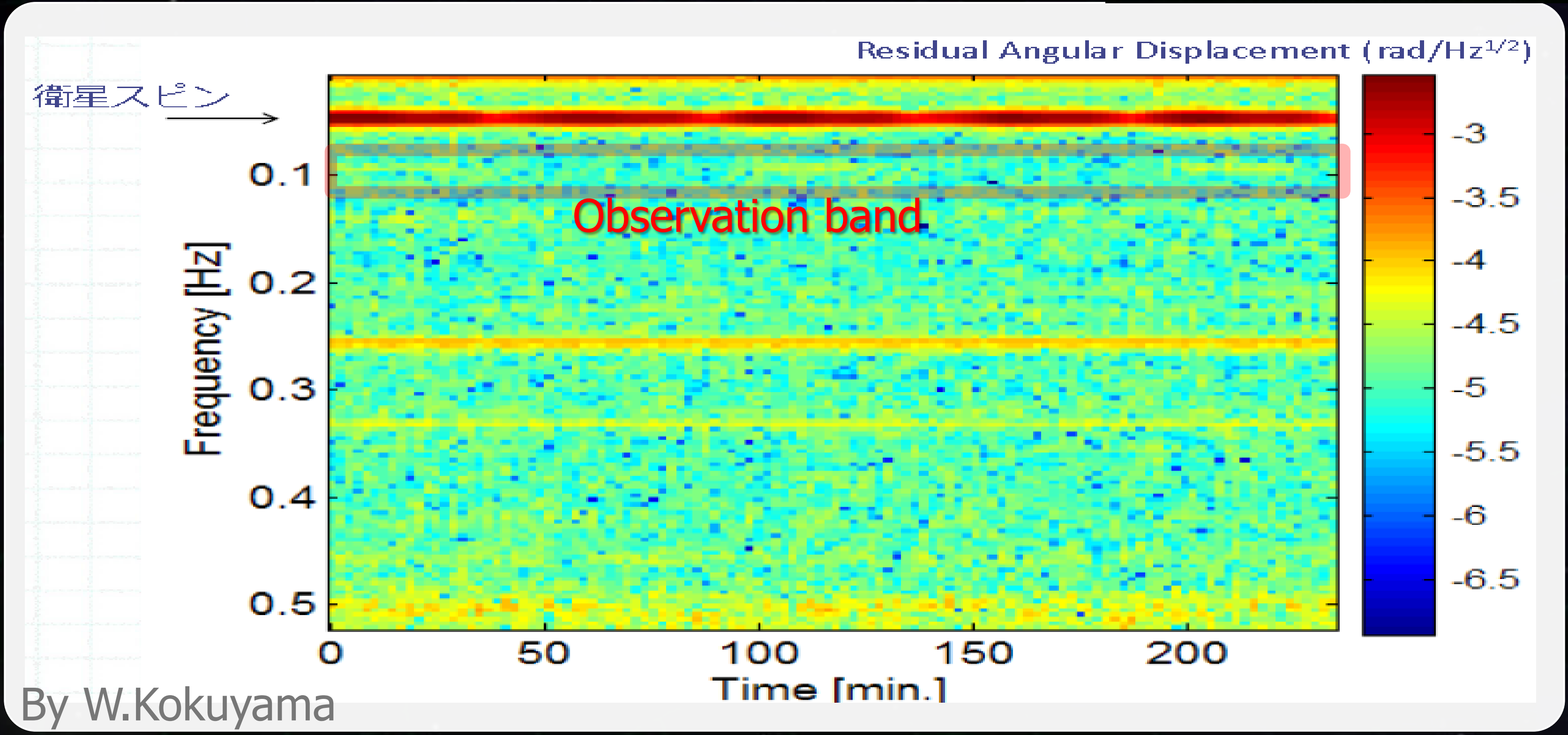


Observation by SWIM

Continuous data taking

Jun 17, 2010 ~120 min.
July 15, 2010 ~240 min.





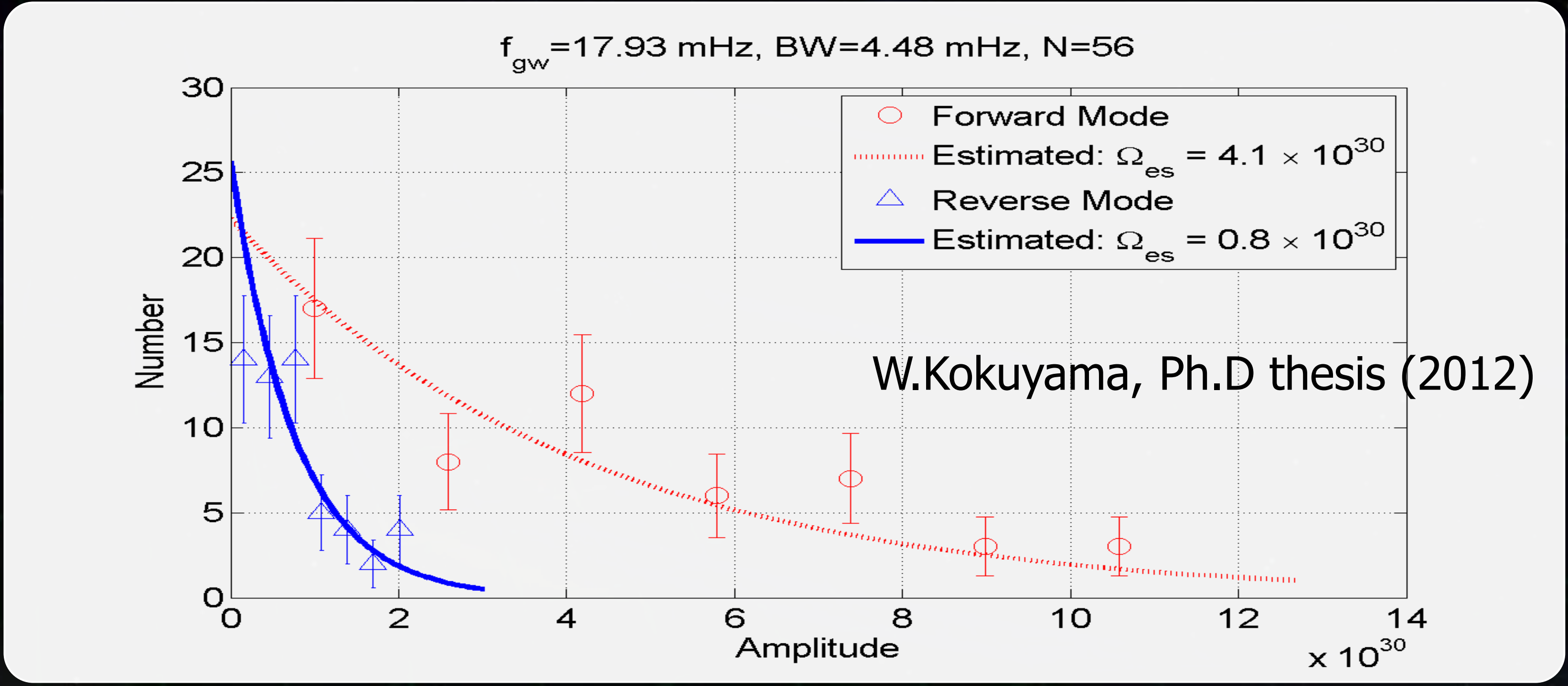
Upper Limit on GWB

Upper Limit at two frequencies (two polarizations)

'Forward' mode $\Omega_{gw}^{FW} = 1.7 \times 10^{31}$

'Reverse' mode $\Omega_{gw}^{RE} = 3.1 \times 10^{30}$

(C.L. 95%, f0 18mHz, BW 4mHz)



Next Prototype plan

Medium-scale TOBA

- One more prototype step before the 10-m TOBA.
  - Scientific outcomes.
  - Common techniques with KAGRA, ET, …
  - Realistic both in technology and the budget.

⇩

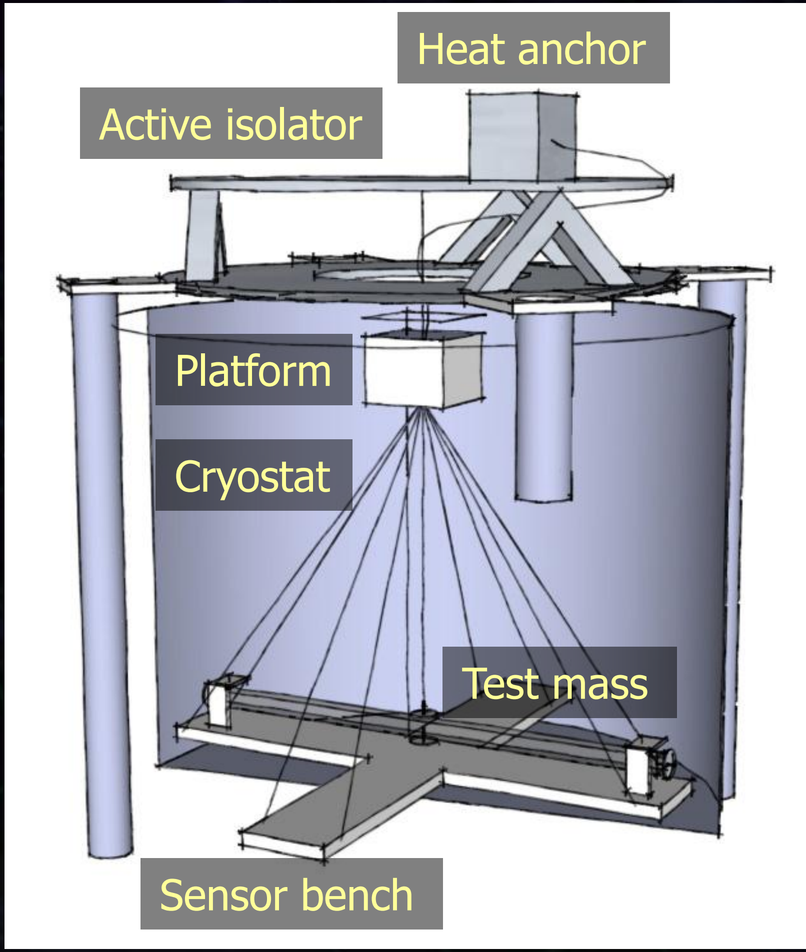
Medium-scale TOBA for Newtonian noise observation.

Medium-scale TOBA

One-meter scale TOBA at cryogenic temp. (2012-)

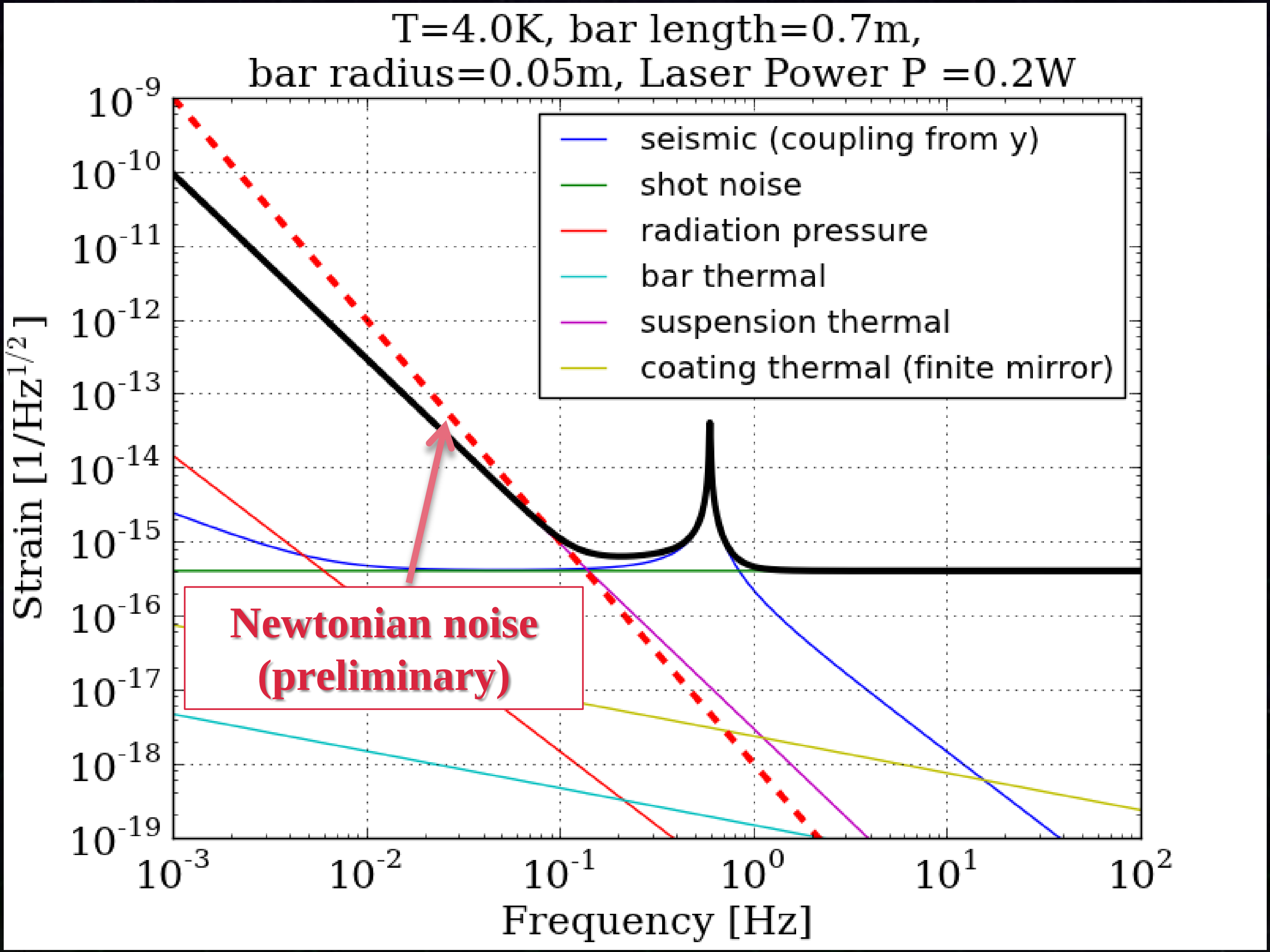
- Intermediate step
  for 10-m scale TOBA
- Low-freq. GW observation
  $h \sim 10^{-15}$ at 0.1Hz
- Newtonian noise sensor

Synergy with interferometers
- Low-freq. observation
- Cryogenic technologies



Preliminary design by A.Shoda

Sensitivity of Mid.-scale TOBA



Summary

Summary (1/2)

- Novel type GW detector : TOBA

  → Low-freq. observation ($\sim 10^{-8}$ – 1 Hz) .

  - Observable Range >10Gpc for BH inspirals.
  - Observation of GWB by MBH at 1μHz.

- First prototypes

  - Small-scale TOBAs at Tokyo and Kyoto

    → First upper limits on GWB at 0.1-0.2Hz band.

  - SWIM as a space-borne rotating TOBA

    → Upper limit on GWB at 18mHz.

Summary (2/2)

- Next prototype plan
  - Medium-scale cryogenic TOBA with length ~1m.
  - Low-freq. GW detector and also a NN sensor.
  - Common techniques with KAGRA, ET, …

4-year (small) fund has been approved in 2012
→ Under design and development

End