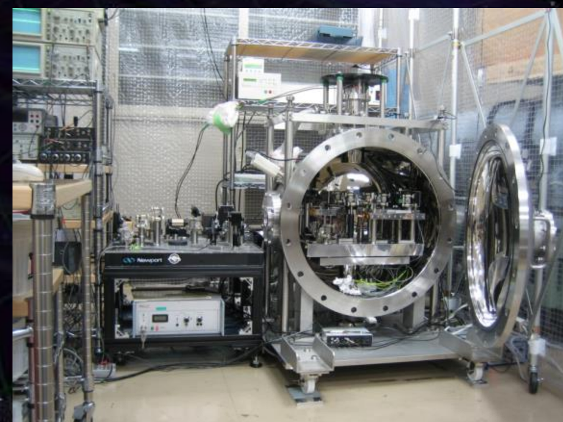
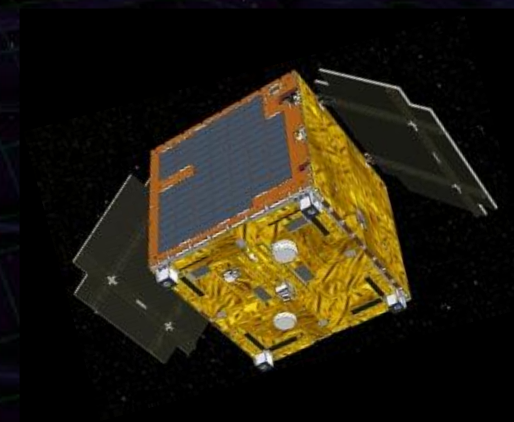
TOBA: Torsion-Bar Antenna

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

京都大学 基礎物理学研究所 談話会 (2013年3月8日, 京都大学)

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

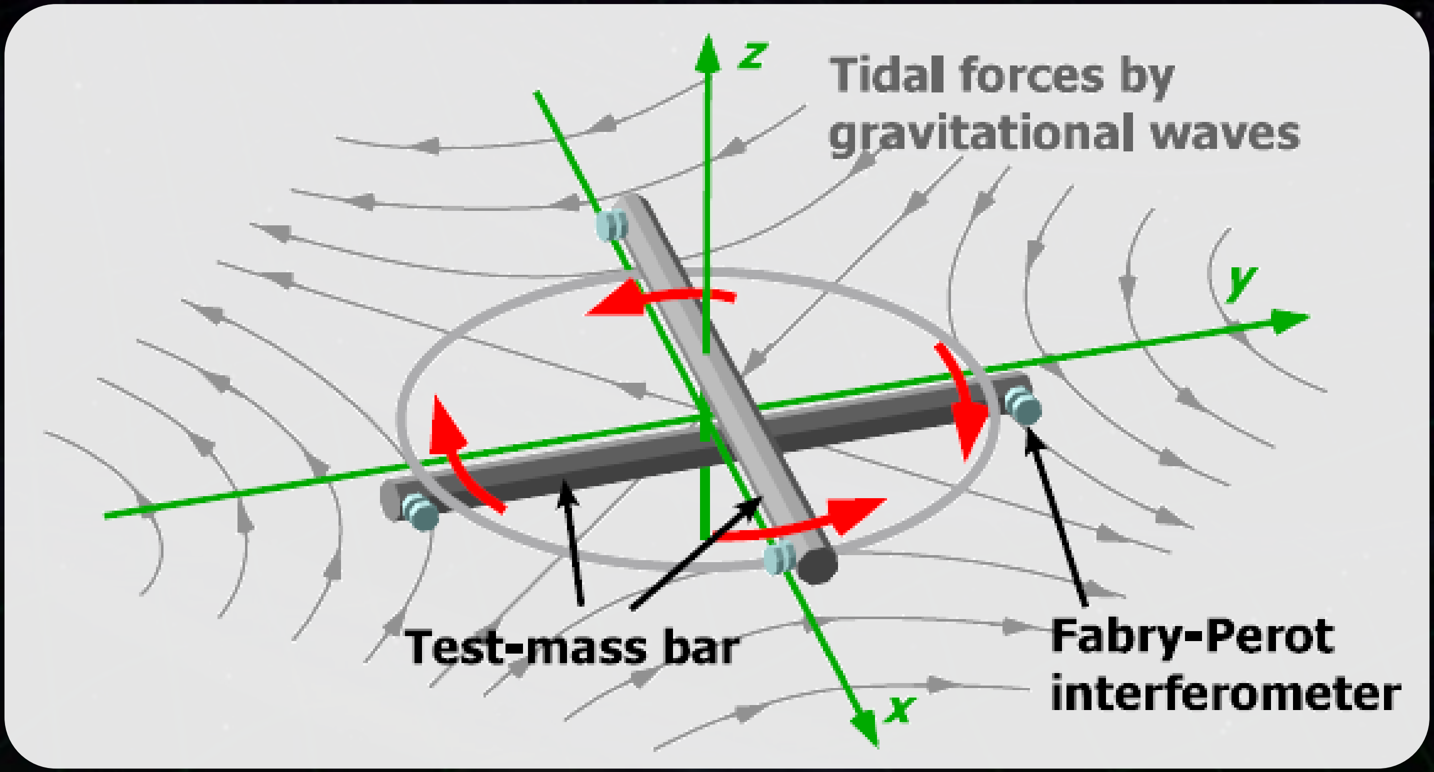
TOBA Introduction

Reference: MA+, PRL (2010)

TOBA

TOBA : Torsion-Bar Antenna

Monitors tidal-force fluctuation caused by GWs.

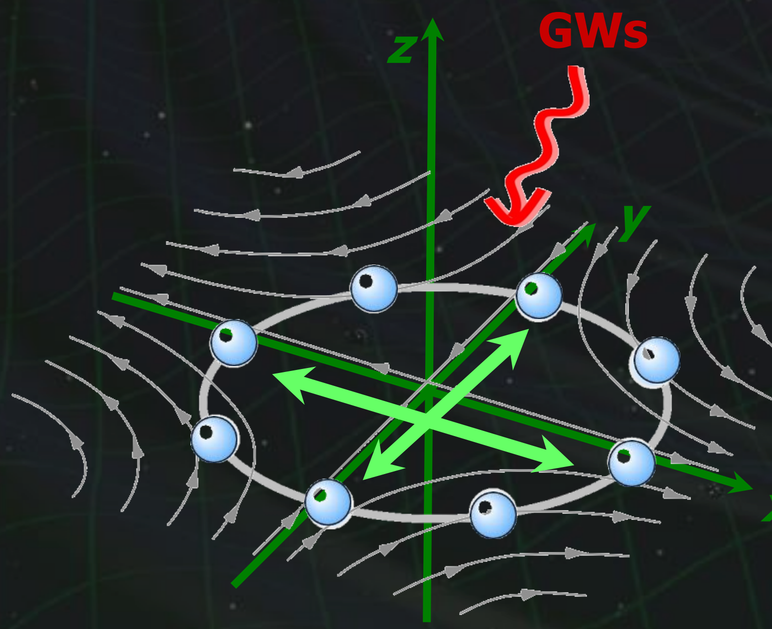


MA+, Phys. Rev. Lett. 105, 161101 (2010)

Detection Principle

Conventional IFO antenna

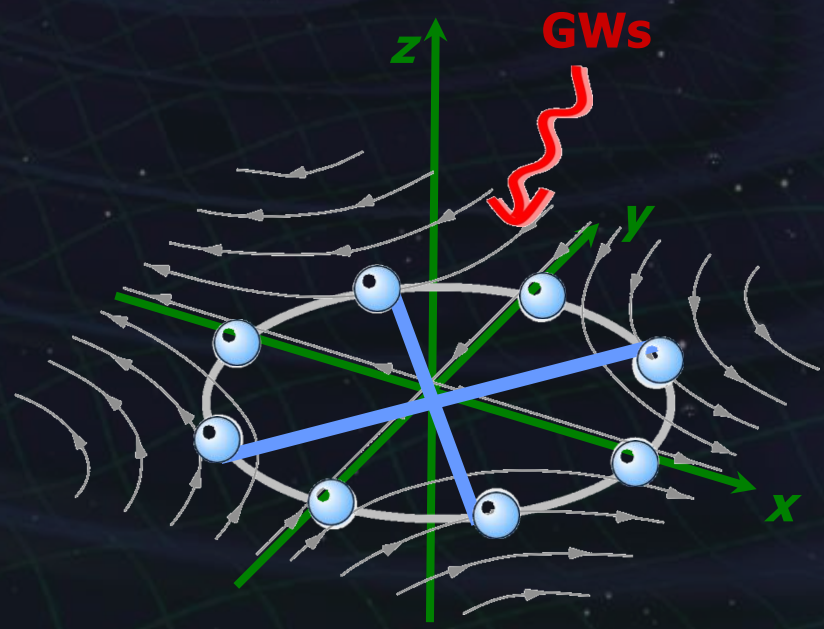
Detect differential length change



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

Torsion-bar antenna

Detect differential rotation



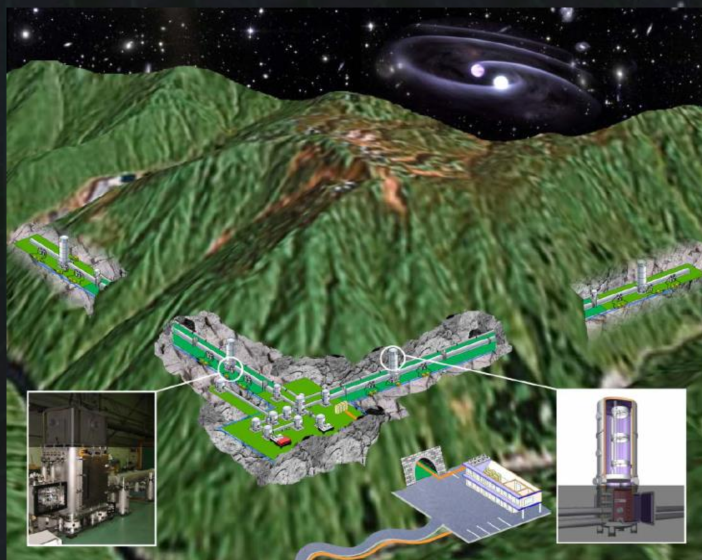
Angle $h \sim \delta\theta \sim \frac{\delta L}{L}$

Changes in tidal forces using free test masses

Interferometer and TOBA

Conventional IFO

Obs. band 10Hz-1kHz

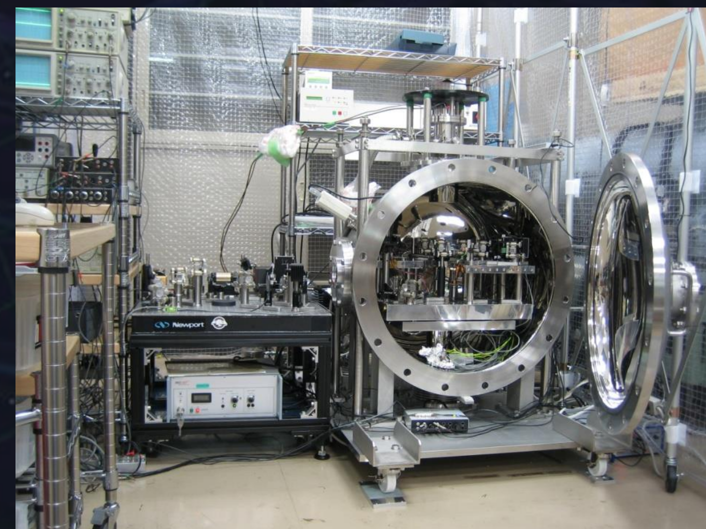


Suspended as pendulum
(Obs. band >>1Hz)

Long baseline
→ High sensitivity
$\mathrm{SQL} \propto 1/(M \cdot L^2)^{1/2}$

TOBA

Obs. band 10mHz-1Hz

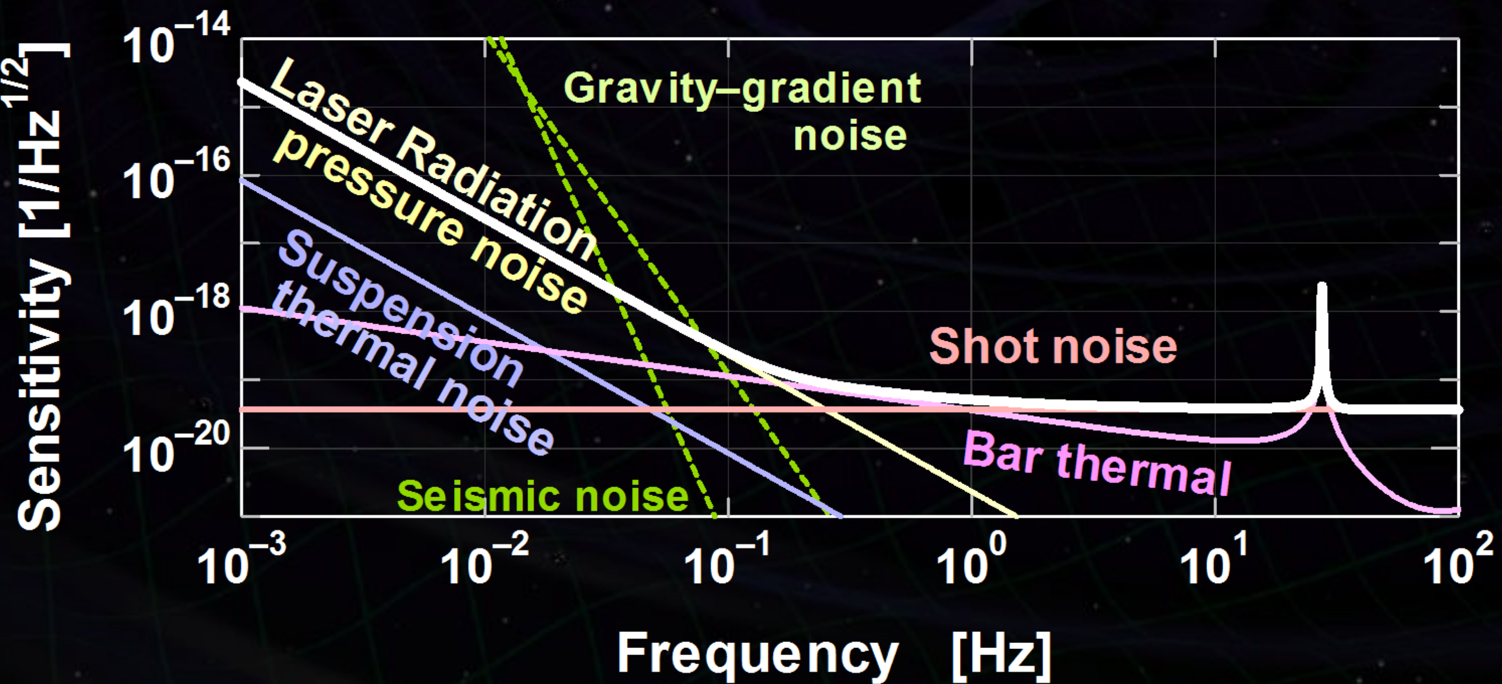


Torsion pendulum
(Obs. band >> 1mHz)

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)



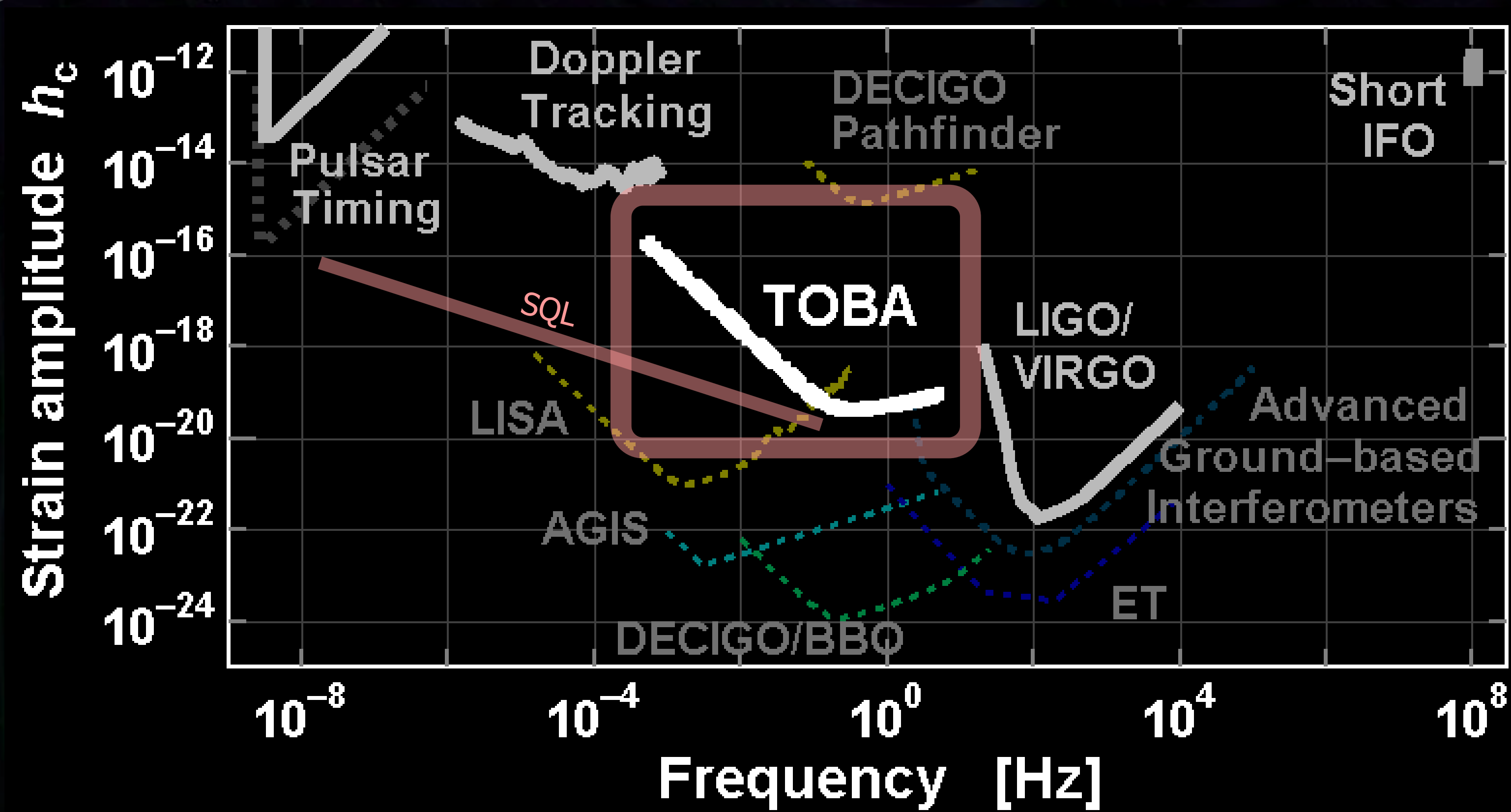
Bar length : 10m, Mass : 7600kg
Laser source : 1064nm, 10W
Cavity length : 1cm, Finesse : 100
Bar Q-value : 10^5 , Temp: 4K
Support Loss : 10^{-10}

Laser Freq. noise < $10\mathrm{Hz/Hz}^{1/2}$,
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

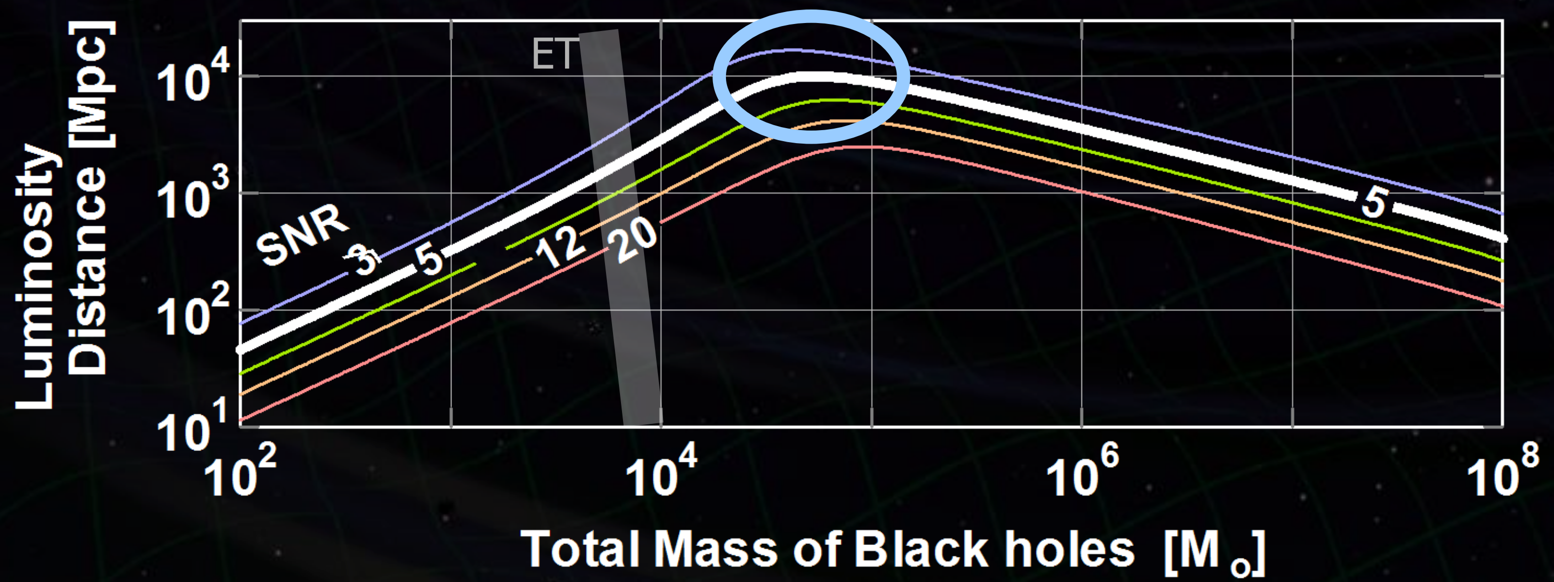


Characteristic amplitude : $h_c = \tilde{h} \times \sqrt{f_{\rm center}}$ (Dimensionless strain)

Observable Range

GWs from binary BH mergers

⇒ Obs. Range ~10Gpc ($\sim 10^5 M_\odot$, SNR = 5)



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

Background GWs

Observable GW energy density ratio

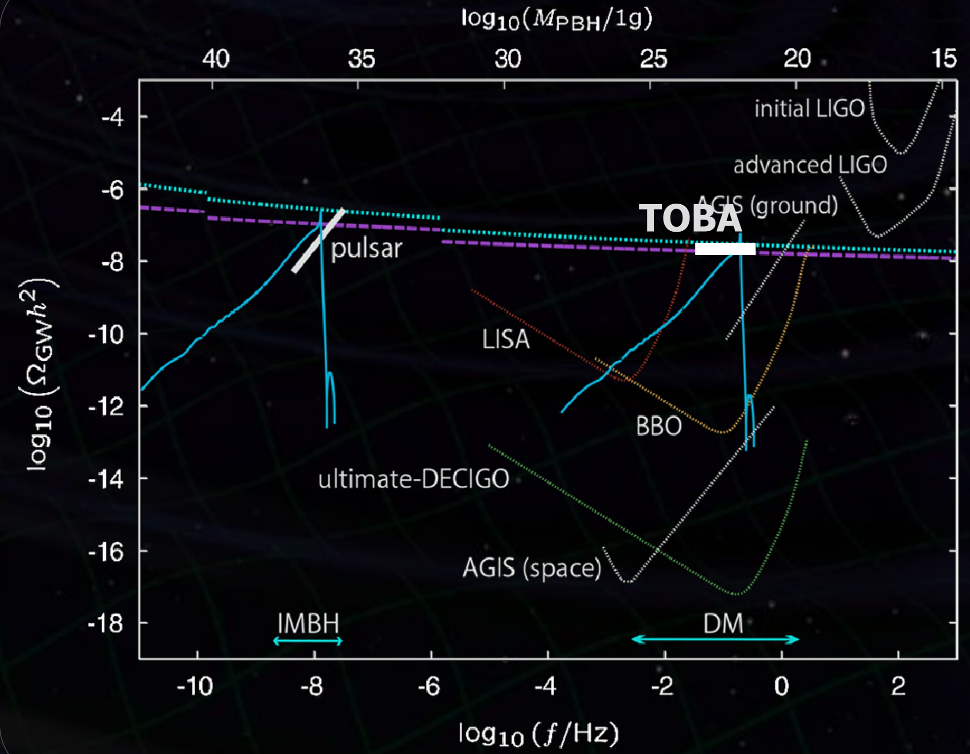
$$\Omega_{gw} \sim 10^{-7}$$

(1-yr obs. by 2 TOBAs)

Beat BBN upper limit

GW by primordial tensor perturbation

R.Saito and J.Yokoyama, PRL 102, 161101 (2009)



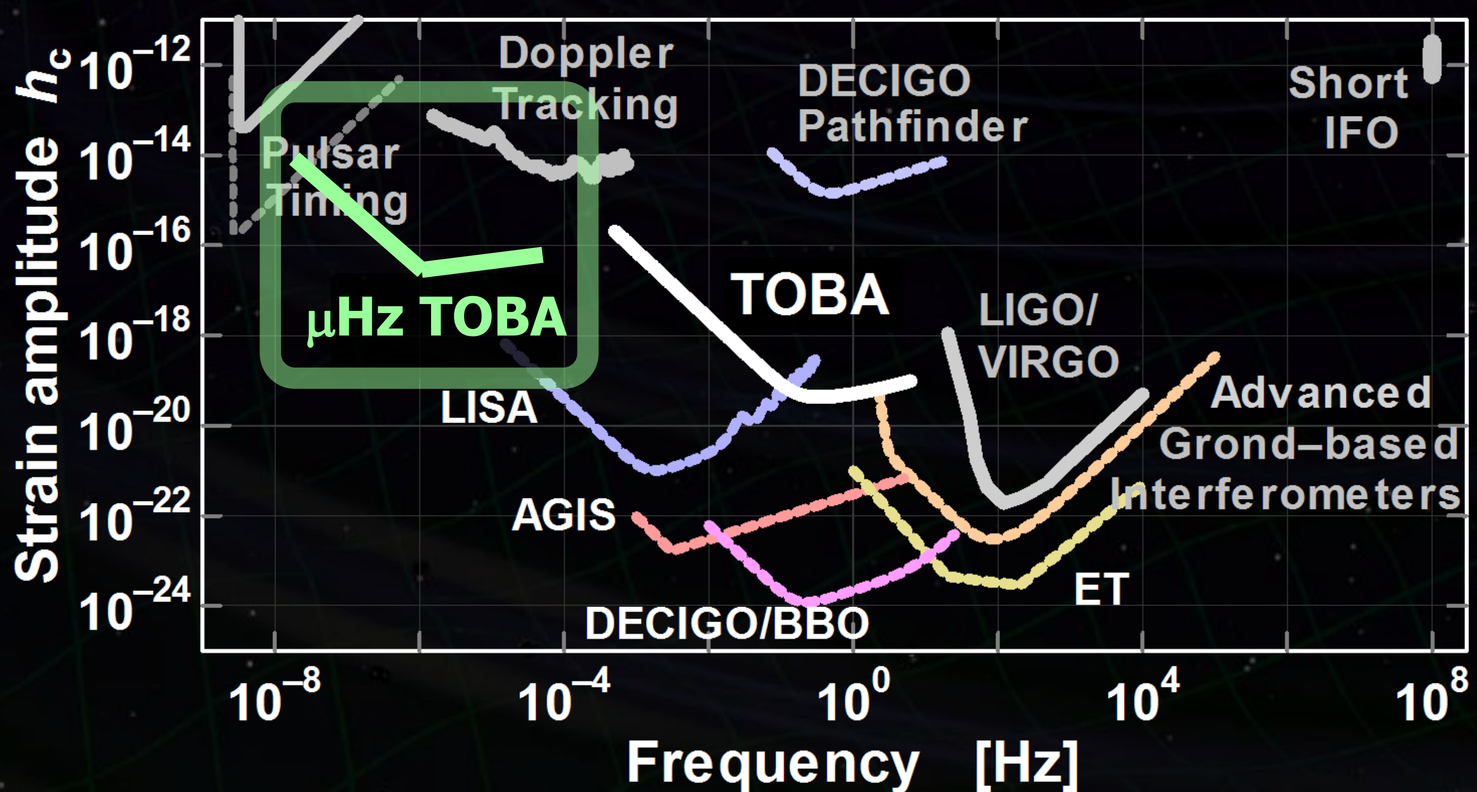
Micro-Hz TOBA

Tune center freq. to μHz

(Laser power 1mW, Rotation TOBA in space)

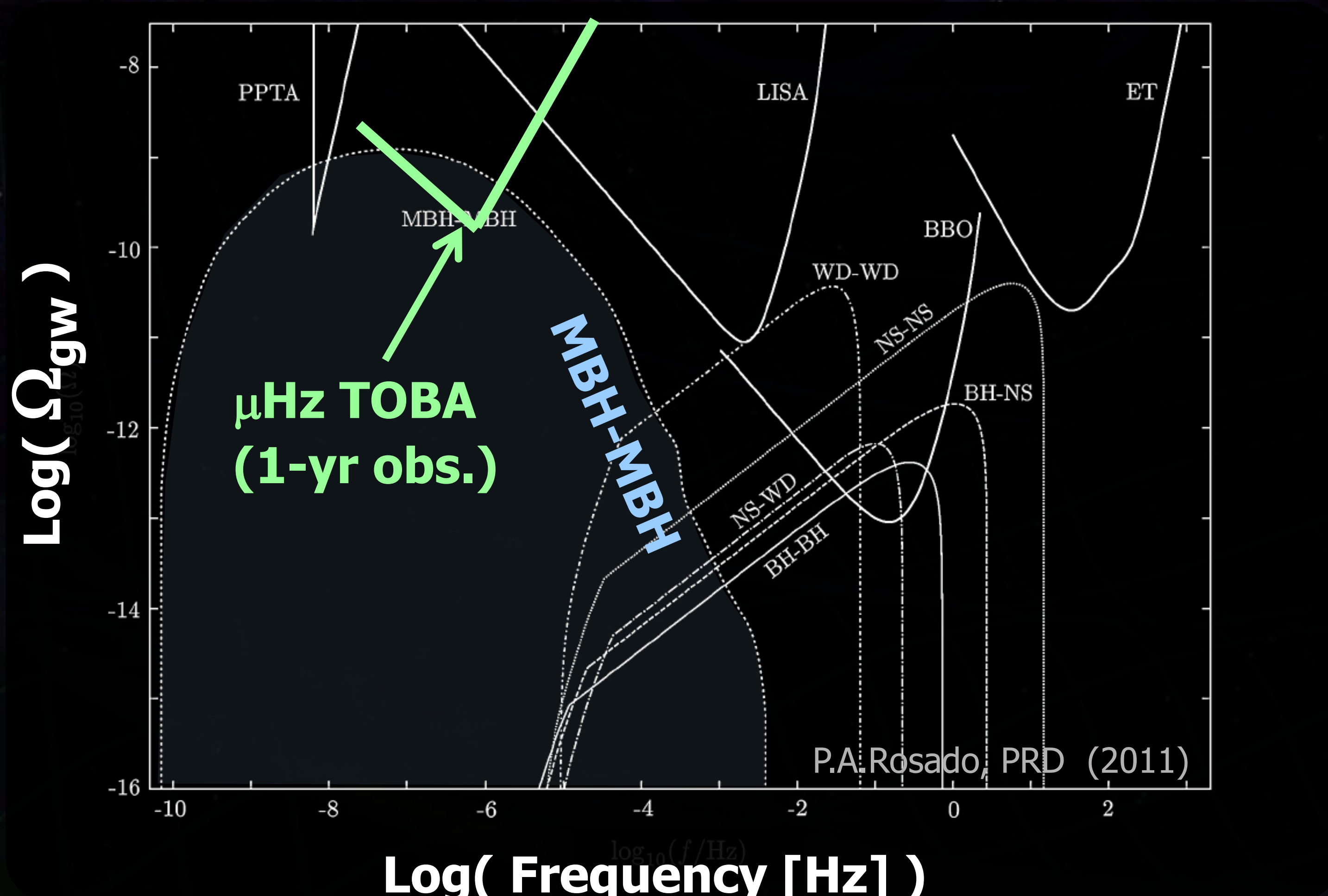
⇨ Bridge the Pulsar-timing and LISA

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

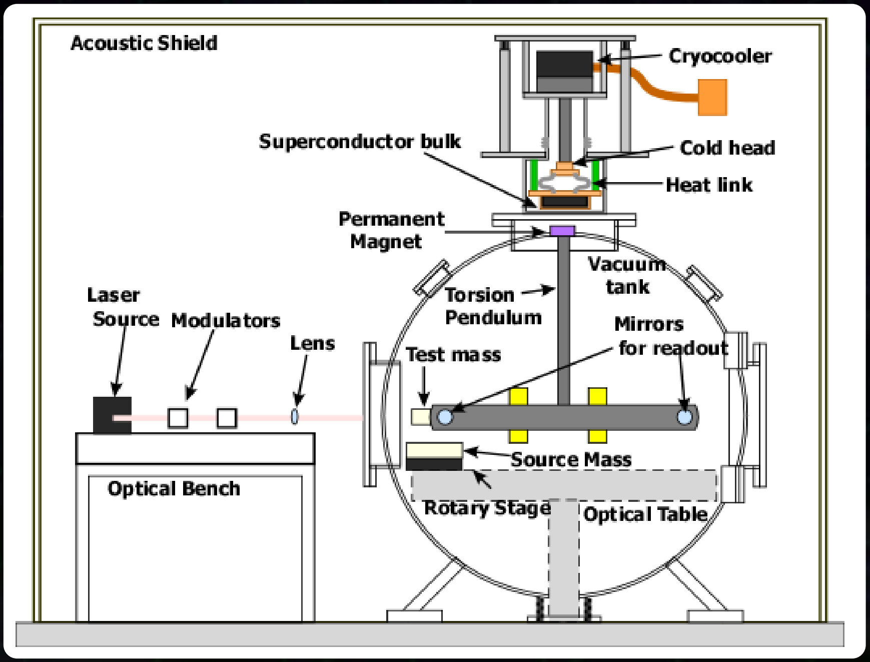


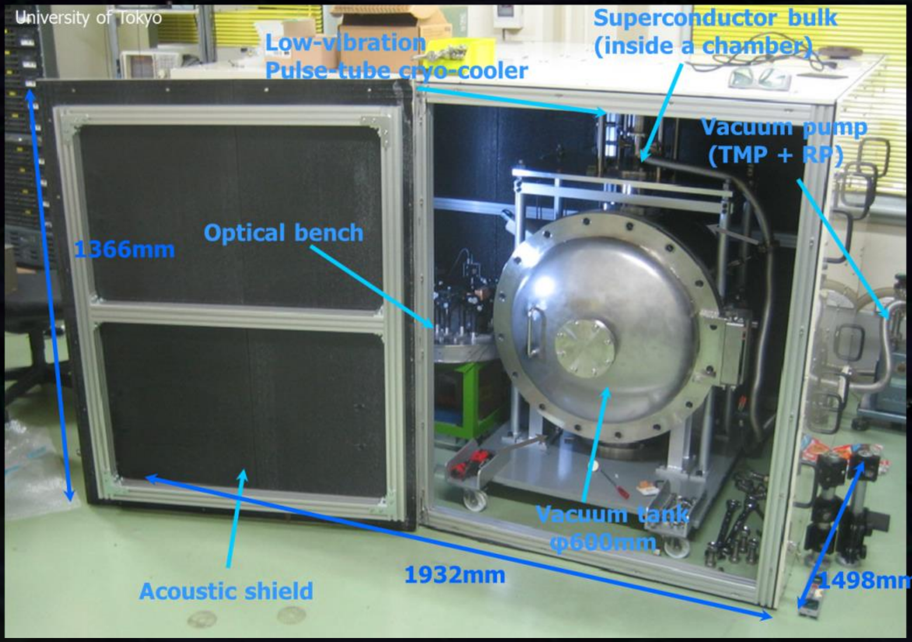
Prototype Tests

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

First TOBA Prototype

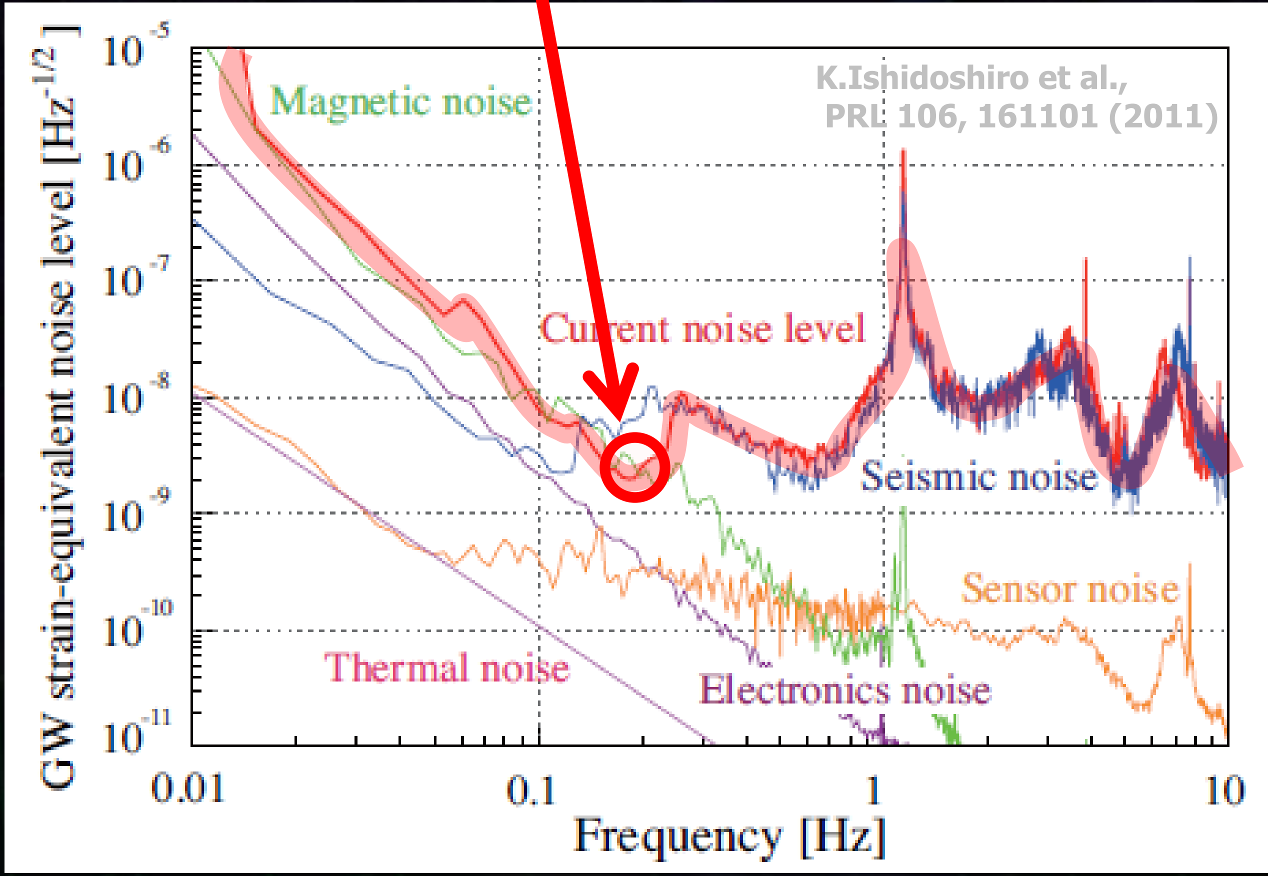
- Small-scale TOBA prototype (Univ. Tokyo, 2006 -)
  - 20cm test-mass bar at room temperature
  - Torsion pendulum by super-conductive levitation
  - Sensor : Michelson interferometer with Nd:YAG laser





Sensitivity of Small TOBA

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

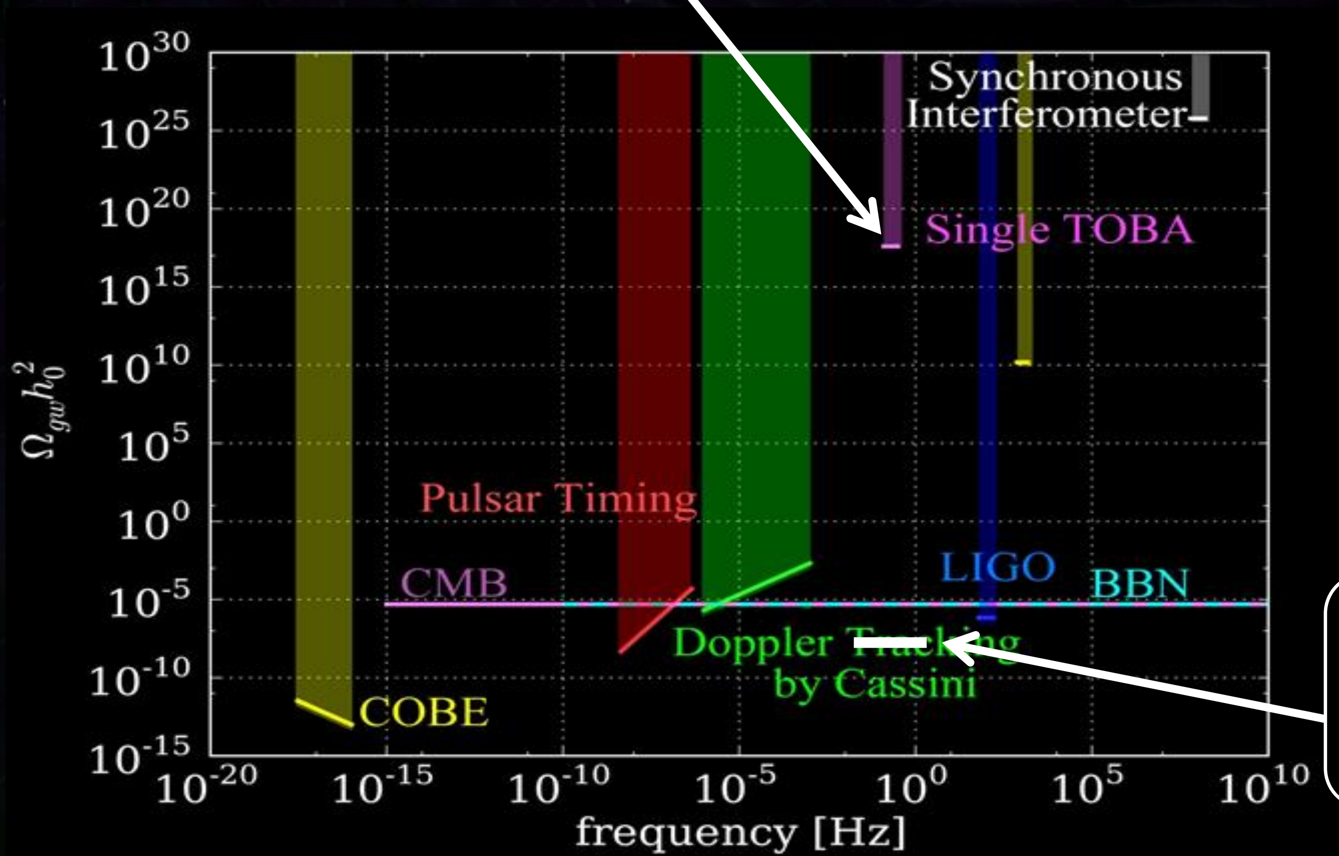


Limited by magnetic disturbances and seismic coupling

Comparison with Previous Results

New upper limit at unexplored frequency band of 0.2Hz

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

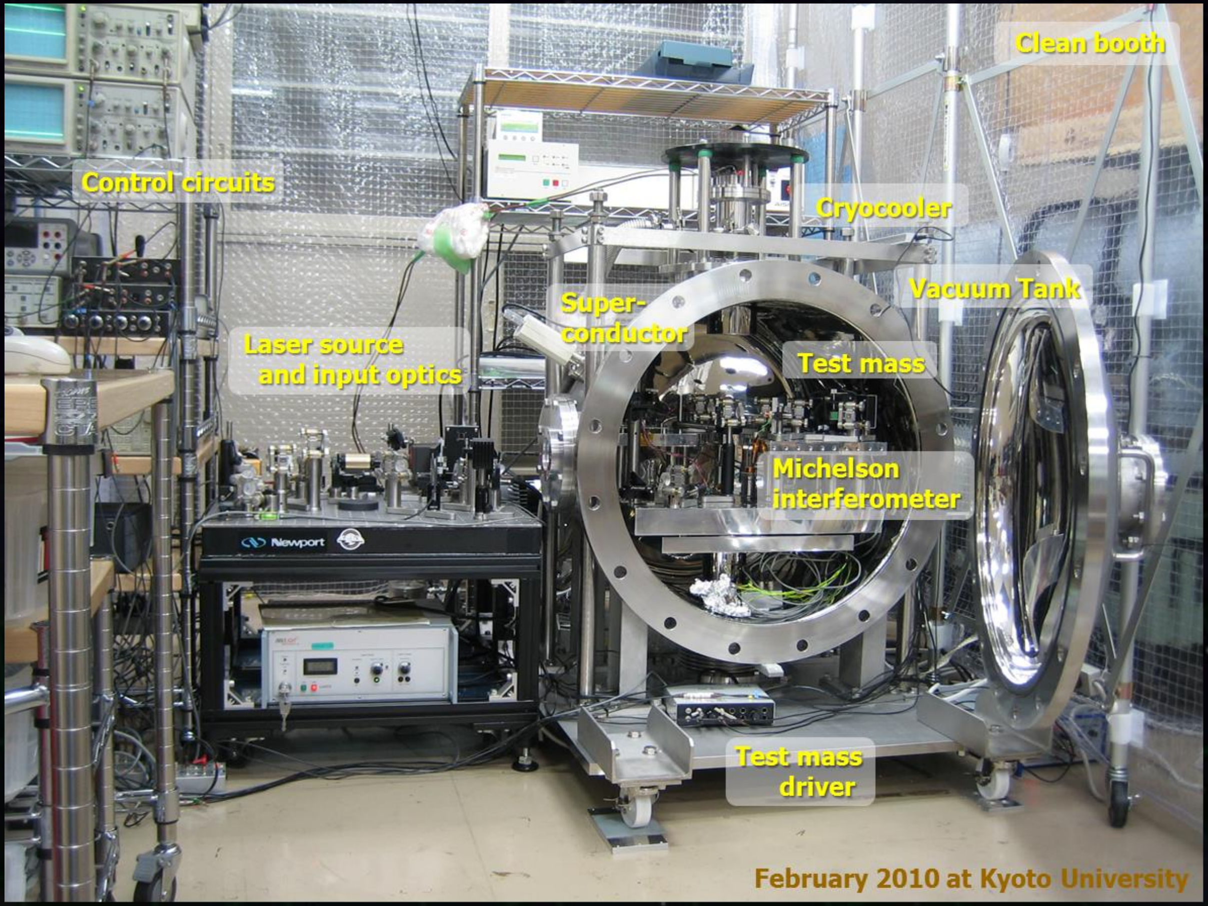


10-m TOBA estimation (1-yr obs.)

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

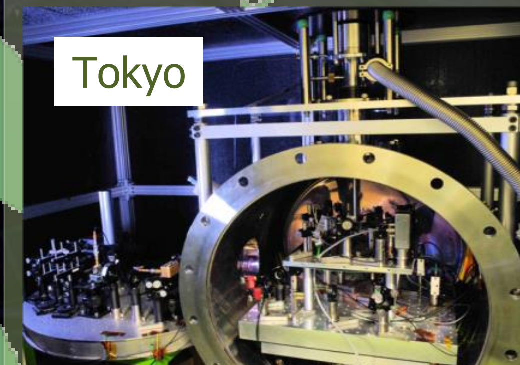


Observation with Two Detectors

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

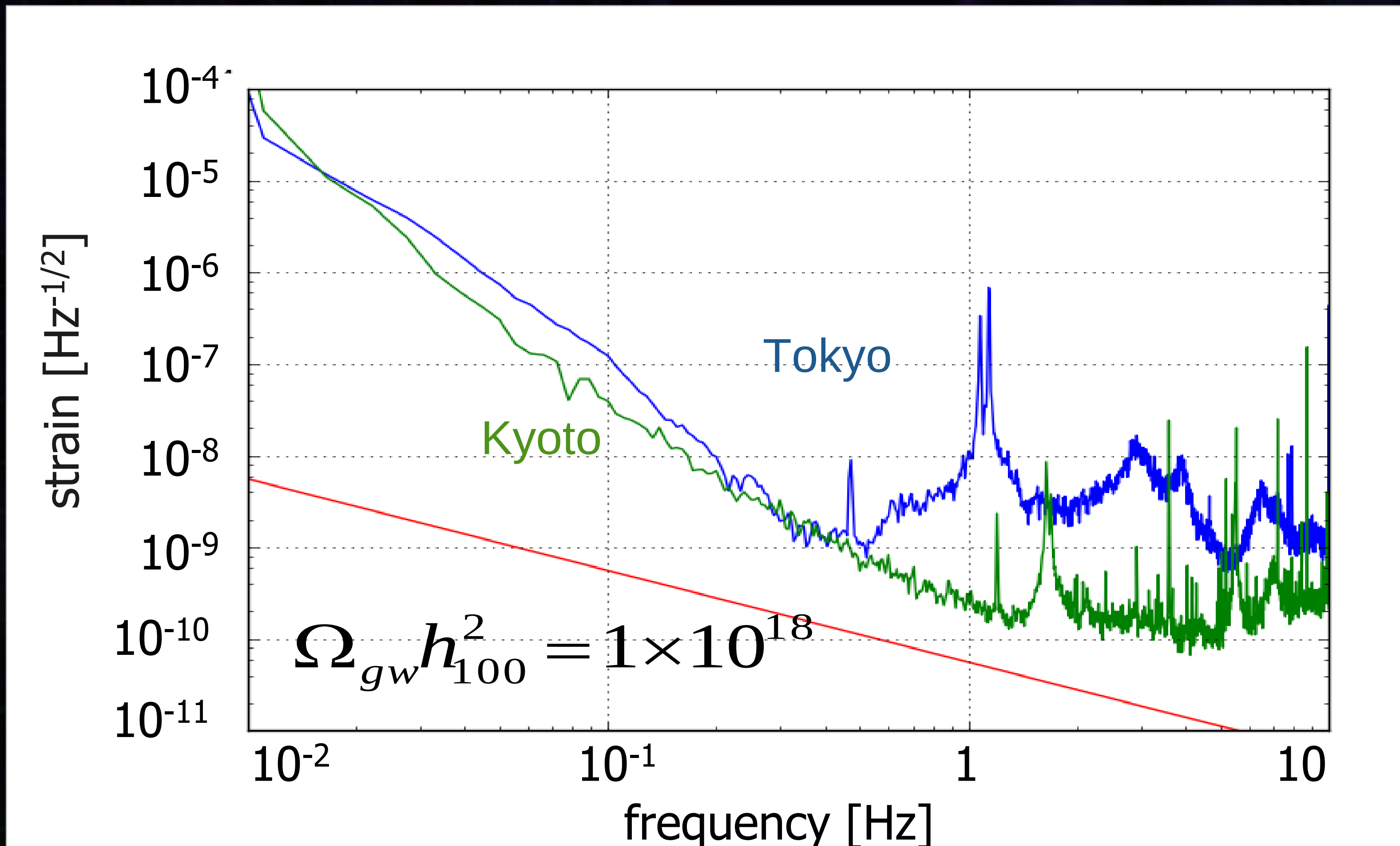


Fig. By A.Shoda

Upper Limit by Two TOBAs

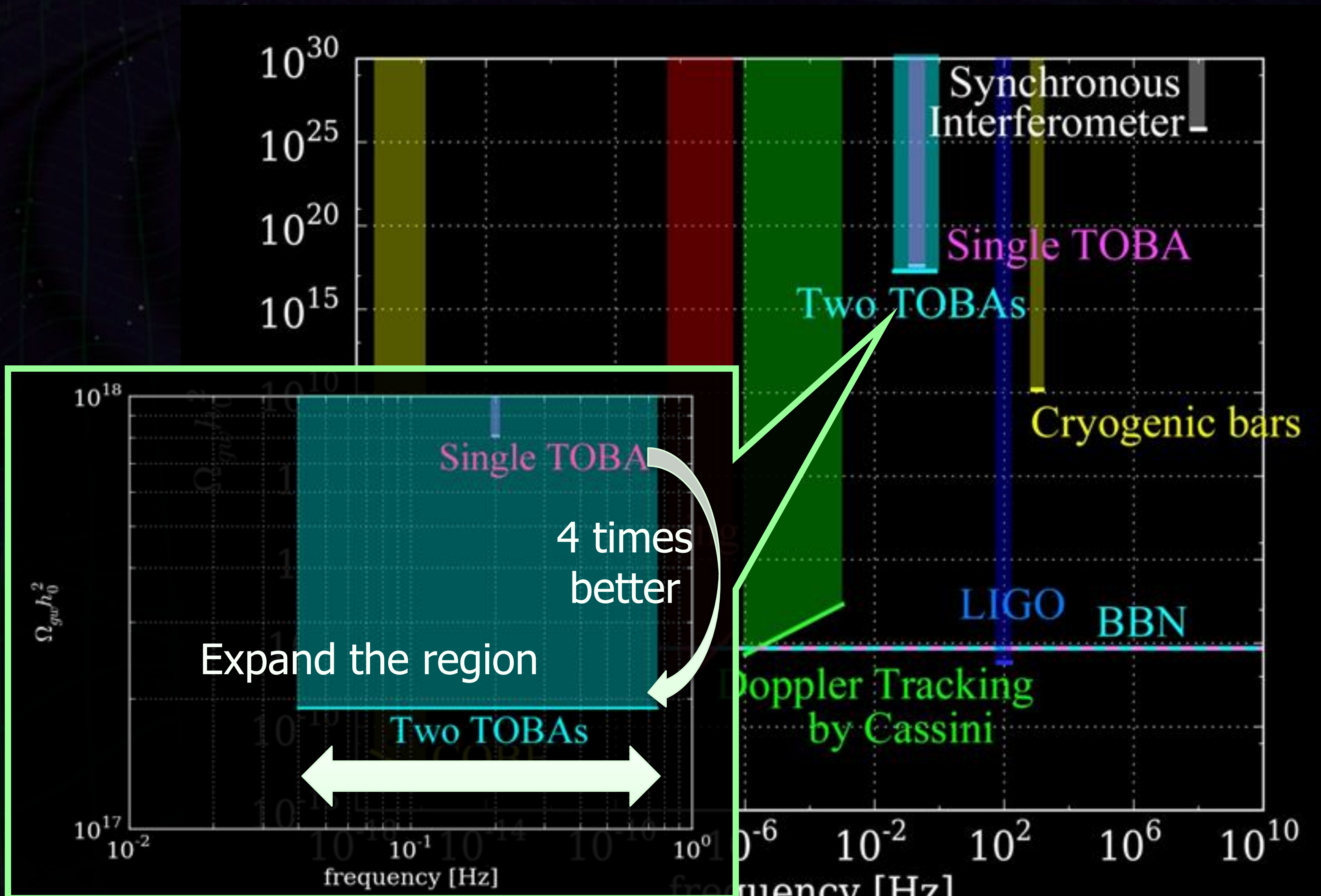
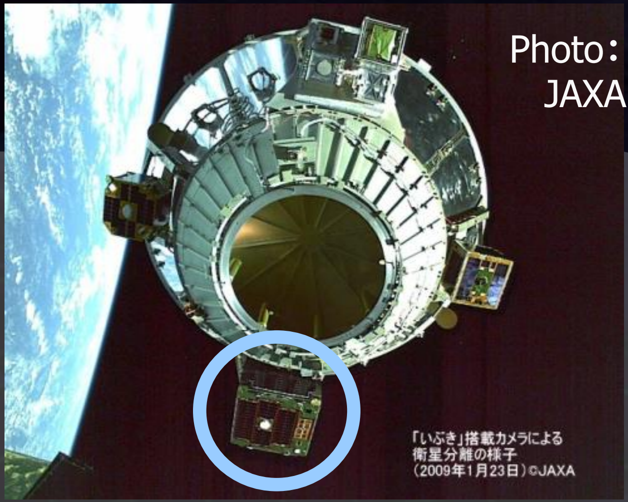


Fig. By A.Shoda

Space TOBA : SWIMμν

Small Module SWIMμν on SDS-1

Launched Jan. 2009, Terminated Sept. 2010



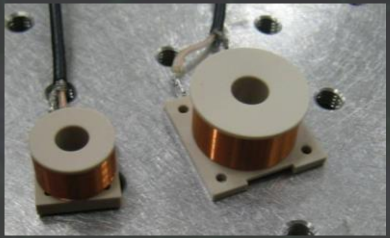
TAM: Torsion Antenna Module with free-falling test mass
(Size : 80mm cube, Weight : ~500g)

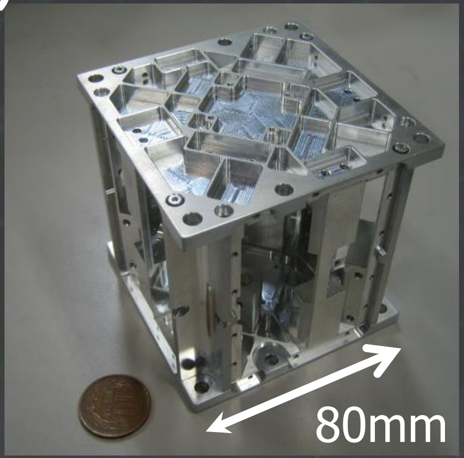
Test mass

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

Photo sensor

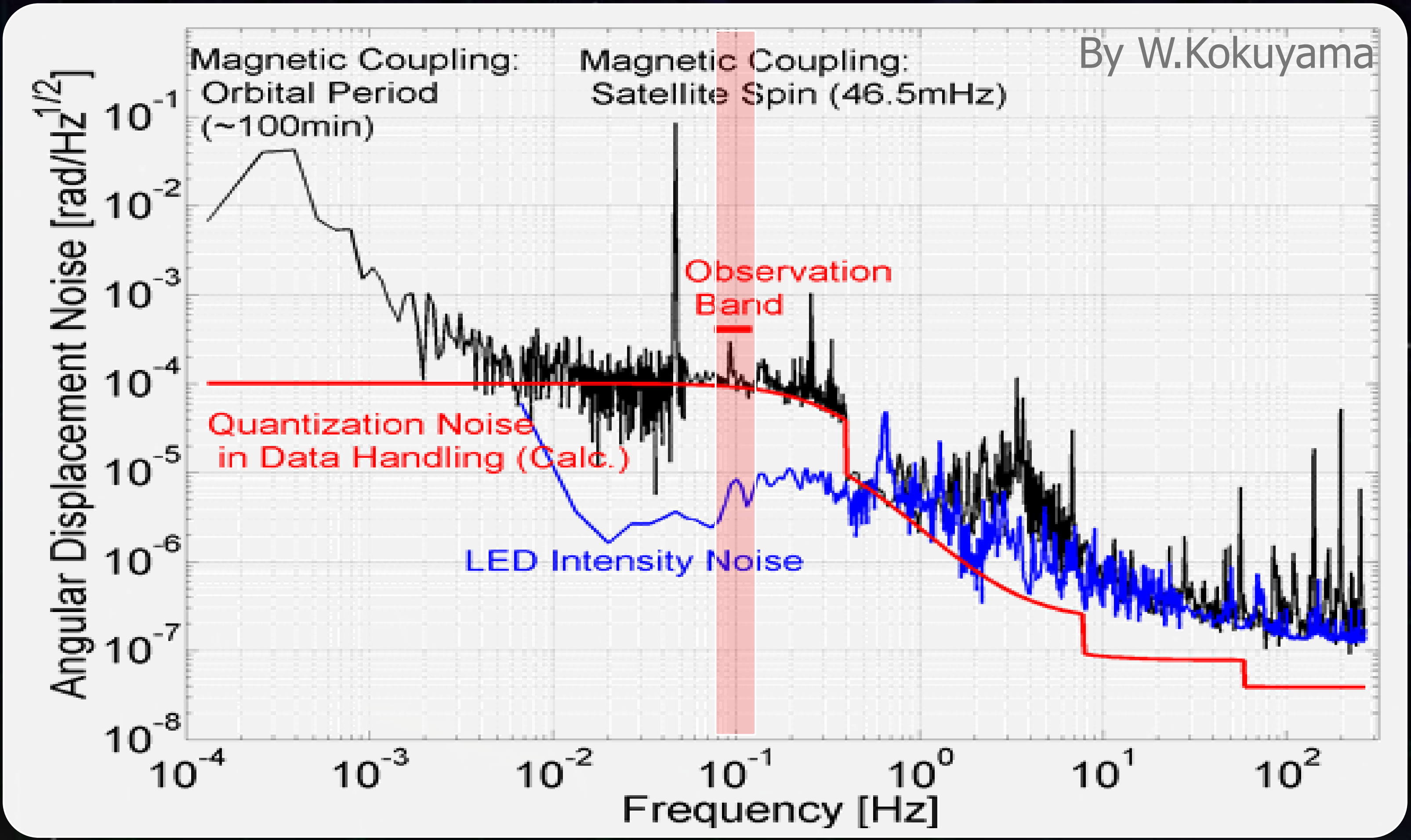
Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion





Sensitivity

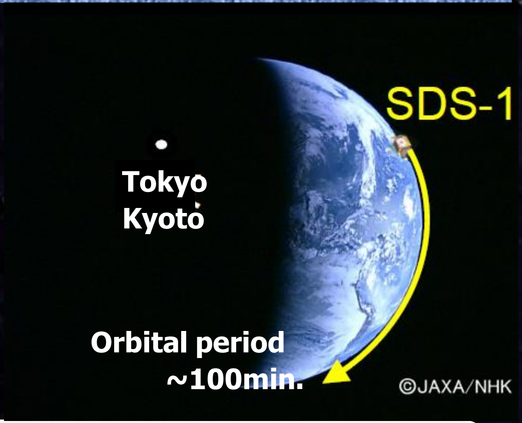
Though limited by non-fundamental noises,
best as a space-borne GW detector.

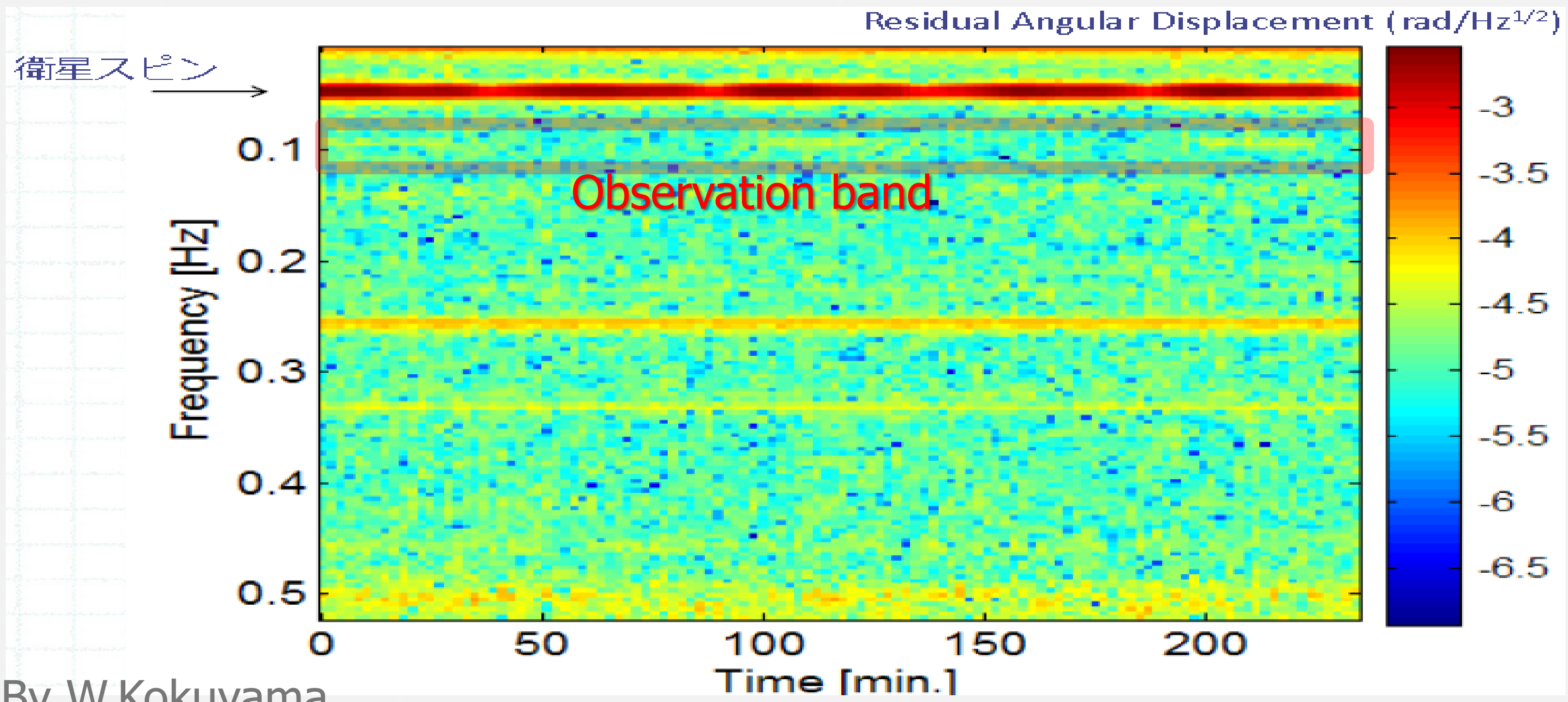


Observation by SWIM

Continuous data taking

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





By W.Kokuyama

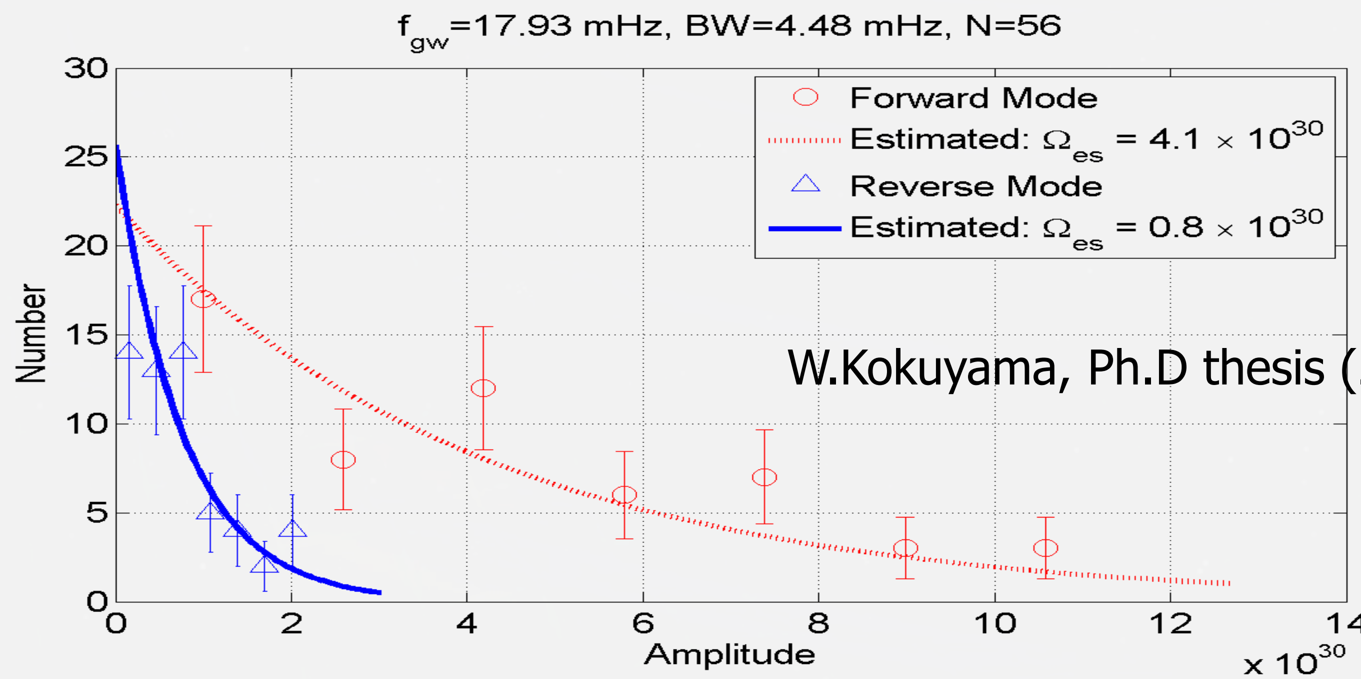
Upper Limit on GWB

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)



W.Kokuyama, Ph.D thesis (2012)

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.

⇩

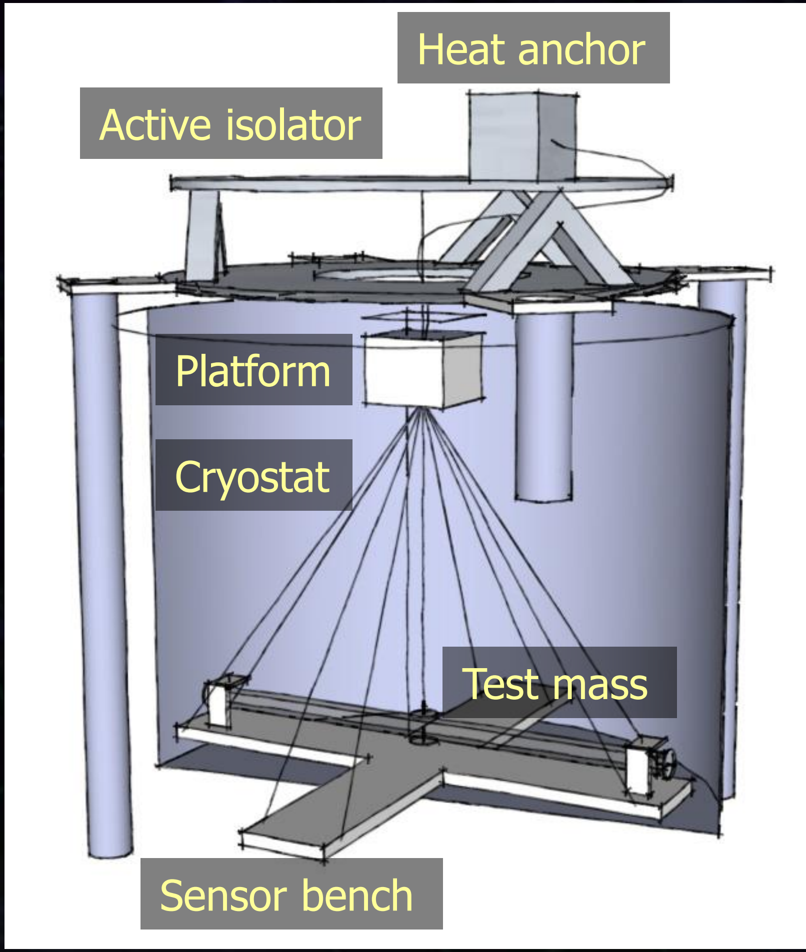
Medium-scale TOBA for Newtonian noise observation.

Medium-scale TOBA

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

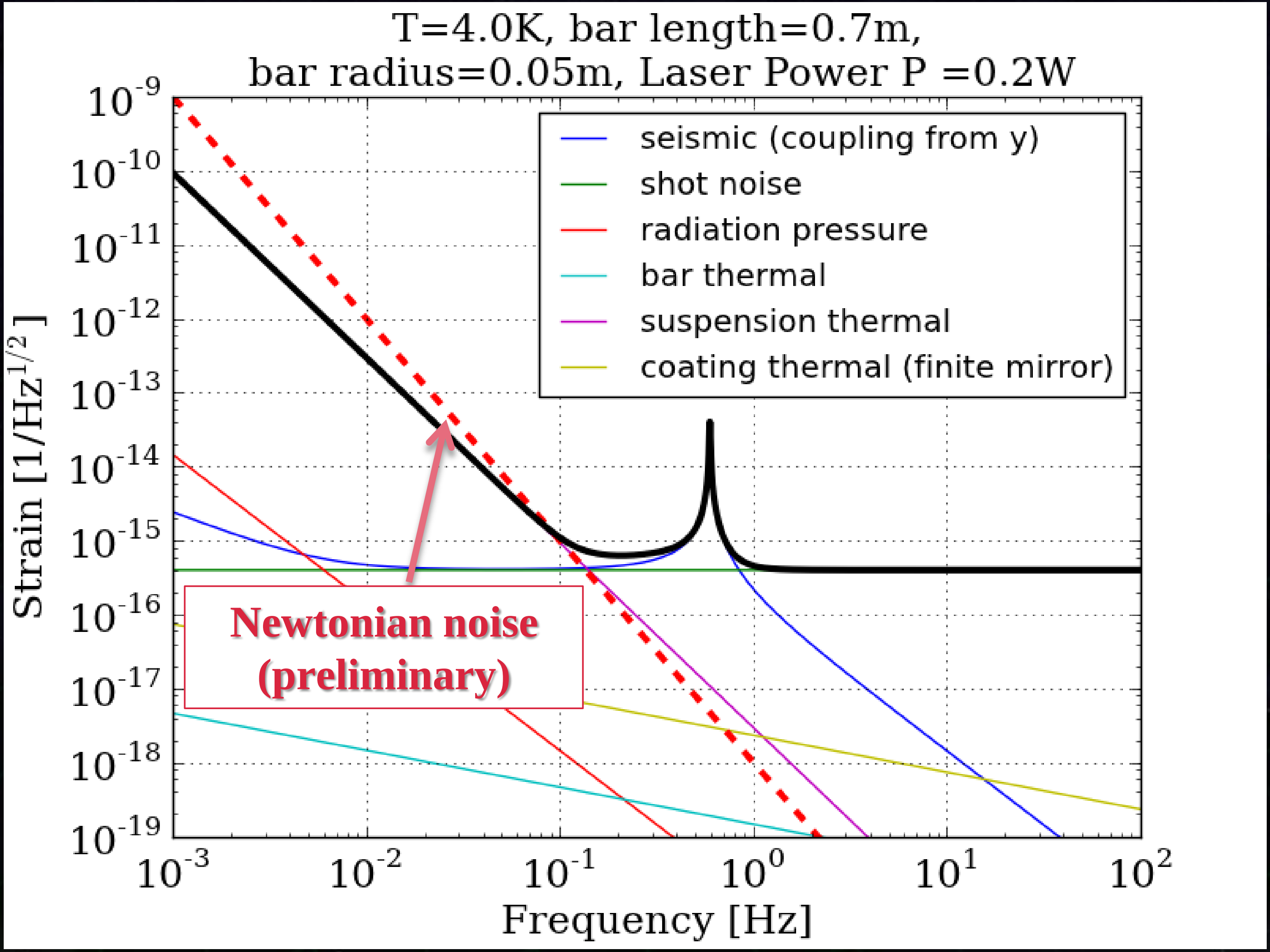
- Intermediate step for 10-m scale TOBA
- Low-freq. GW observation $h \sim 10^{-15}$ at 0.1Hz
- Newtonian noise sensor

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



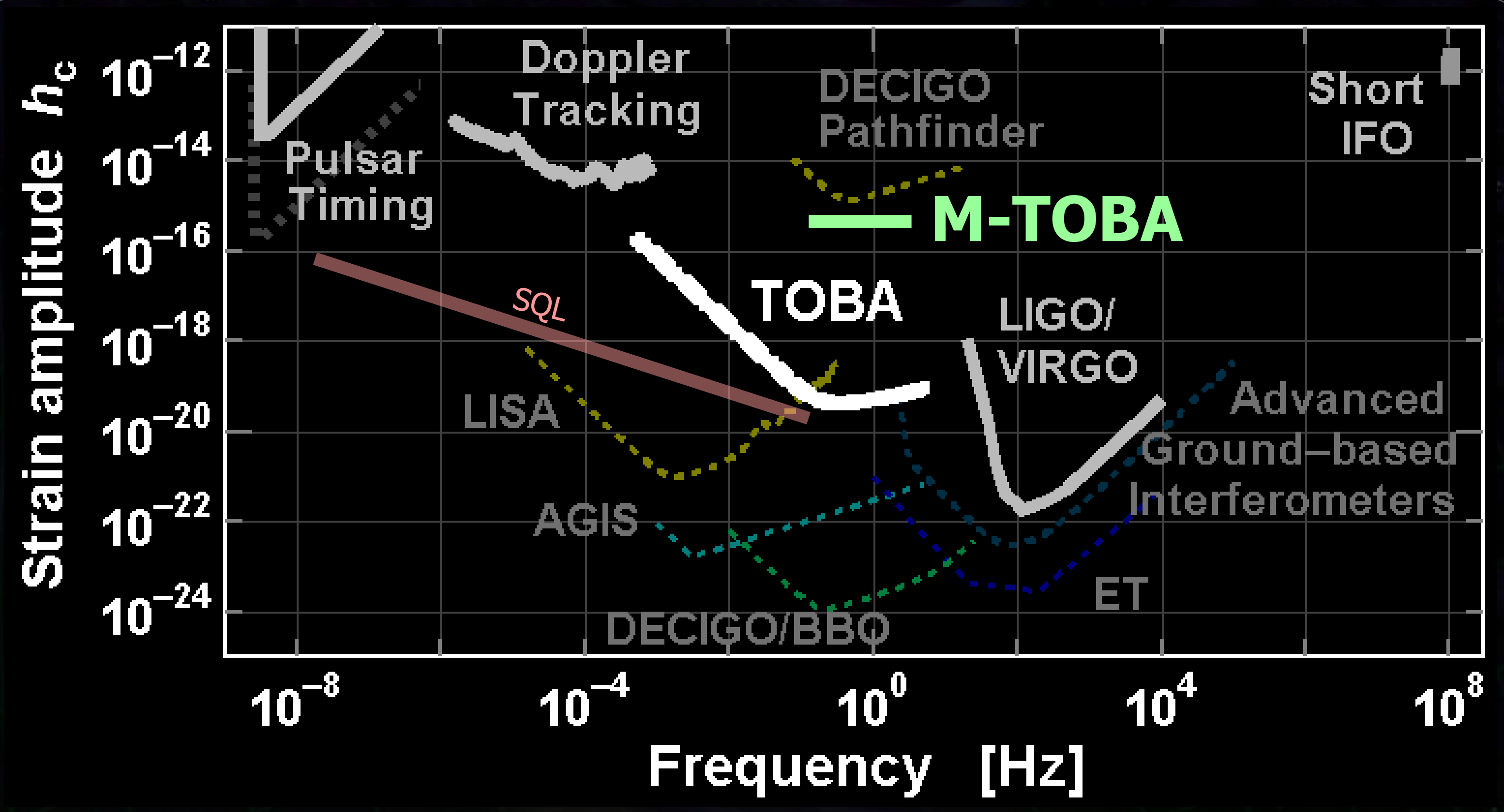
Preliminary design by A.Shoda

Sensitivity of Mid.-scale TOBA



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)

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