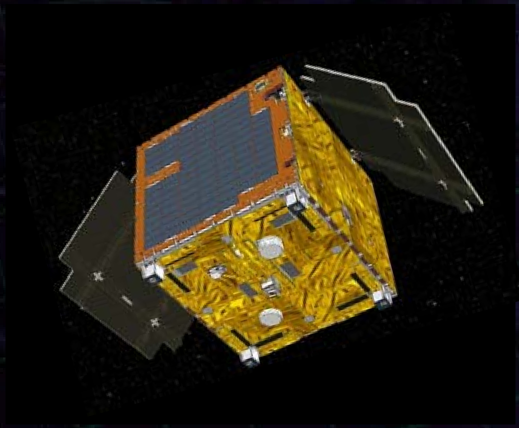
TOBA: Torsion-Bar Antenna

Small-scale TOBA at Tokyo

Small-scale TOBA at Kyoto



SWIM on SDS-1 satellite

Masaki Ando (Kyoto University)

K. Ishidoshiro, K. Okada, A. Shoda, W. Kokuyama, K. Yagi, K. Yamamoto, H. Takahashi, N. Kanda, Y. Aso, N. Matsumoto, K. Tsubono, A. Takamori

Abstract

Low-freq. GW observation

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

Novel GW detector : TOBA (Torsion-Bar Antenna)

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

1. TOBA

Concept and Sensitivity

Prototype results

2. Rotating TOBA

Concept

Prototype results

Reference:
- M.Ando, et. al, Phys. Rev. Lett. 105, 161101 (2010)
- K.Ishidoshiro, et. al, Phys. Rev. Lett. 106, 161101 (2011)
- A. Shoda, presentation at GWPAW2011

TOBA

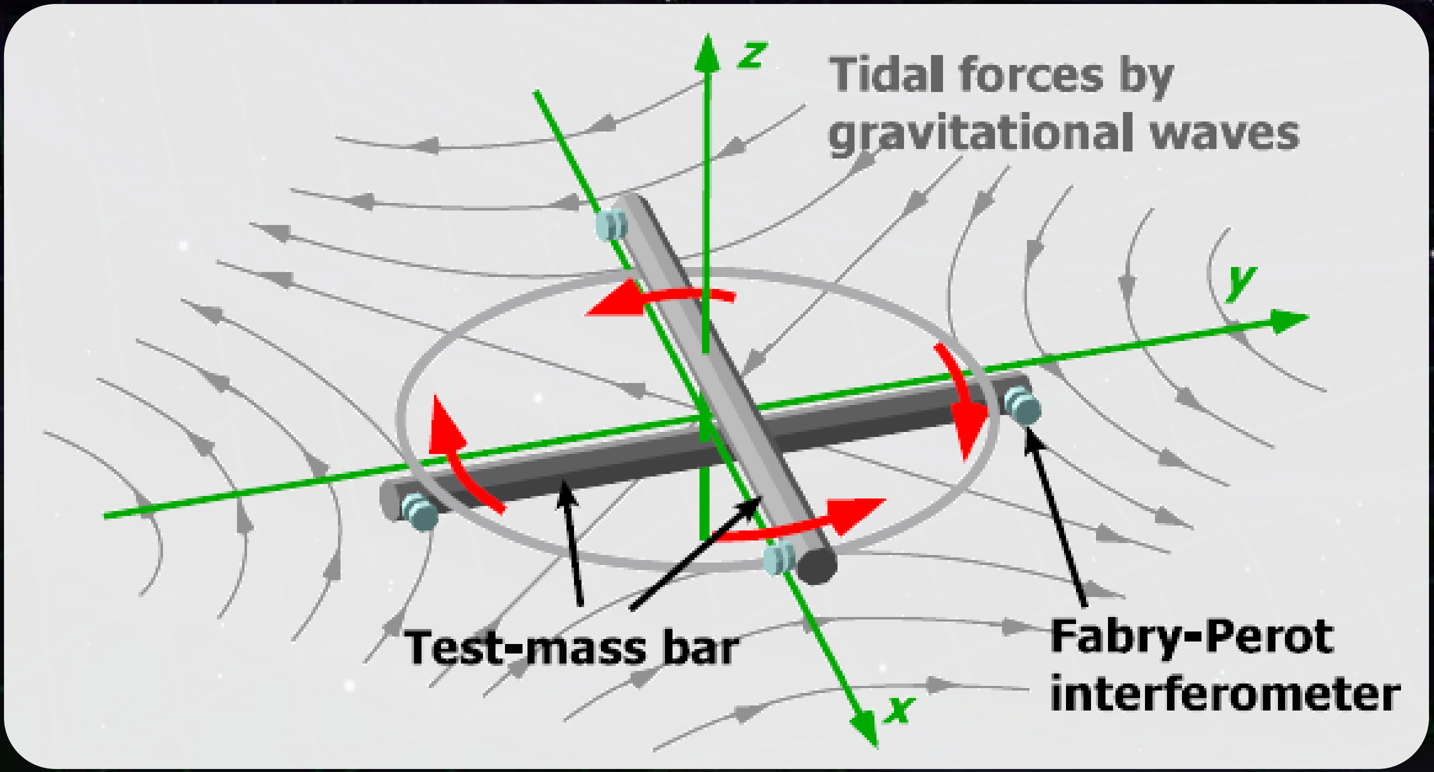
Reference:
- M.Ando, et. al, Phys. Rev. Lett. 105, 161101 (2010)

TOBA

TOBA : Torsion-Bar Antenna

Monitors tidal-force fluctuation caused by GWs.

- Two test-mass bars, placed orthogonal to each other.
- Monitor differential angular fluctuation by interferometers.



M.Ando, et. al, Phys. Rev. Lett. 105, 161101 (2010)

Detector response

Equation of Motion of a test-mass bar

$$I\left(\ddot{\theta}+\frac{\omega_0}{Q}\dot{\theta}+\omega_0^2\theta\right)=\frac{1}{4}q^{ij}\cdot\ddot{h}_{ij}(t)$$

I : Moment of Inertia

q^{ij} : Dynamic quadrupole moment

$$\tilde{\theta}(\omega)=\frac{1}{2}\alpha\tilde{h}_\times(\omega) \quad (\omega \gg \omega_0)$$

α : shape factor, between 0 to 1

Dumbbell → α = 1

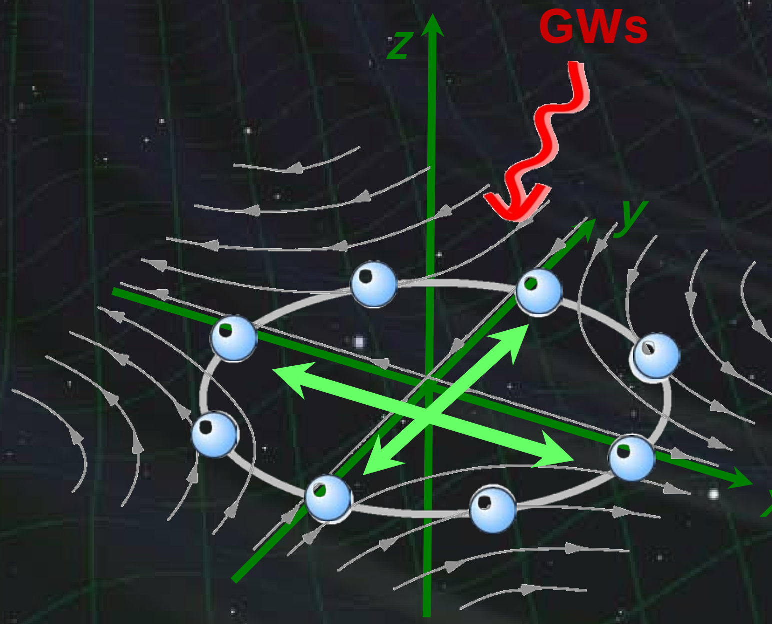
Dimension less,

Independent of matter density

Detection principle

Conventional IFO antenna

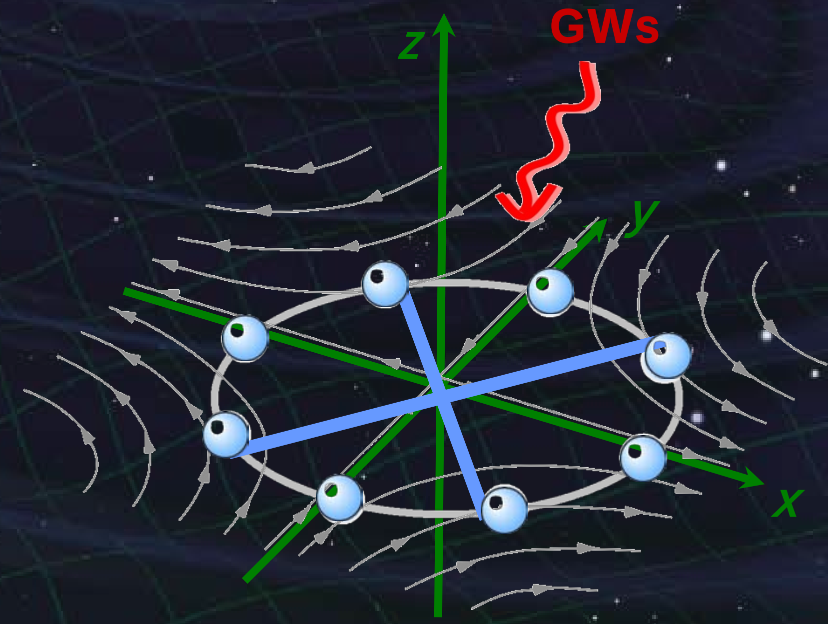
Detect differential length change



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

Torsion-bar antenna

Detect differential rotation



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

Observe change in tidal forces using free test masses

Advantages

Conventional IFO

Obs. band 10Hz-1kHz

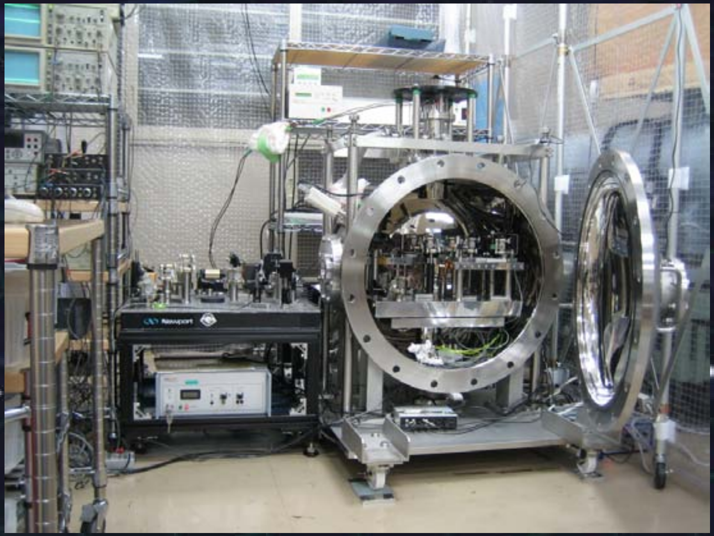
Suspended as pendulum
(Res. Freq. ~1Hz)

Long baseline
→ High sensitivity

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

TOBA

Obs. band 10mHz-1Hz

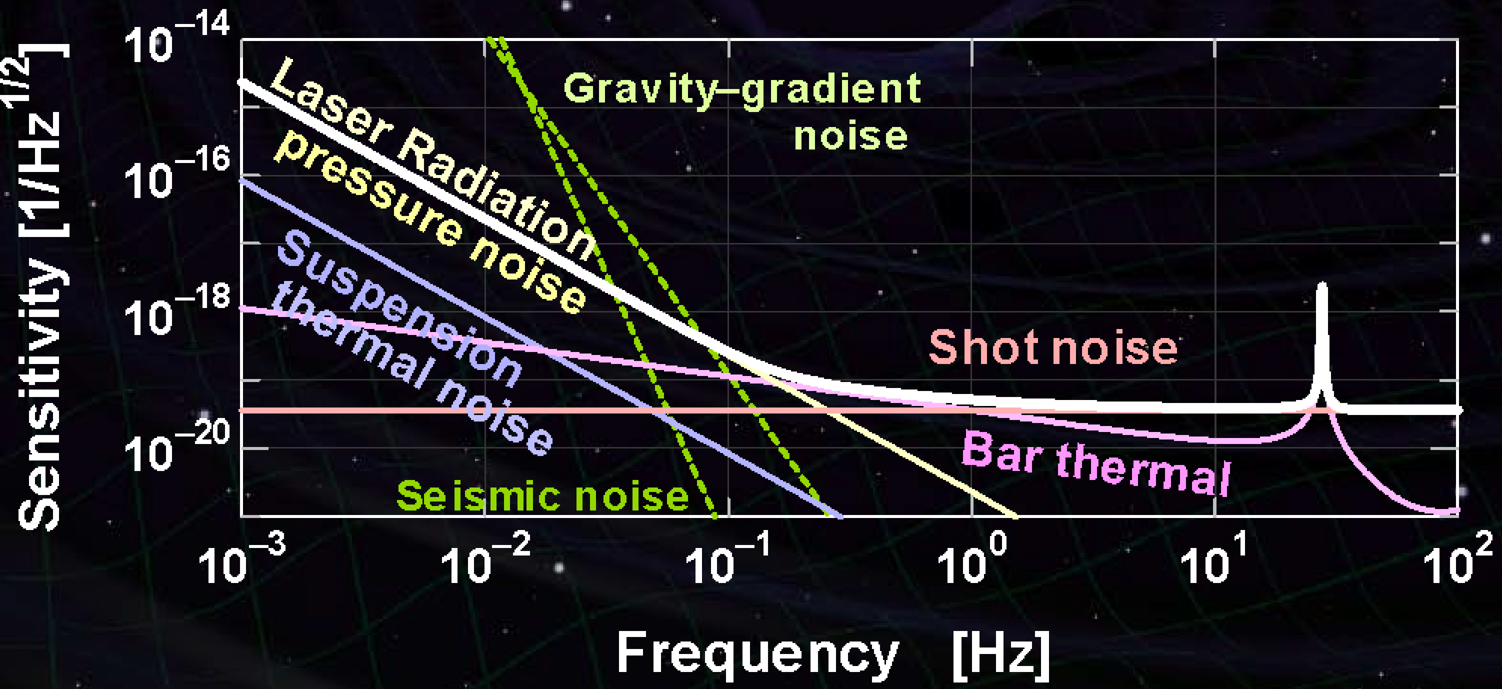


Torsion pendulum
(Res. freq ~1mHz)

Shorter length
→ Simple config.
Common-mode rejection

Fundamental noise level of TOBA

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}

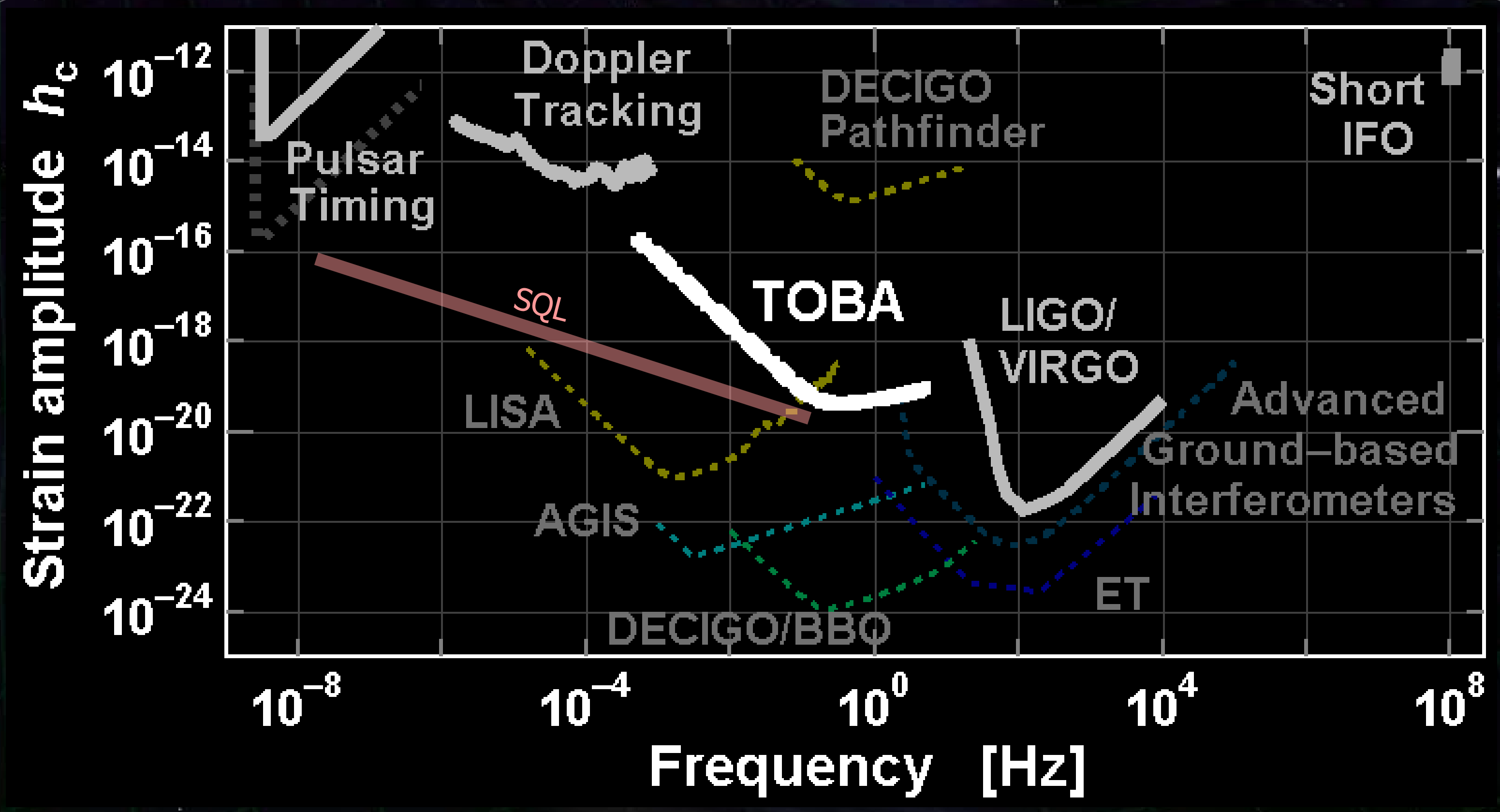
Laser Freq. noise < $10\mathrm{Hz}/\mathrm{Hz}^{1/2}$,
Freq. Noise CMRR>100
Intensity noise < $10^{-7}/\mathrm{Hz}^{1/2}$,
Bar residual RMS motion < 10^{-12} m

TOBA Sensitivity

Comparison with the other detectors

DECIGO/BBO band:

Between ground-based detectors and LISA bands

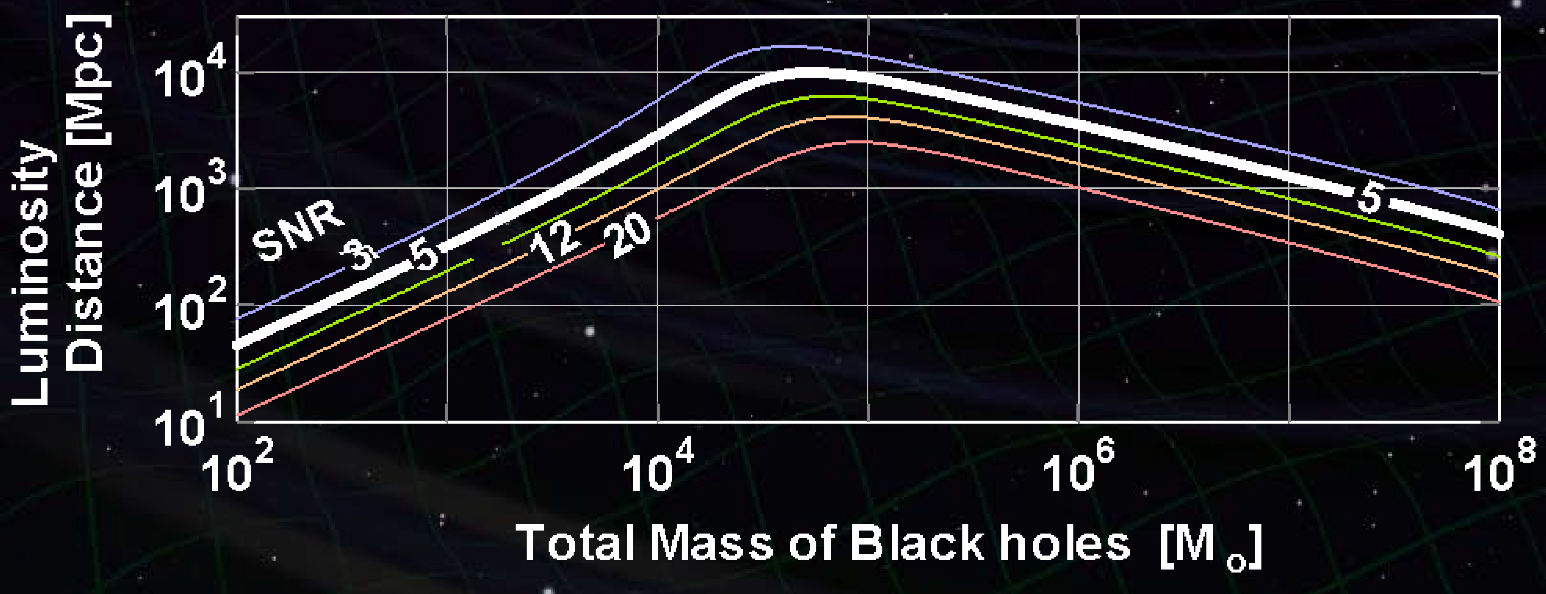


Characteristic amplitude : $h_c = \tilde{h} \times \sqrt{f_{\mathrm{center}}}$ (Dimensionless strain)

Observable range

GWs from binary BH mergers

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



Calculation by K.Yagi

Background GWs

Observable GW energy density ratio

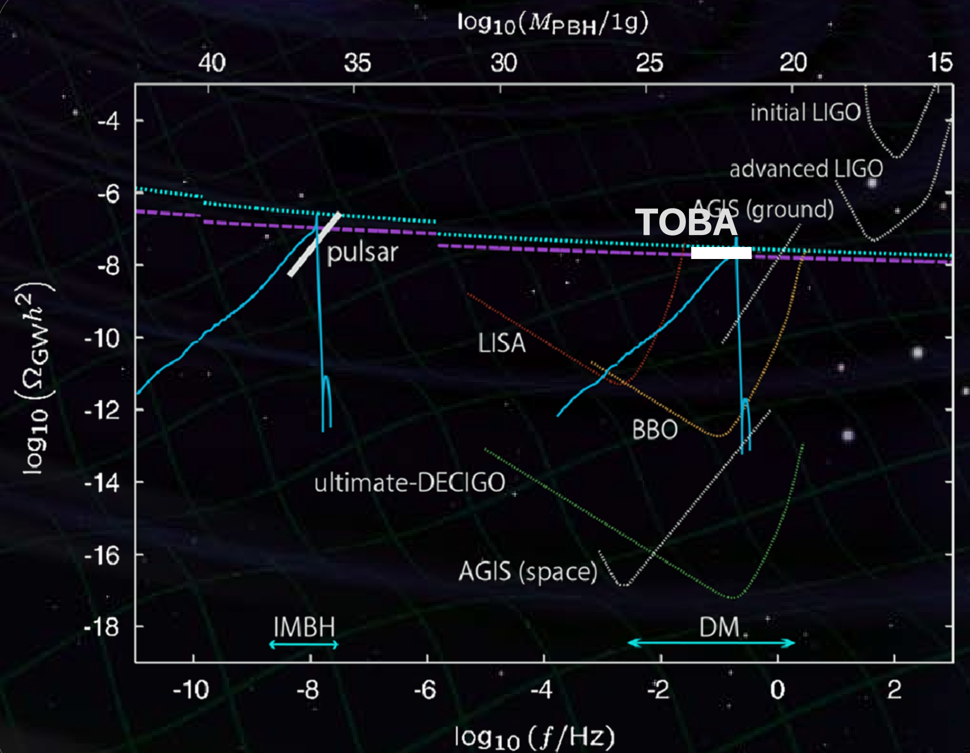
$$\Omega_{gw} \sim 10^{-7}$$

(1-yr obs. by 2 TOBAs)

Beat BBN upper limit

GW by primordial tensor perturbation

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



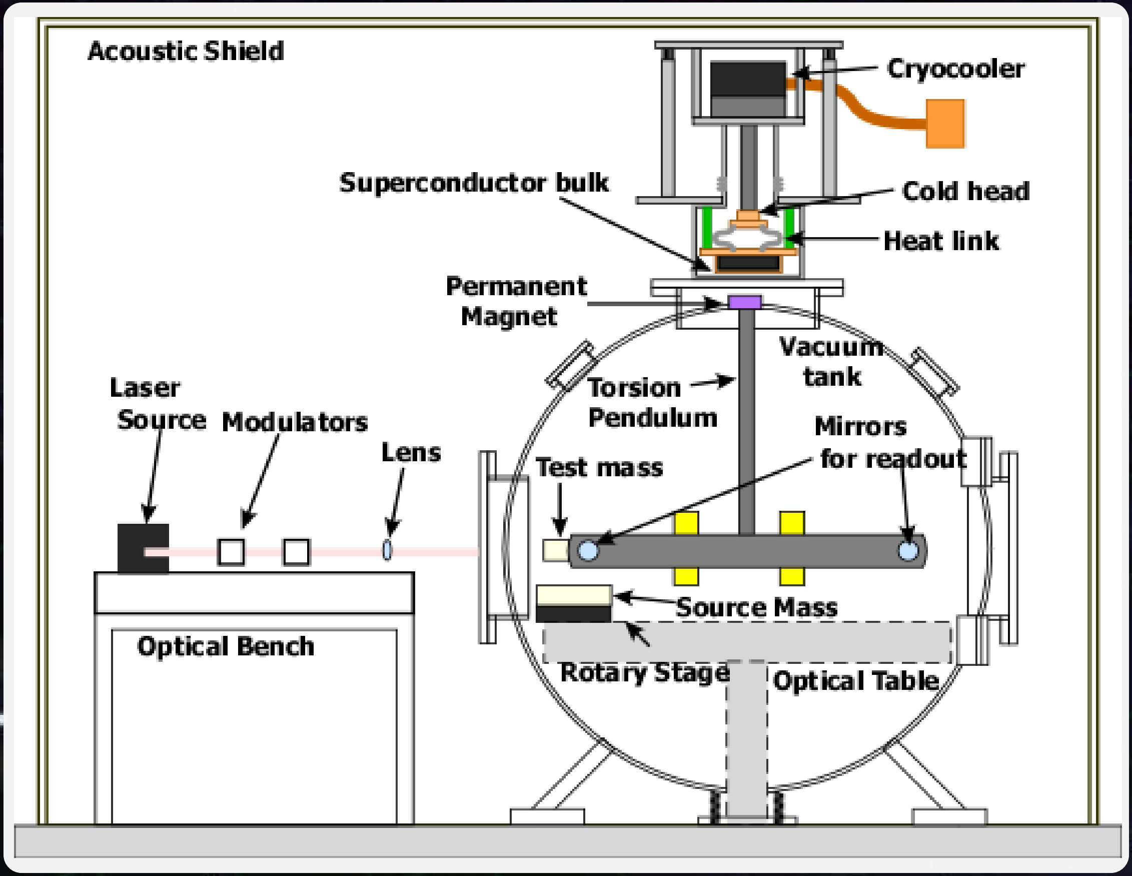
Prototype test

Reference:

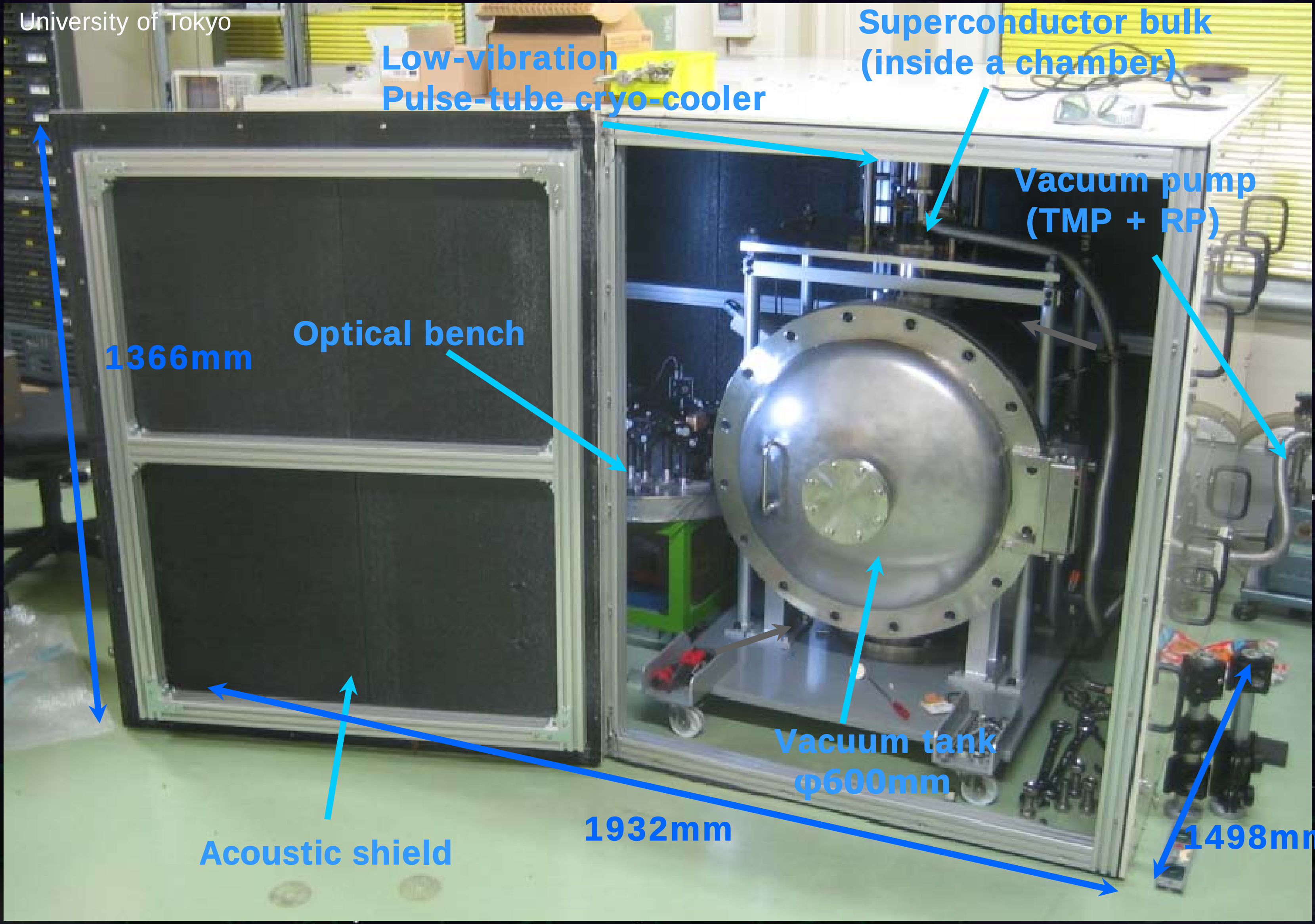
- K.Ishidoshiro, et. al, Phys. Rev. Lett. 106, 161101 (2011)
- A. Shoda, presentation at GWPAW2011

Small-scale TOBA

- Optical readout
  - Mirrors at both edges of the test-mass bar
    - → Form Michelson interferometer
    - Sensitive angular sensor
  - Nd:YAG laser source
    - Wavelength 1064nm
    - Power 50mW
- Test-mass bar
  - Length ~200mm, Weight 160g
  - Made of Aluminum
  - Room temperature
- Suspension
  - Magnetic levitation by pinning effect of type-II superconductor
  - Superconductor bulk
    - $Gd_1Ba_2Cu_3O_{6.9}$: 70.9%
    - $Gd_2Ba_1Cu_1O_7$: 19.2%
    - ϕ600mm, t 20mm, Tc ~92K
  - Low-vibration cryo-cooler
    - Operation temp. ~65K
- Vacuum system
  - Pressure 10^{-5} Pa by TMP+RP
  - Acoustic shield enclosure



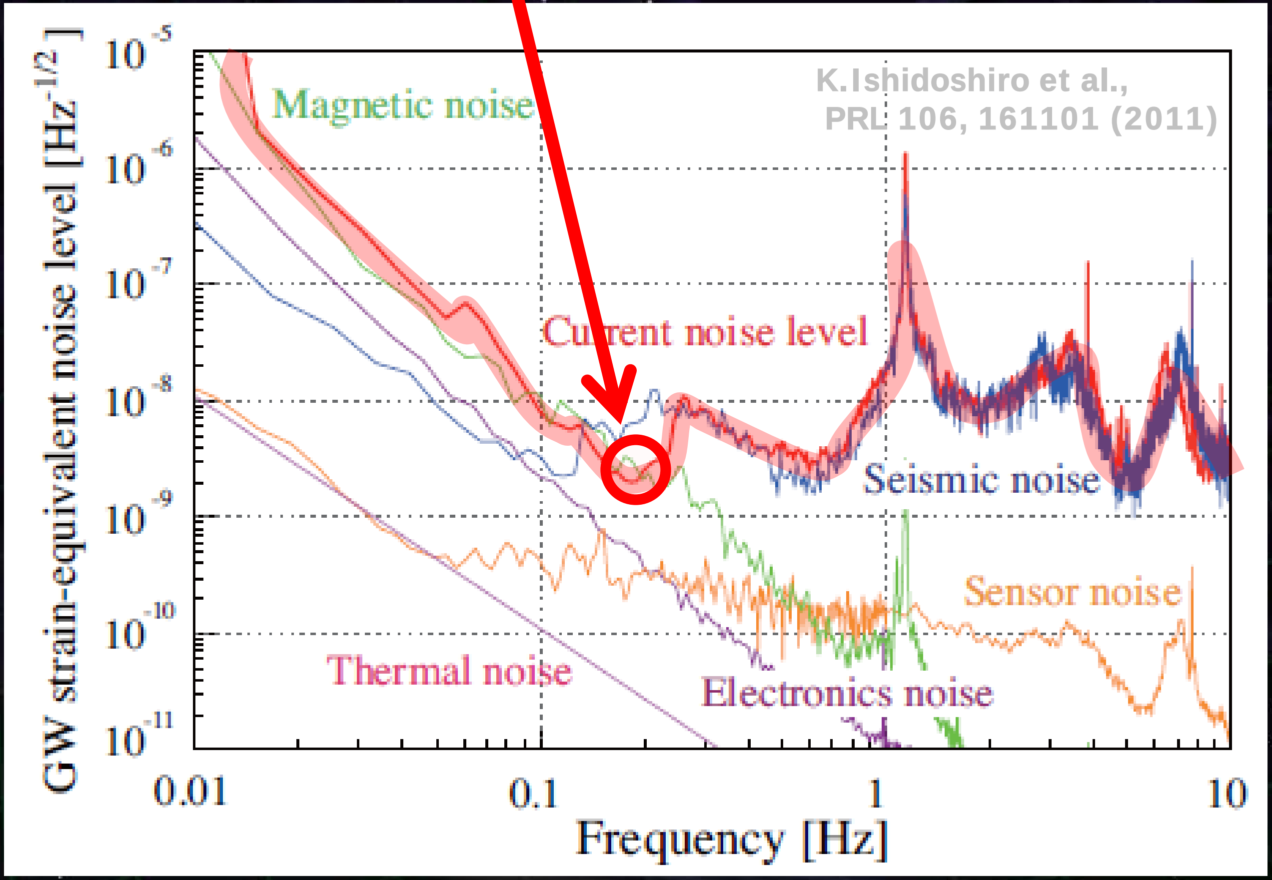
Small-scale TOBA at Tokyo



Sensitivity of small TOBA

Small-scale TOBA at University of Tokyo

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



Limited by magnetic disturbances and seismic coupling

GWB observation by small TOBA

- Observation run by small-scale TOBA at the University of Tokyo
  One-night observation → 7.5 hours' data
  Use stable 3.5 hours' data

⇩

- Data analysis for stochastic background GW
  Assume isotropic, unpolarized GWB

GWB energy density ratio

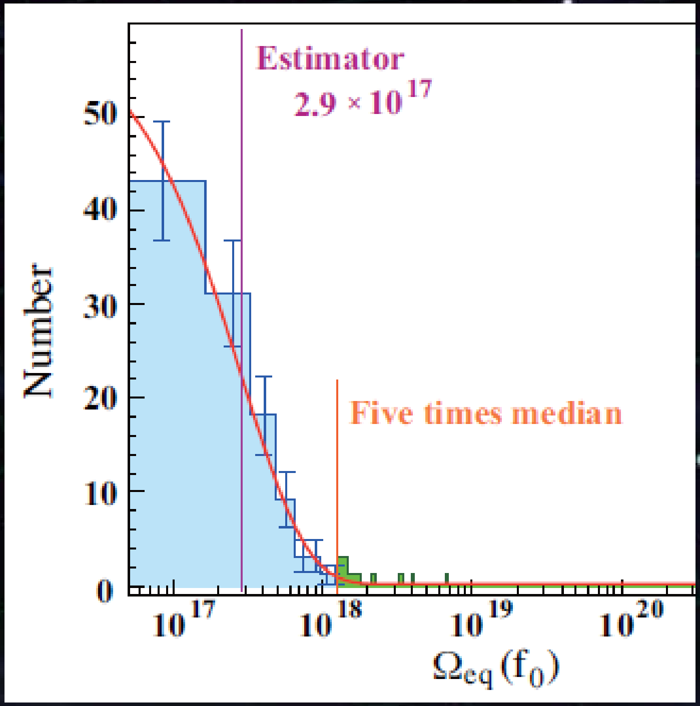
$$\Omega_{eq}(f_0) = \frac{10\pi^2}{3H_0^2} f_0^3 \tilde{h}^2(f_0)$$

Hubble constant H_0 = 70 [km/s/Mpc]

Divide obs. data into 120 segments

→ Average and distribution

$f_0 = 0.2\,[\mathrm{Hz}],\ f_{BW} = 0.01\,[\mathrm{Hz}]$



Upper limit on GWB

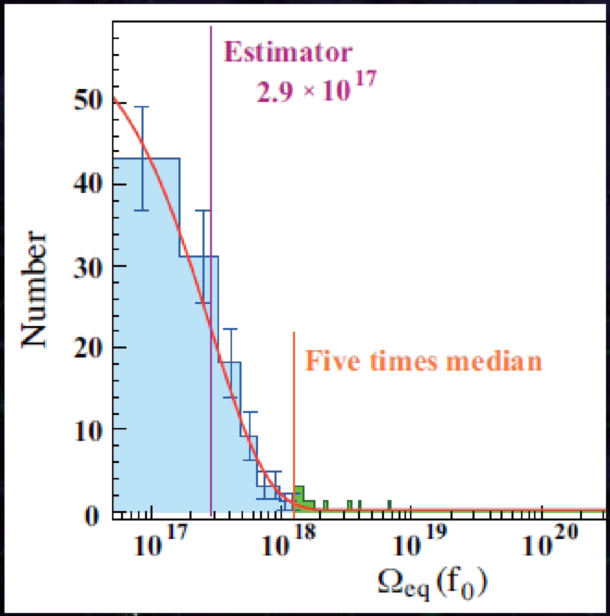
- Distribution → Averaged power at 0.2Hz

$$\overline{\Omega_{eq}} = 2.9 \times 10^{17}$$

⇨ Upper limit on Ω_{gw}

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

Conservative upper limit including calibration error ($\delta h/h$ ~ 10%) and the other systematic errors.



Some details...

Probability to have larger result than $\overline{\Omega_{eq}}$

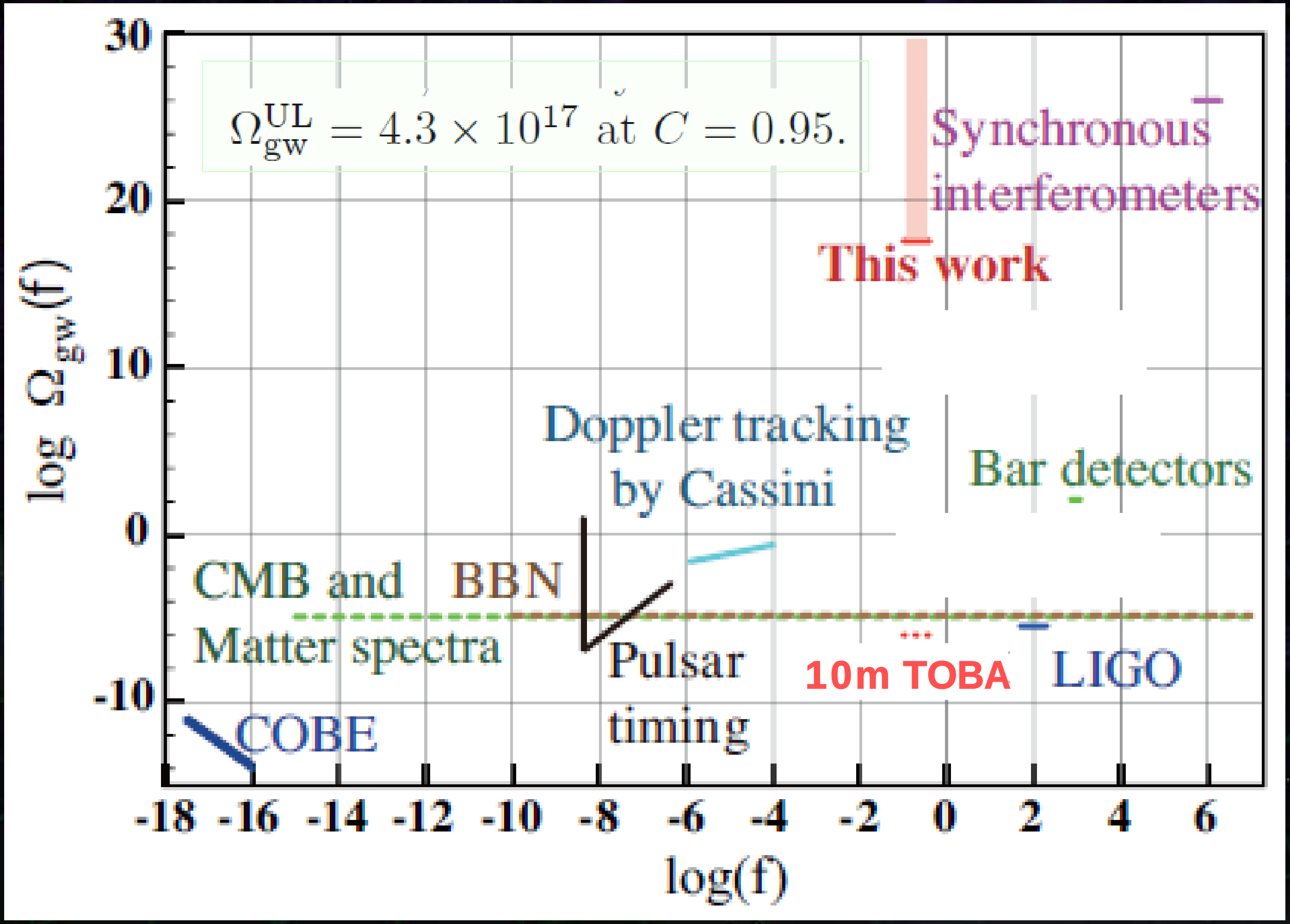
$$C = \int_{\overline{\Omega_{eq}}}^{\infty} P(\Omega_{es}|\Omega_{gw})\, d\Omega_{es}$$

Distribution with Ω_{gw} assuming Gaussian dist.

$$P(\Omega_{es}|\Omega_{gw}) \propto \exp\left[-\frac{(\Omega_{es}-\Omega_{gw})^2}{2\Omega_{gw}^2/N}\right]$$

Comparison with previous results

New upper limit at unexplored frequency band of 0.2Hz

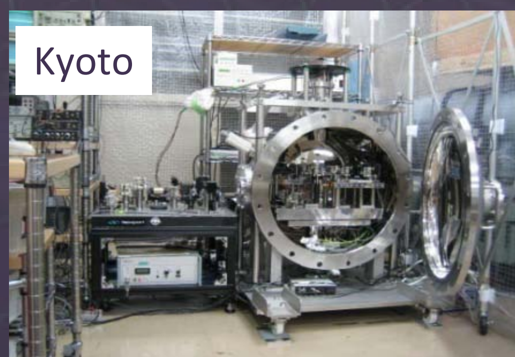


Observation with two detectors

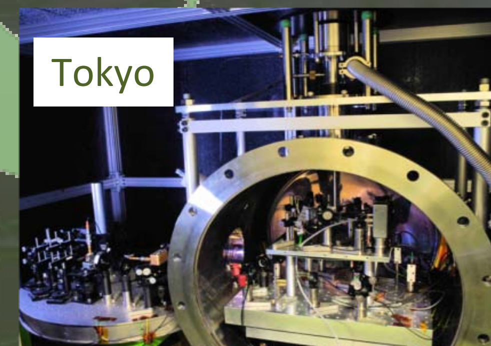
Observation with two detectors places at Tokyo and Kyoto, Japan.

Comparable sensitivity, Separation : 370km

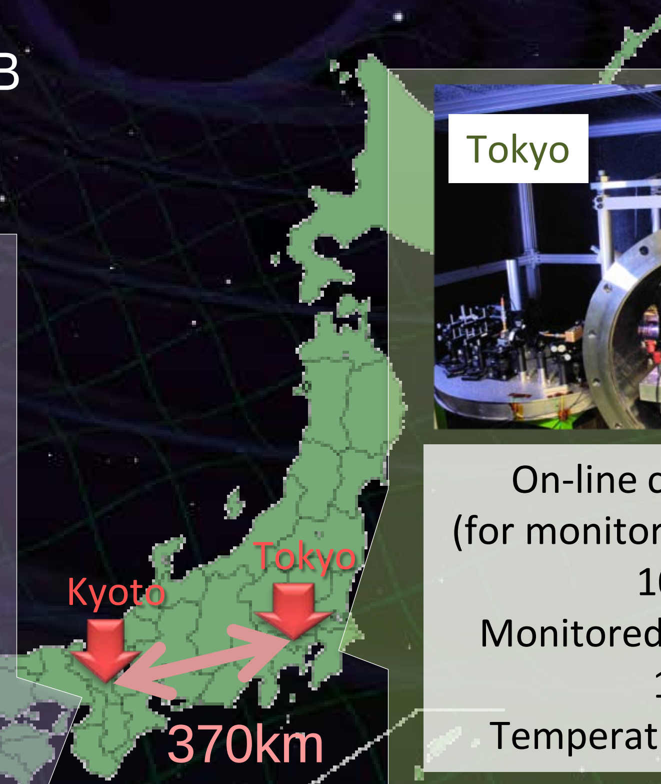
⇨ Better upper limit on GWB
Possible detection



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

Data analysis underway → $\Omega_{gw}^{UL} < 9 \times 10^{15}$ is expected

(1/50 better upper limit than that by one detector)

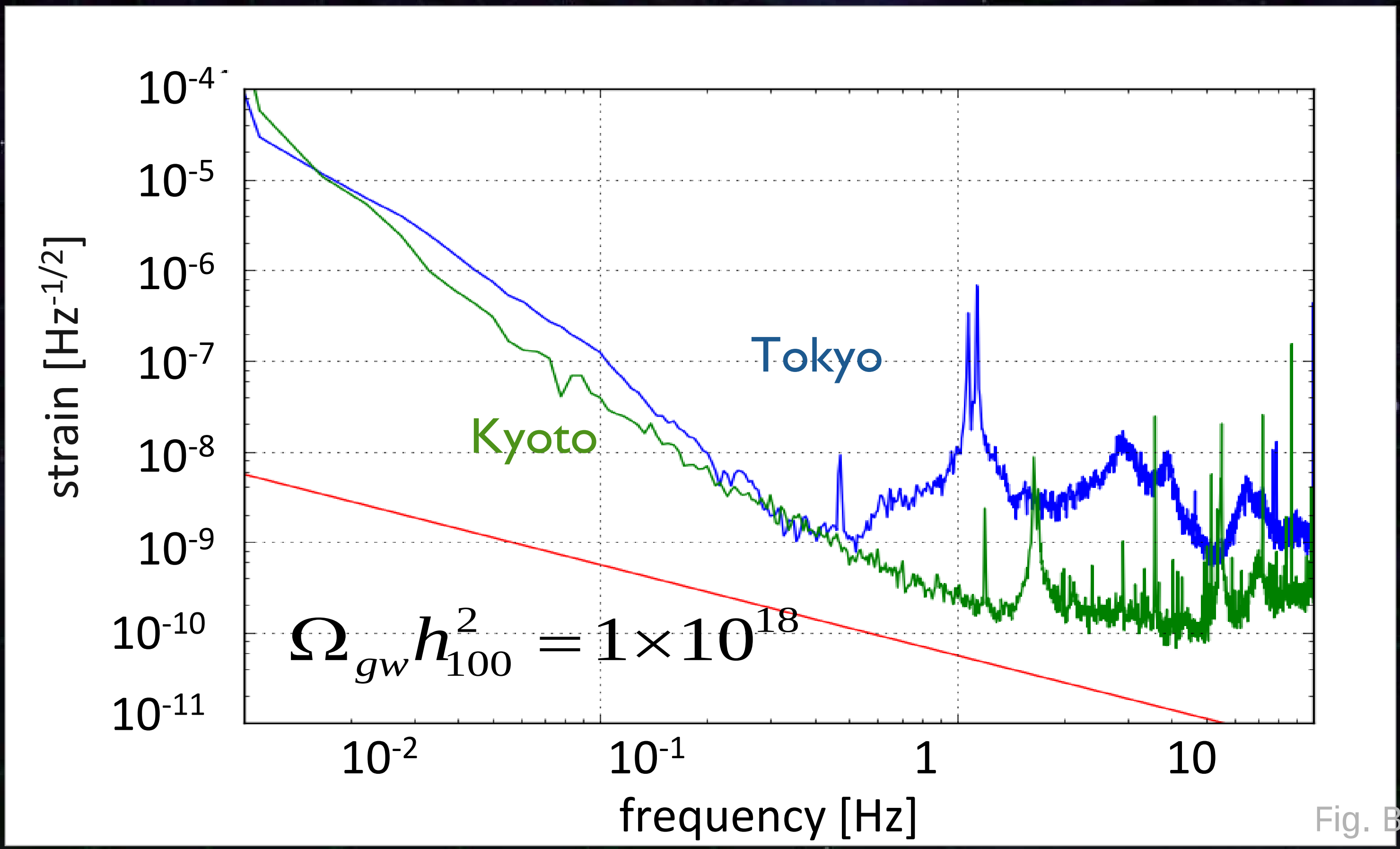


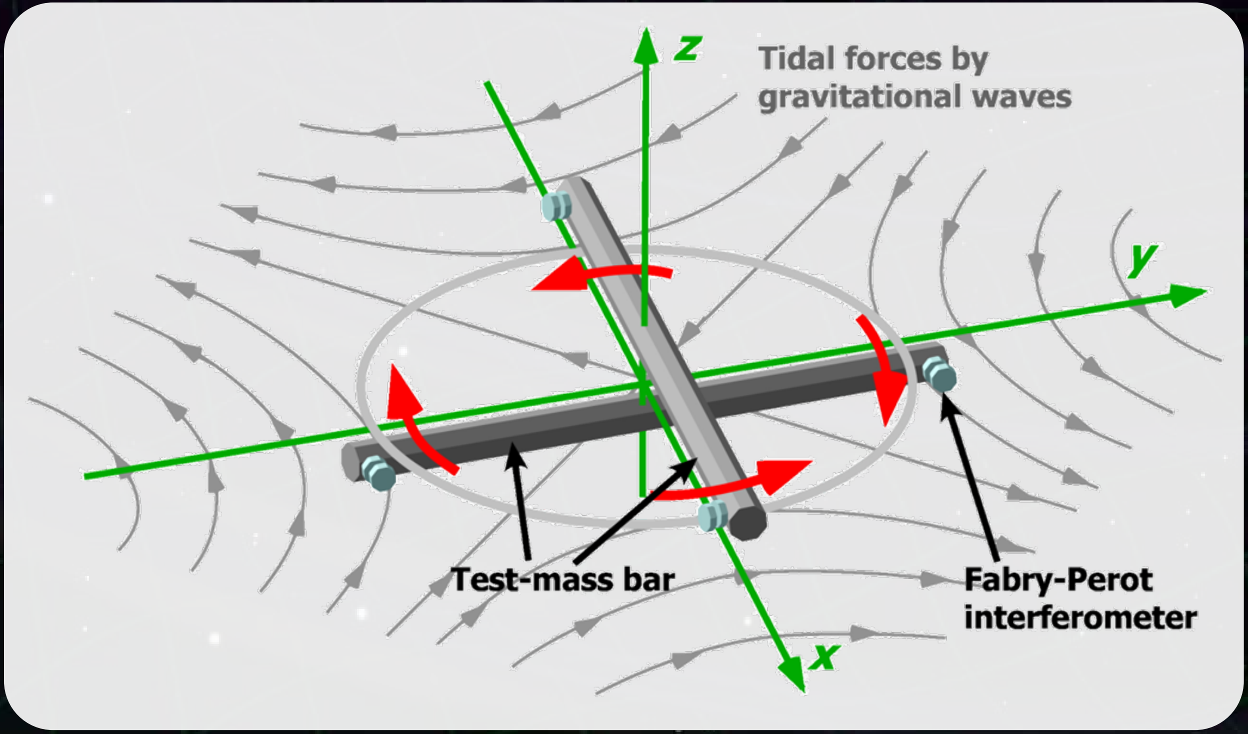
Fig. By A.Shoda

Rotating TOBA

Rotating TOBA

Rotate the detector along its axis

- Very low-freq. GW signal (~10^{-8} – 10^{-4} Hz) is up-converted to 2 x (Rotation freq.)



Rotating TOBA

Equation of Motion of a test-mass bar

$$I\left(\ddot{\theta}+\frac{\omega_0}{Q}\dot{\theta}+\omega_0^2\theta\right)=\frac{1}{4}q^{ij}\cdot\ddot{h}_{ij}(t)$$

I : **Moment of Inertia**

q^{ij} : **Dynamic quadrupole moment**

Rotation

$$\theta_{\mathrm{diff}} \simeq \alpha\left(\frac{\omega_{\mathrm{g}}}{2\omega_{\mathrm{rot}}}\right)^2\left[h_\times \cos(2\omega_{\mathrm{rot}}t)+h_+\sin(2\omega_{\mathrm{rot}}t)\right],$$

GW with very-low freq. (ω_g)
appears as high freq. ($2\omega_{rot}$) signal by up-conversion.

Advantage:

- Extract two independent polarization signals.
- Observable at high freq.→ easy to avoid low-freq. noises.
- Allow intermitted observation.

Sensitivity by R-TOBA

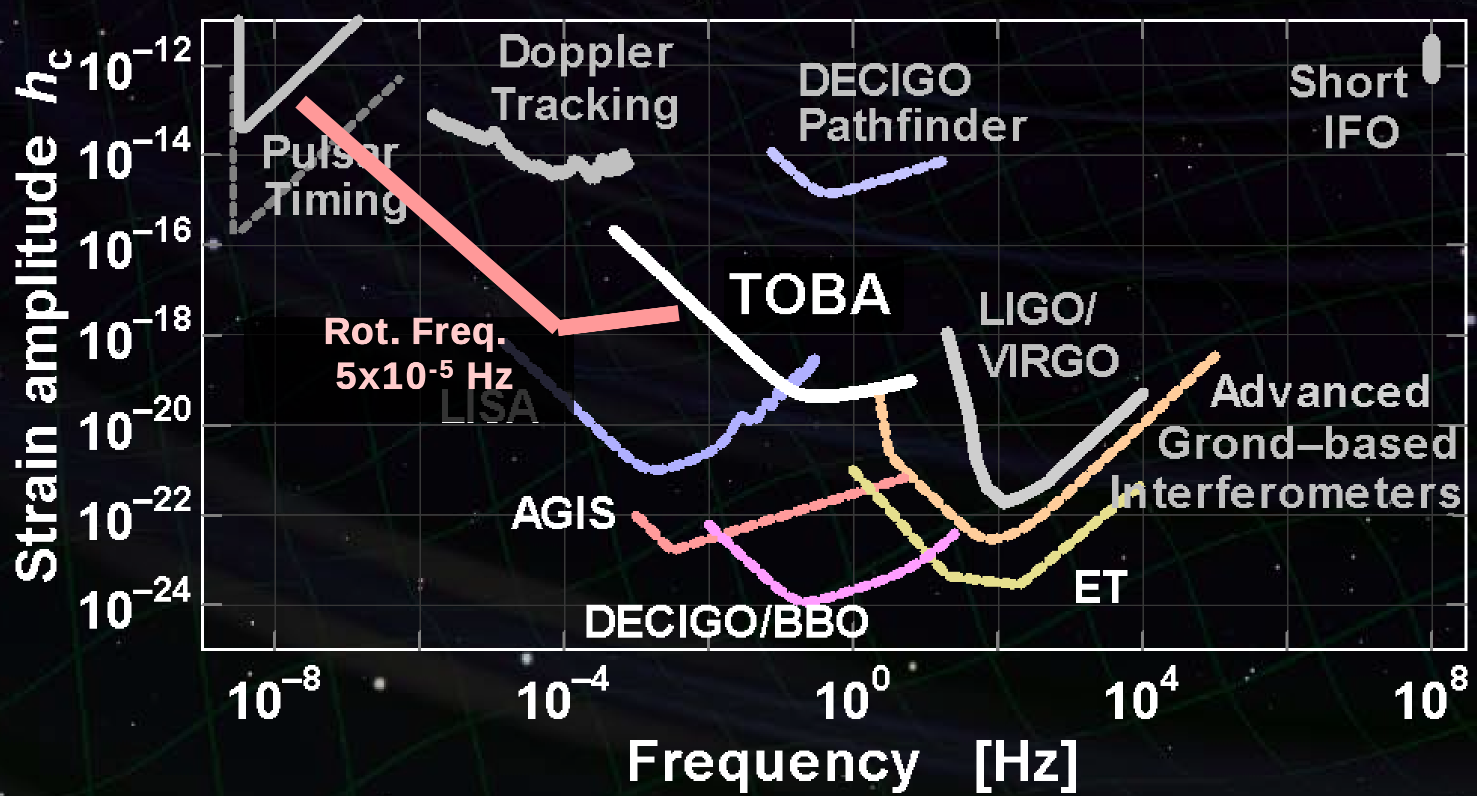
Sensitivity example

Rotation freq. 5×10^{-5} Hz

Laser power 1mW

⇨ Bridge the Pulsar-timing and LISA bands

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}



Rotating TOBA prototype

(SWIM on SDS-1 satellite)

Reference:

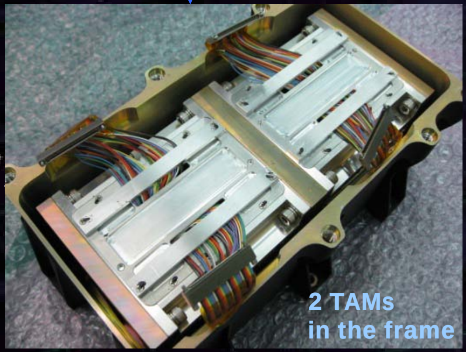
- W. Kokuyama, presentation at GWADW2010

SWIMμν GW sensor

Tiny GW sensor : Test-mass length ~ 50mm

Launch in Jan. 2009, Decommission in Sept. 2010

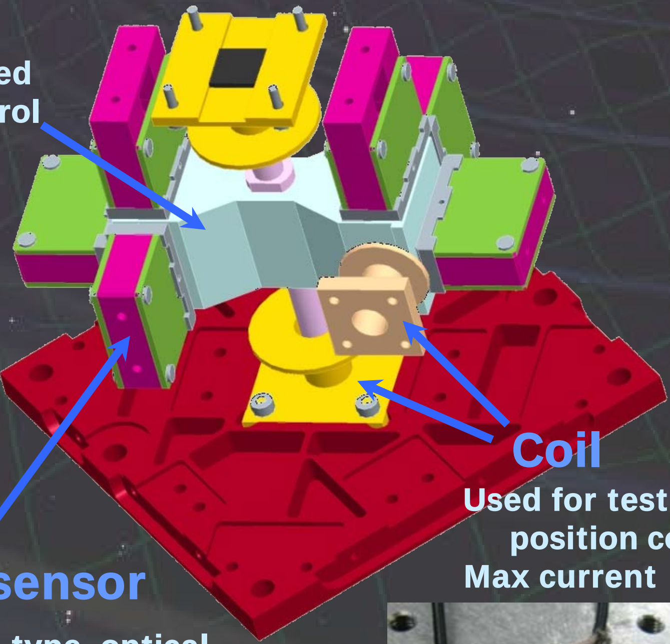
Successful operation and data-taking



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



Coil

Used for test-mass position control
Max current ~100mA

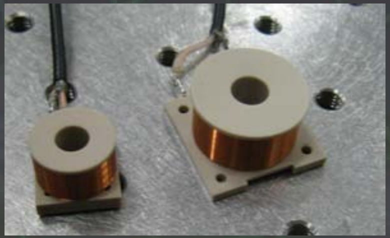
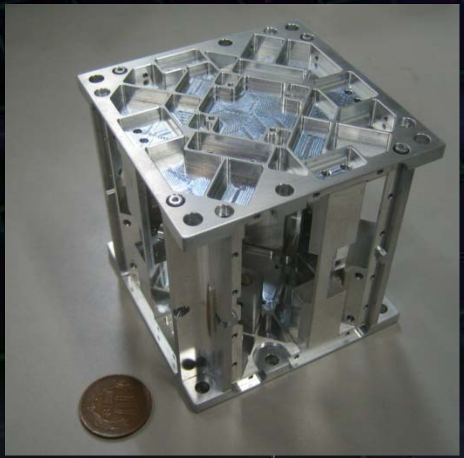


Photo sensor

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



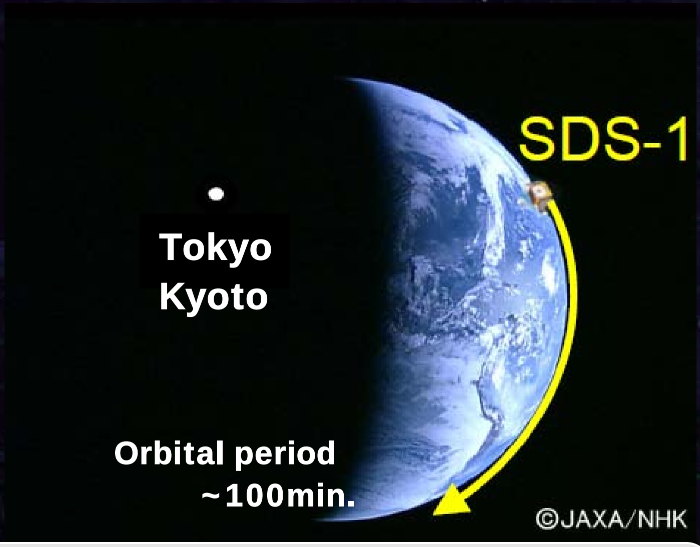
Observation by SWIM

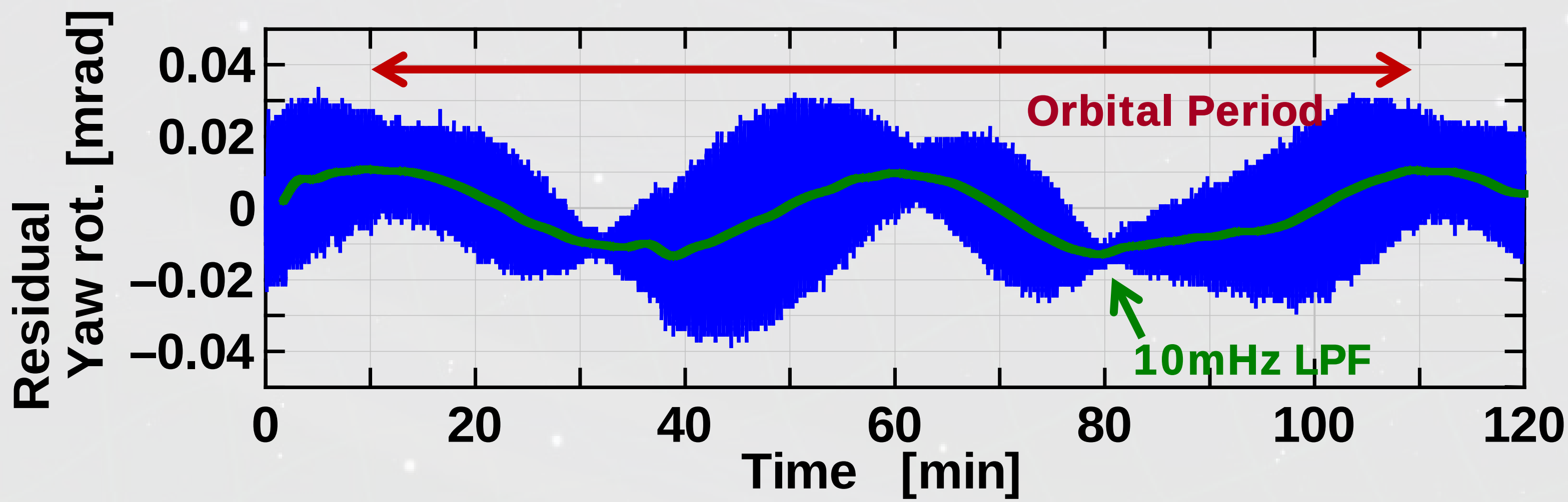
Continuous data taking

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

Simultaneous observation
with ground-based detectors

⇨ Data analysis

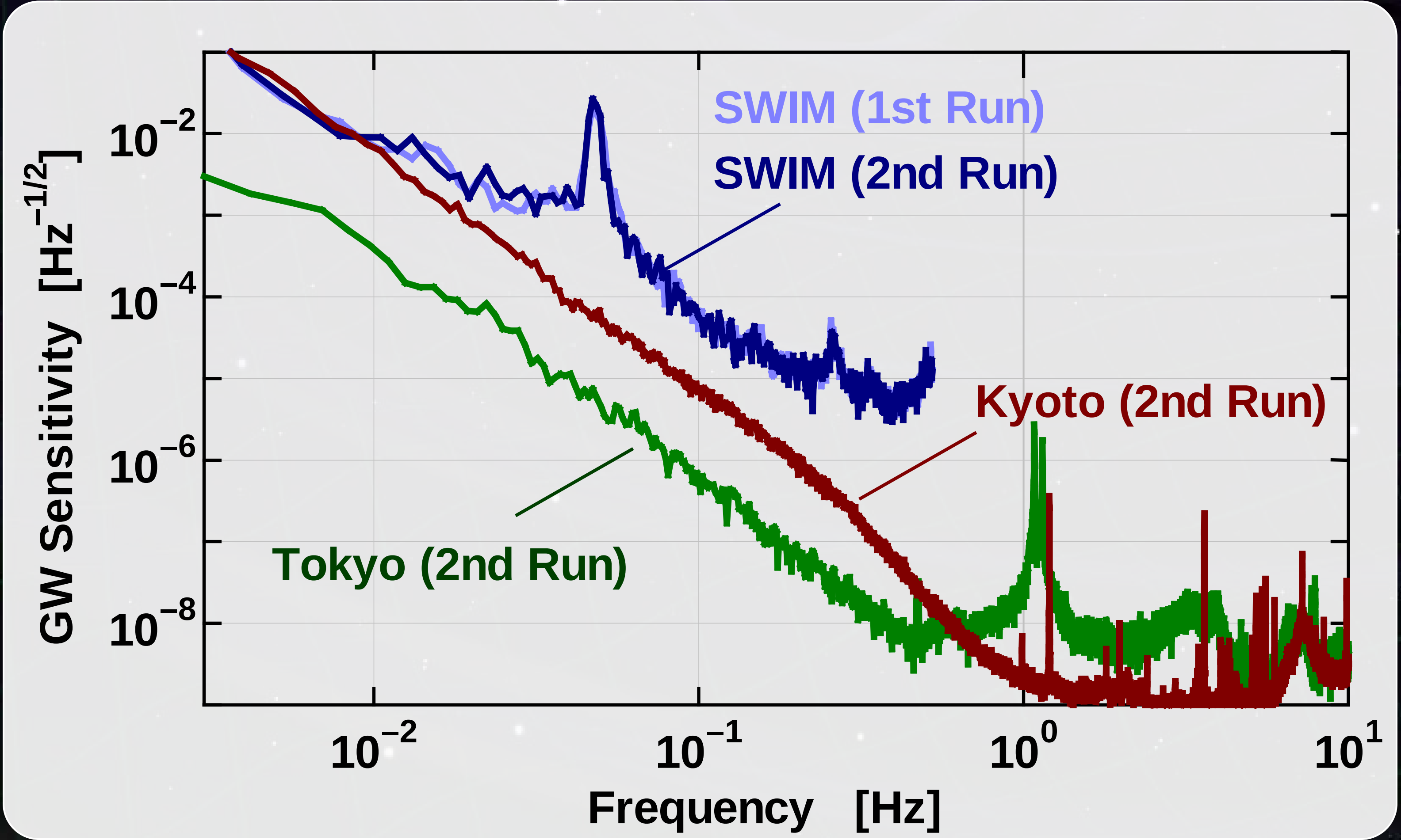




Sensitivity

Observation by SWIM and ground-based detectors

1st run June 17 2010, 2nd run July15 2010



Summary

Summary (1/2)

Propose a novel type GW detector : TOBA

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

- Observable Range of 10Gpc for BH binary inspiral with realistic detector parameters.
- Having sensitivity to low-freq. (1mHz-0.1Hz) GWs even with ground-based configuration.
- Rotation operation enables us lower freq. (<1mHz) GWs.

- Ground-based configuration
  - Simpler and lower-cost detector.
  - Reduction of seismic and Newtonian noises is critical.
- Space-borne mission
  - Free from seismic disturbances.
  - Spin spacecraft naturally becomes a rotating TOBA.

Summary (2/2)

Ground-based prototype tests

- Single small-scale TOBA with length ~20cm
  - → Set a new upper limit at 0.2Hz for GWB.
- Observation run with two separated small-scale TOBA
  - → Data analysis in progress.
  - 1/50 better GWB upper limit is expected.

Prototype in space

- Tiny module named SWIMμν, length ~5cm
  - In orbit operation for ~1.5 years.
  - More than 6-hours' observation data.
  - → Data analysis in progress.

Discussions

New motivations for GW research field...

- Optical readout noise
- Low freq. seismic isolation and reduction of Newtonian noise.
- Material, bar shape, and thermal noise
- Cryogenic system

- New possibility as a space mission

- GW sources at different freq. band
  - Between pulsar timing and LISA
  - Between LISA and ground-based detectors
- Data analysis schemes
  - Rotating TOBA configuration
  - Distributed multiple detectors

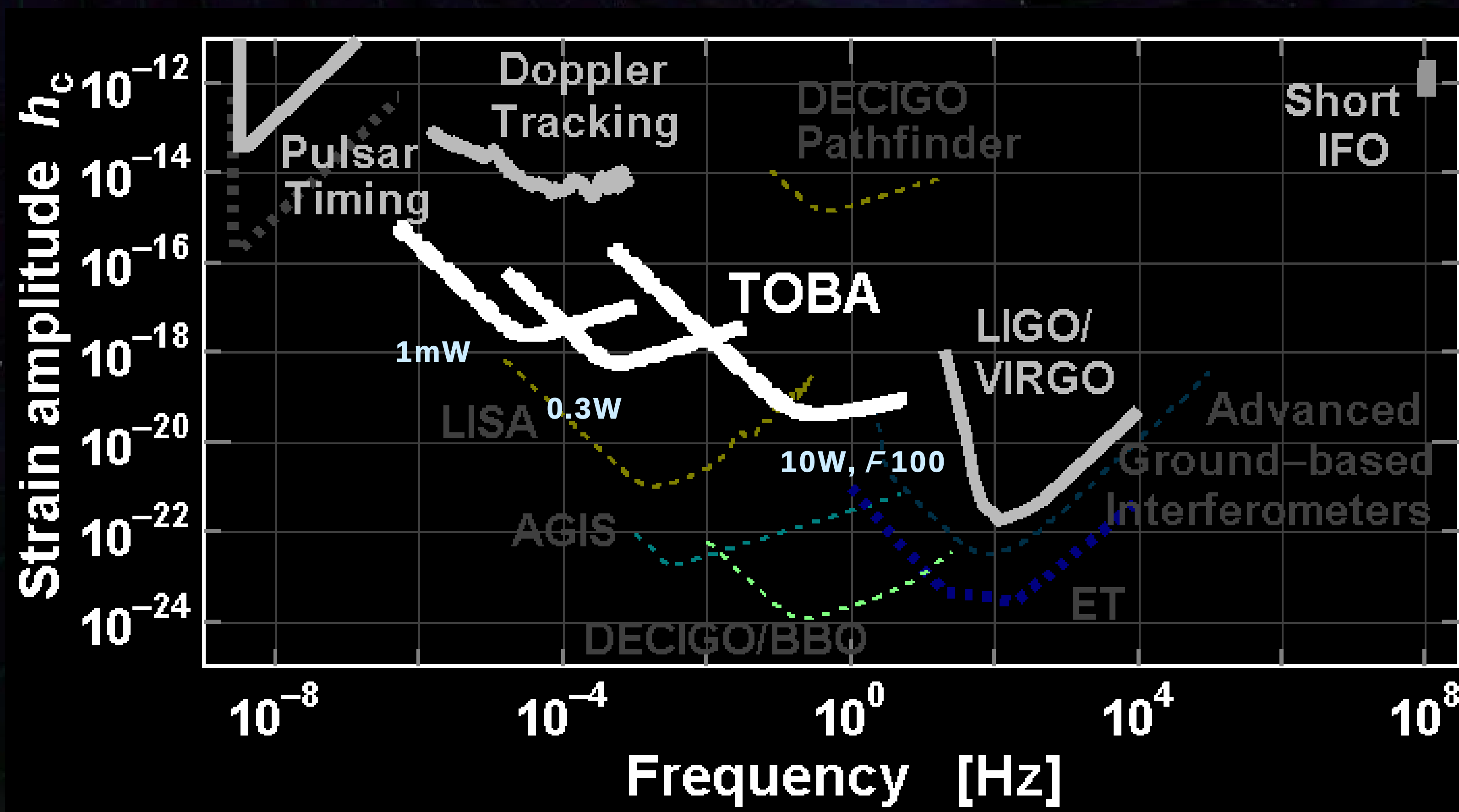
End

Backups

TOBA Sensitivity

Sensitivity example

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



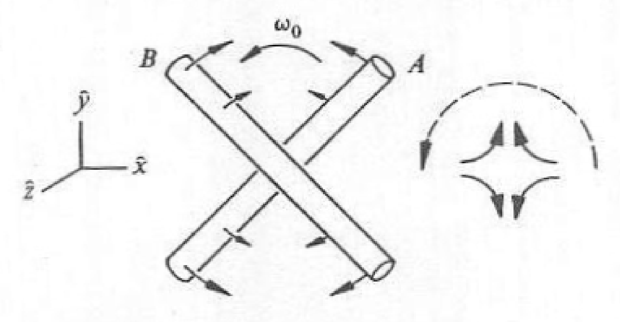
Topic

Homodyne detection

Ideas of :

Bar rotation by tidal acceleration by GW
Detection of Circularly polarized GWs
Heterodyne detection method

V.B.Braginsky, Ya.B.Zel'dovich, and V.N.Rudenko
Sov. Phys.- JETP Lett. 10 (1969) 280.
Being introduced in:
C.W.Misner, K.S.Thorne, J.A.Wheeler,
'Gravitation' W.H.Freedman (1973) pp.1016.

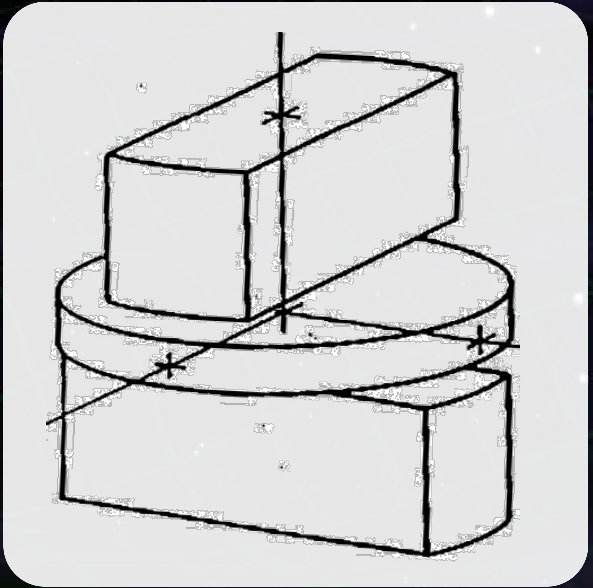


(f) Angular accelerations of rotating bars ["Heterodyne detector"; see Braginsky, Zel'dovich, and Rudenko (1969)]

Observation with torsion antenna :

Cryogenic torsion antenna to observe continuous GWs from Grab pulsar

S.Owa, et al.,
'Cryogenic Detector for Gravitational Radiation from the Crab Pulsar'
Proceedings of the fourth Mercel Grossmann Meeting on General Relativity (1986).

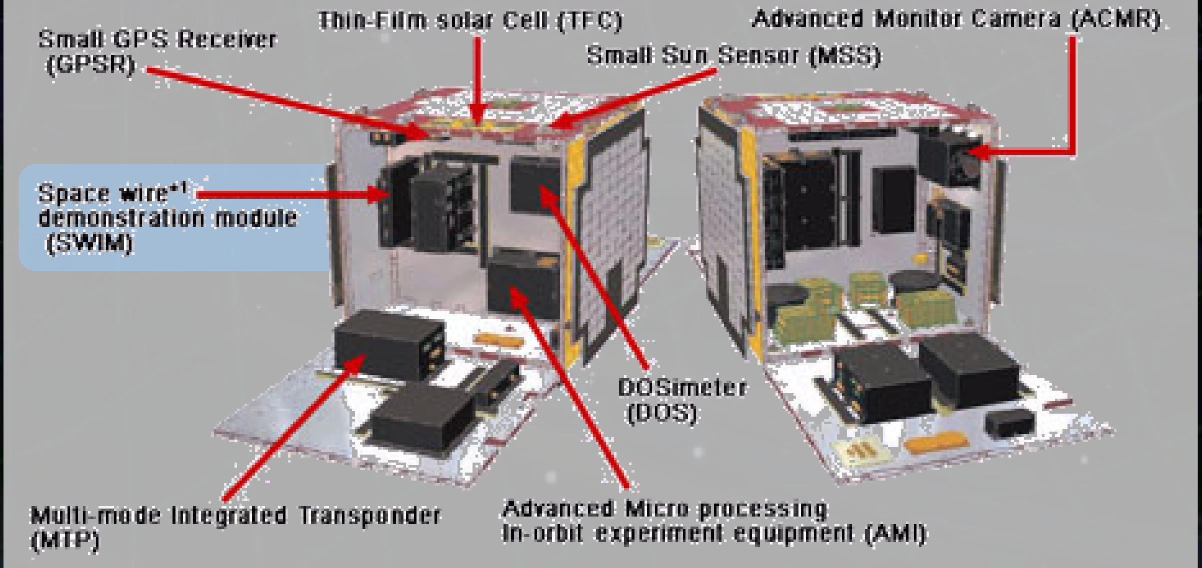


SDS-1衛星での実証

SDS-1 (Small Demonstration Satellite - 1)

JAXA開発による100kg級の技術実証衛星

- Size：70x70x60cm,Weight：100kg
- Power：>100W, Downlink：~5kbps
- Orbit　：SSO (~660km)
- Spin stabilization and 3-axis attitude control
- Mission Lifetime：~Half year (nominal)



http://www.iat.jaxa.jp/info/prm/2007/019/01.html

SDS-1 and GOSAT
(Press Release, November 4, 2008)
Photo from Mainich Newspaper Web

SDS-1/SWIM

SDS-1/SWIM

2005年 検討・開発開始.
2009年 1月23日打上げ.
2011年 9月 運用停止.
全ての機器で
full success以上を達成.

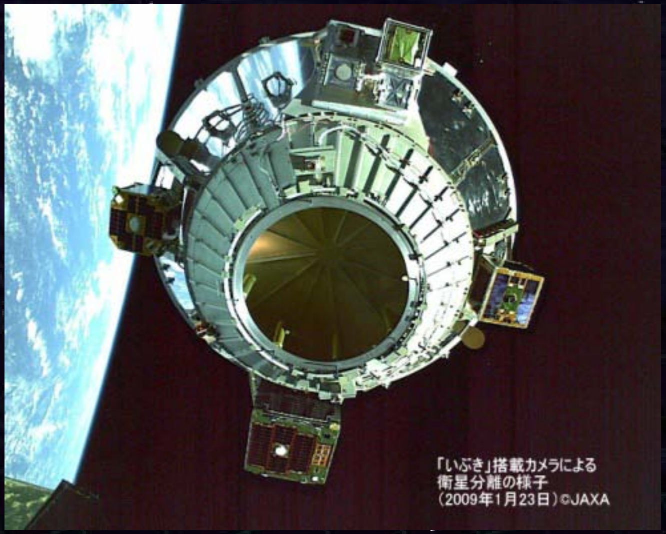


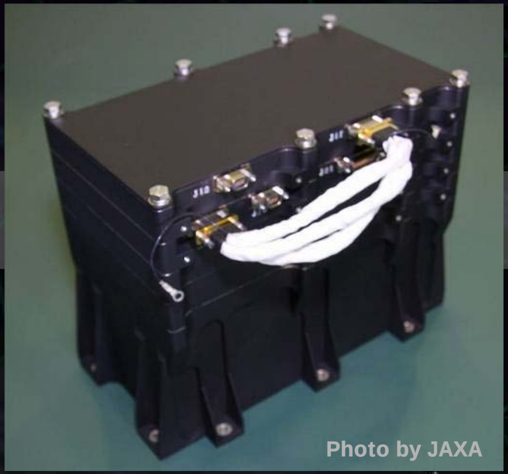
写真: JAXA

SpaceCube2: Space-qualified Computer

CPU: HR5000
(64bit, 33MHz)
System Memory:
2MB Flash Memory
4MB Burst SRAM
4MB Asynch. SRAM
Data Recorder:
1GB SDRAM
1GB Flash Memory
SpW: 3ch

Size: 71 x 221 x 171
Weight: 1.9 kg
Power: 7W

SWIMμν : User Module



Processor test board
GW+Acc. sensor
FPGA board
DAC 16bit x 8 ch
ADC 16bit x 4 ch
→ 32 ch by MPX
Torsion Antenna x2
~47g test mass

Data Rate : 380kbps
Size: 124 x 224 x 174
Weight: 3.5 kg
Power: ~7W

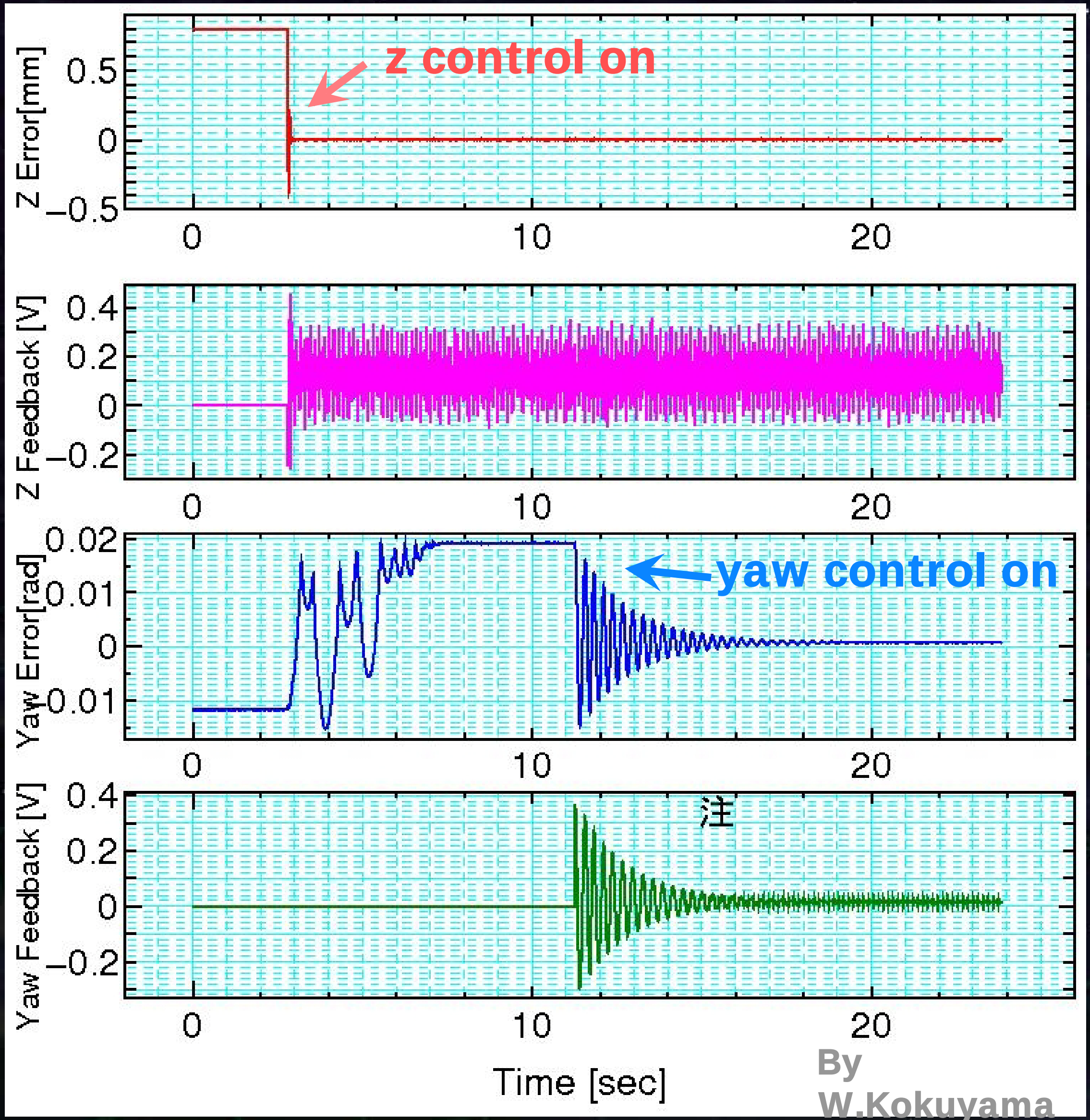
SWIMμν 軌道上実証

SWIM
In-orbit operation

Test mass controlled

- Error signal → zero
- Damped oscillation (in pitch DoF)
- Free oscillation in x and y DoF
- Signal injection → OL trans. Fn.

Operation: May 12, 2009
Downlink: ~ a week

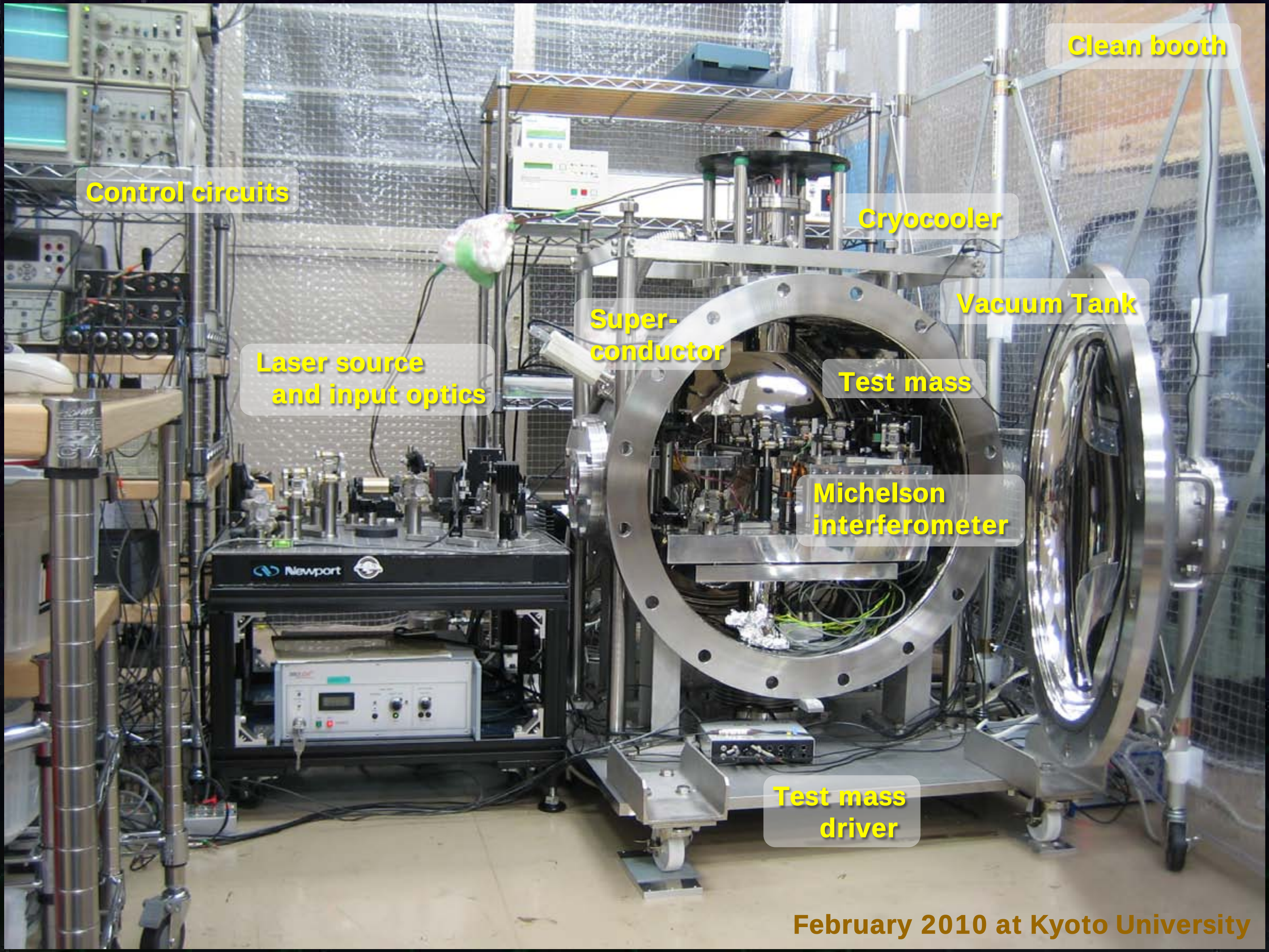


プロトタイプ

2つの地上装置, 1つの衛星搭載モジュール

	ねじれ型重力波検出器A	ねじれ型重力波検出器B	ねじれ型重力波検出器C
	(地球周回軌道, 2009年-)	(東京大学, 2008年-)	(京都大学, 2010年-)
			
試験マス	質量 50g, 長さ 5cm 無重力浮上 +制御	質量 150g, 長さ 20cm 超電導磁気浮上 +制御	質量 340g, 長さ 25cm 超電導磁気浮上 +制御
変動検出	反射型フォトセンサ	レーザー干渉計	レーザー干渉計
位置・姿勢	スピン + 軌道運動	地上静置観測	地上静置観測

Small-scale TOBA at Kyoto

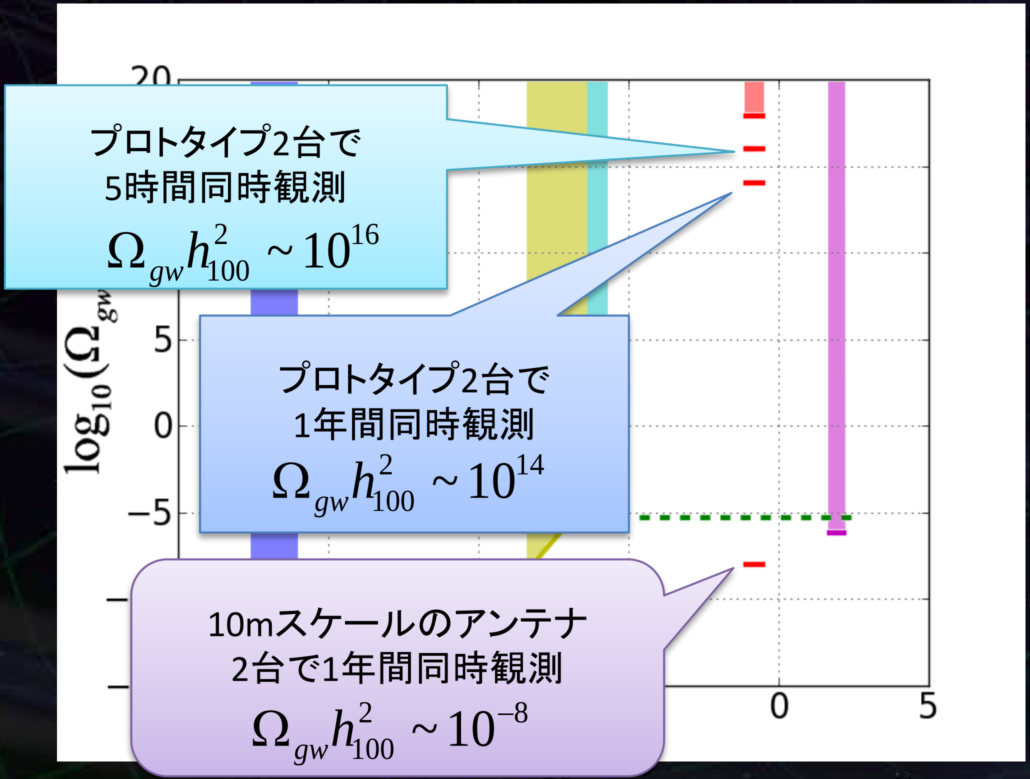


Observation with two detectors

1台の観測では，背景重力波の検出は極めて困難．

検出器の雑音と背景重力波を区別できない．

Fig. By A.Shoda



複数台での

同時観測，相関解析を行う．

信号と雑音を区別できる．

感度を向上できる．

$$\sqrt{T_{\mathrm{obs}}\ \Delta f_{\mathrm{obs}}}$$

程度の向上．

結果の見通し

観測データ (2010年7月) 解析の暫定結果.

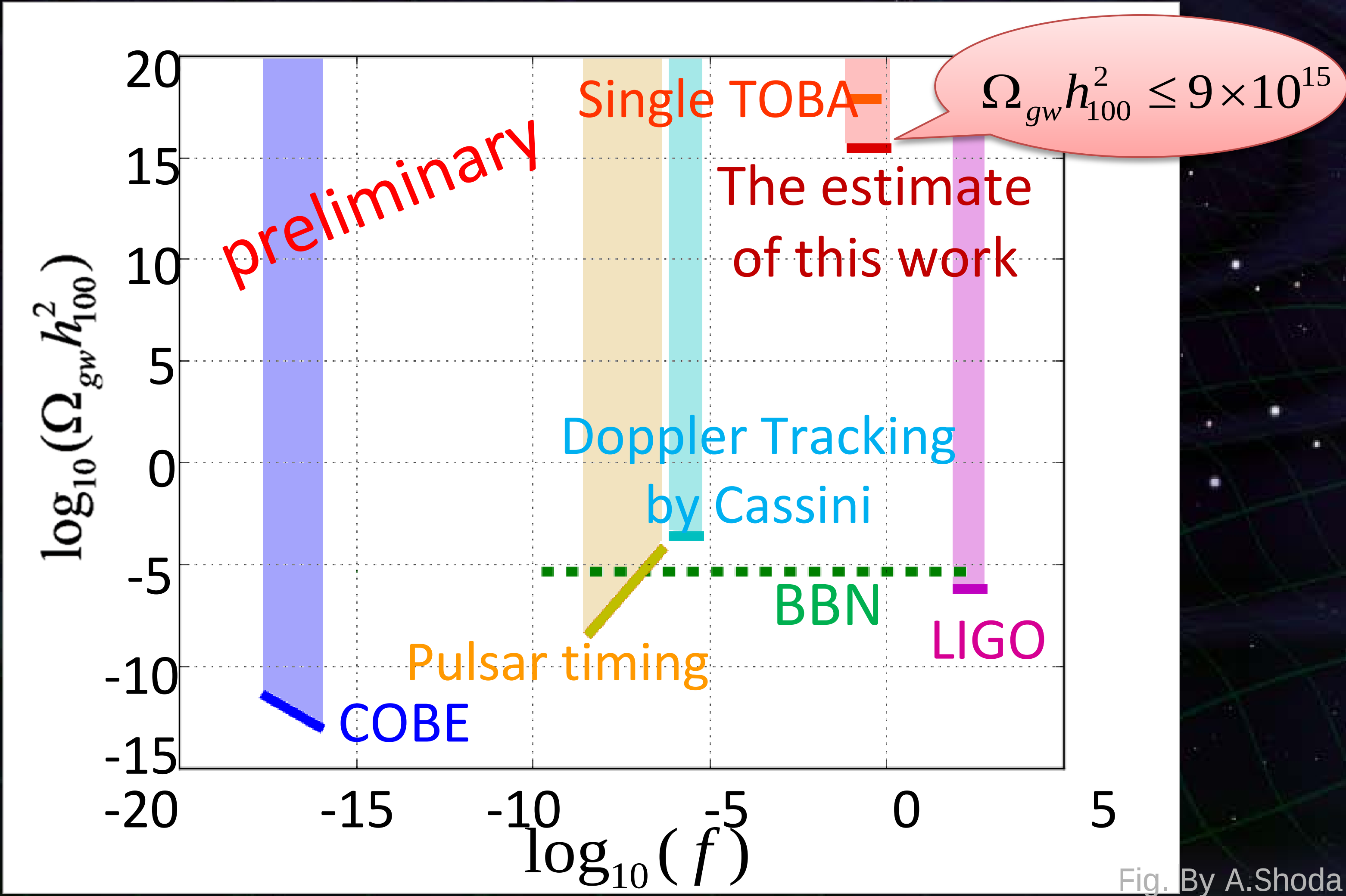


Fig. By A.Shoda