Plan of Lectures

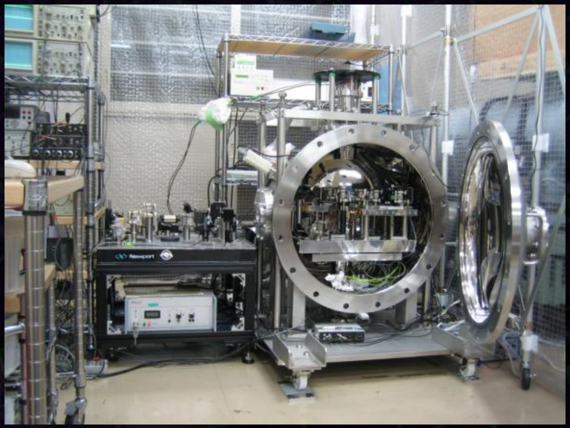
Lecture (I) Ground-based detector : LCGT

Lecture (II) Space-borne detector : DECIGO

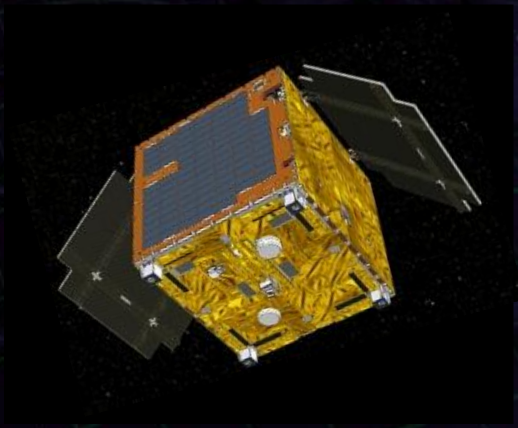
Lecture (III) Novel type detector : TOBA

TOBA: Torsion-Bar Antenna

Small-scale TOBA at Tokyo



Small-scale TOBA at Kyoto



SWIM on SDS-1 satellite

Masaki Ando
(Department of Physics, Kyoto University)

APCTP2011 (August 2, 2011, Pohang, Korea)

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

3. Summary

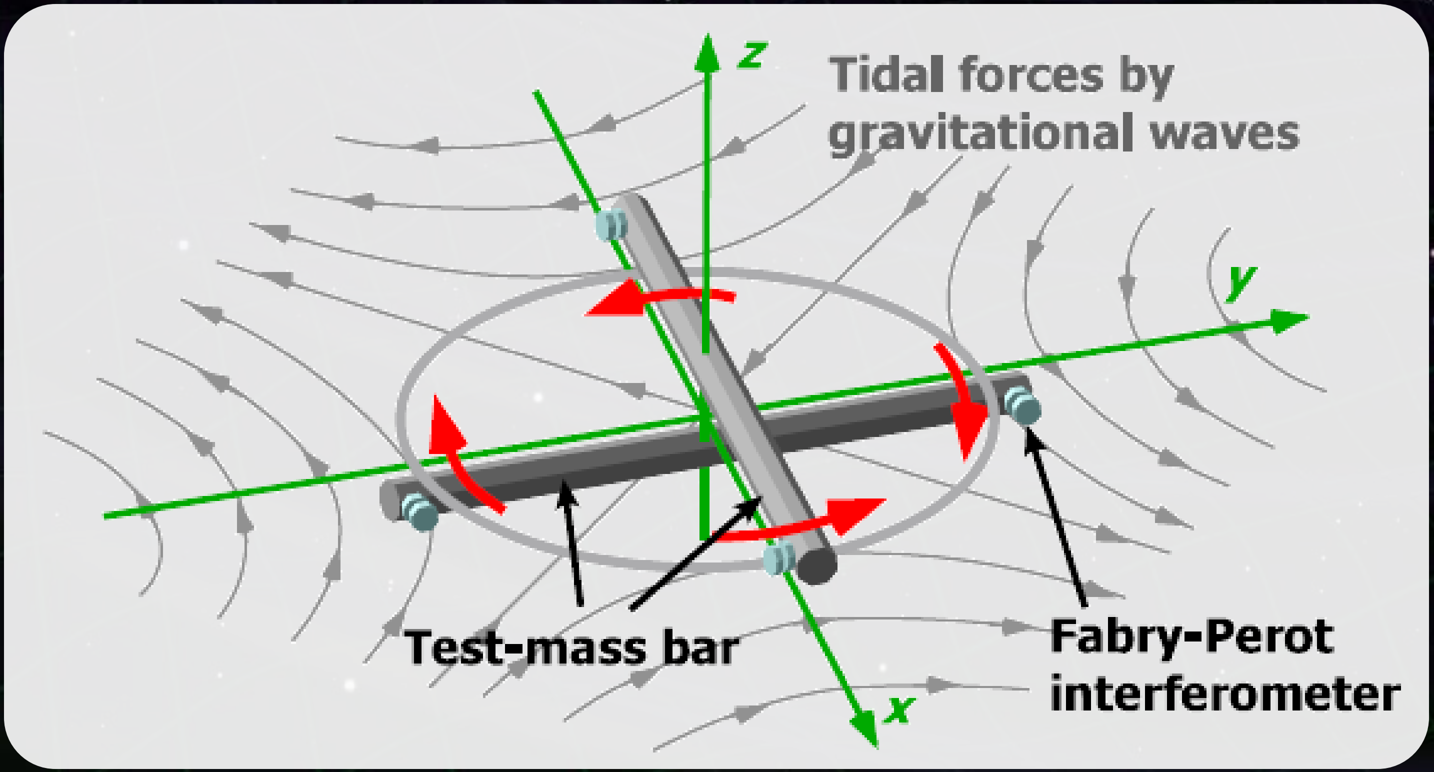
TOBA

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.



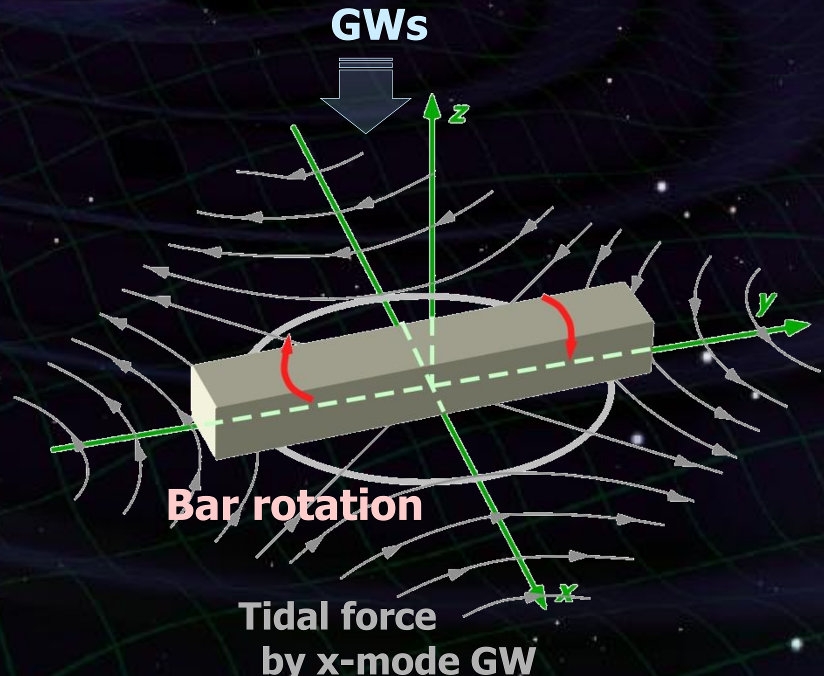
M.Ando, et. al, Phys. Rev. Lett. 105, 161101 (2010)

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



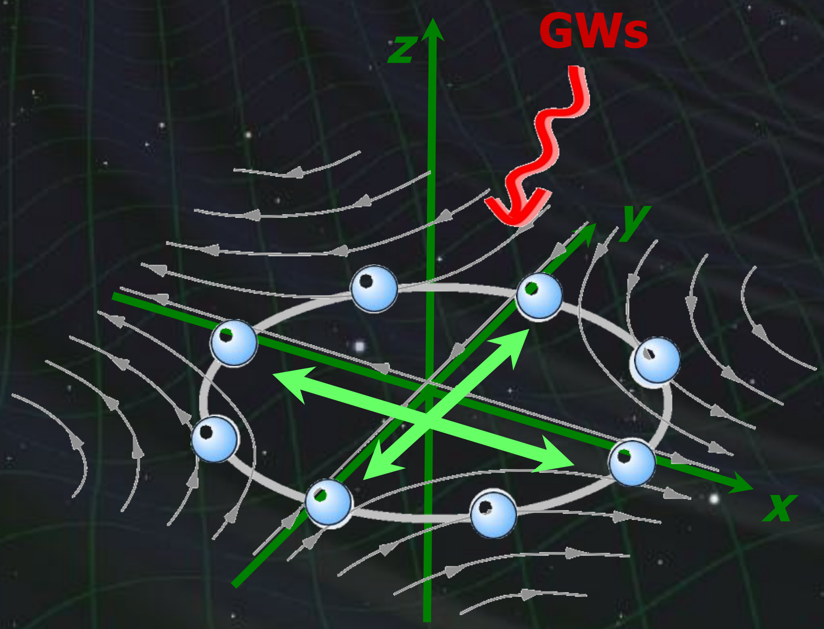
$$\tilde{\theta}(\omega)=\frac{1}{2}\alpha\tilde{h}_\times(\omega) \qquad (\omega\gg\omega_0)$$

α : shape factor, between 0 to 1
Dumbbell → α = 1
Dimension less,
Independent of matter density

Detection principle

Conventional IFO antenna

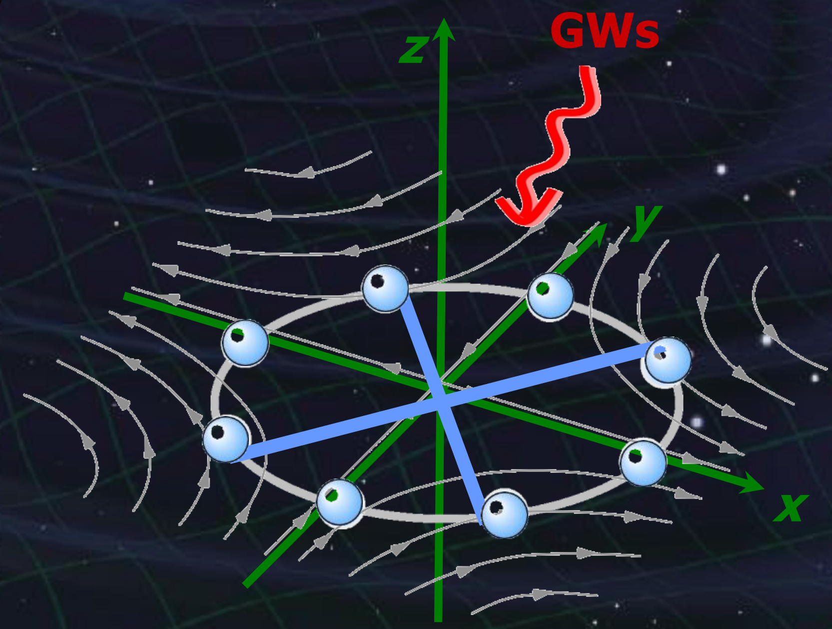
Detect differential length change



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

Torsion-bar antenna

Detect differential rotation



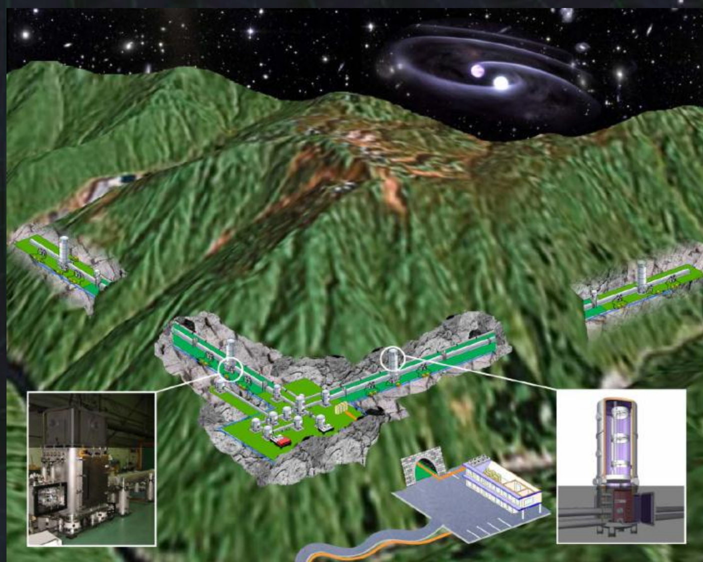
Angle $h \sim \delta\theta \sim \frac{\delta L}{L}$

Observe change in tidal forces using free test masses

Advantages

Conventional IFO

Obs. band 10Hz-1kHz



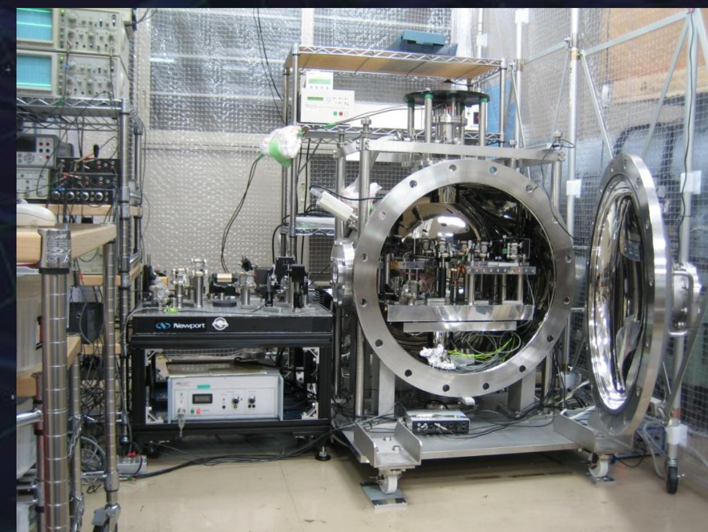
Suspended as pendulum
(Res. Freq. ~1Hz)

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

Realistic design

Example --- assume realistic parameters

Test-mass bar
- Aluminum
- Bar length : 10m, Mass : 7600kg
- Bar Q-value : 10^5 , Temp: 4K

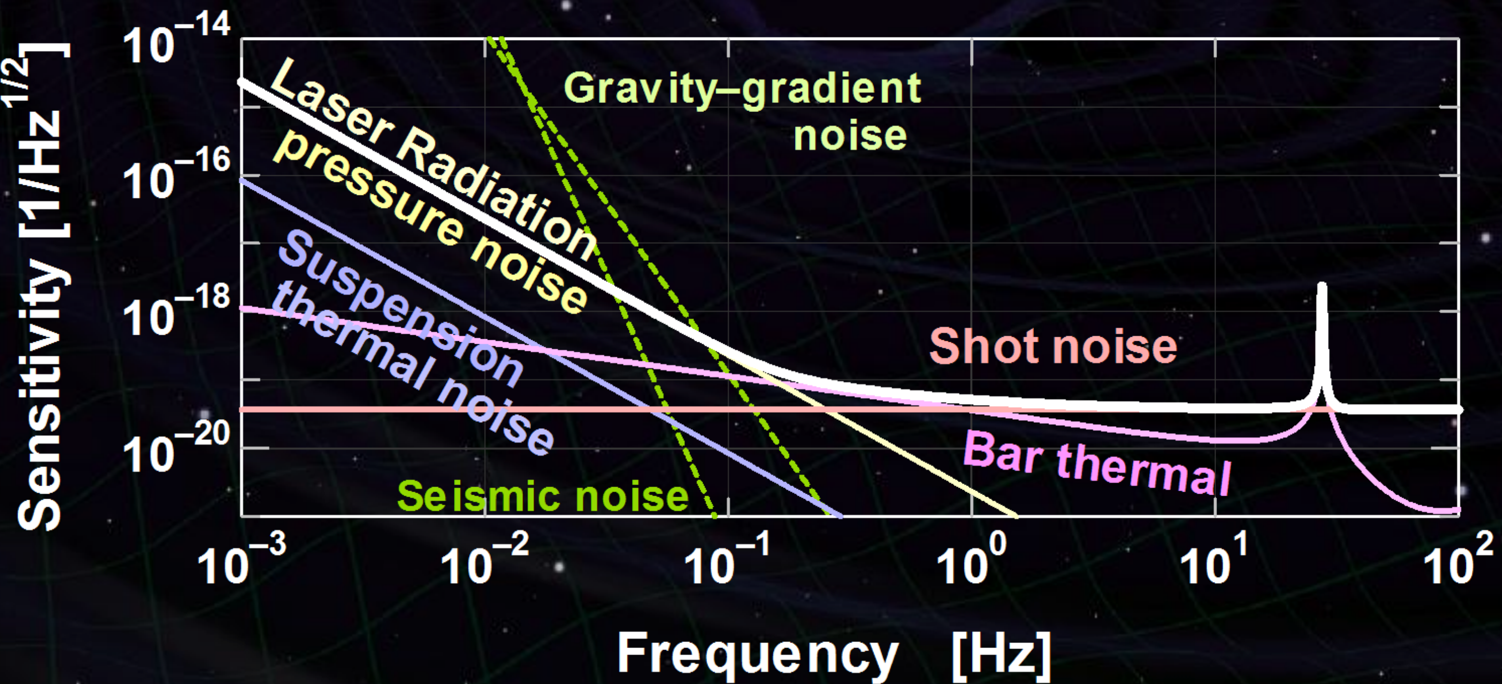
Optical readout (Laser interferometer)
- Laser source : 1064nm, 10W
- Cavity length : 1cm, Finesse : 100

Support Loss : 10^{-10} , Temp: 4K

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

Fundamental noise level of TOBA

Realistic 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}

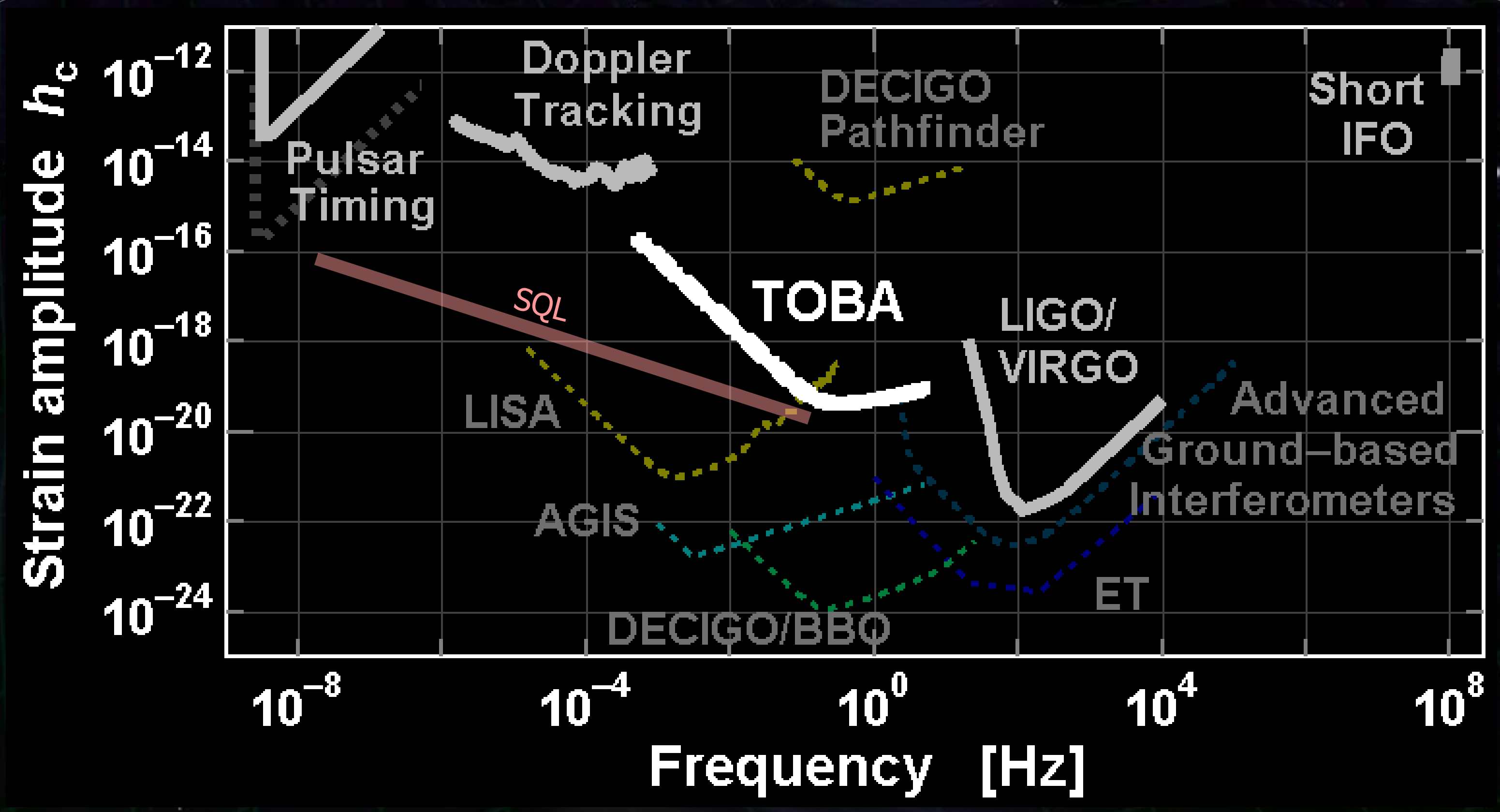
Laser Freq. noise < $10\mathrm{Hz/Hz}^{1/2}$,
Freq. Noise CMRR>100
Intensity noise < $10^{-7}/\mathrm{Hz}^{1/2}$,
Bar residual RMS motion < 10^{-12} m

TOBA Sensitivity

Comparison with the other detectors

DECIGO/BBO band:

Between ground-based detectors and LISA bands

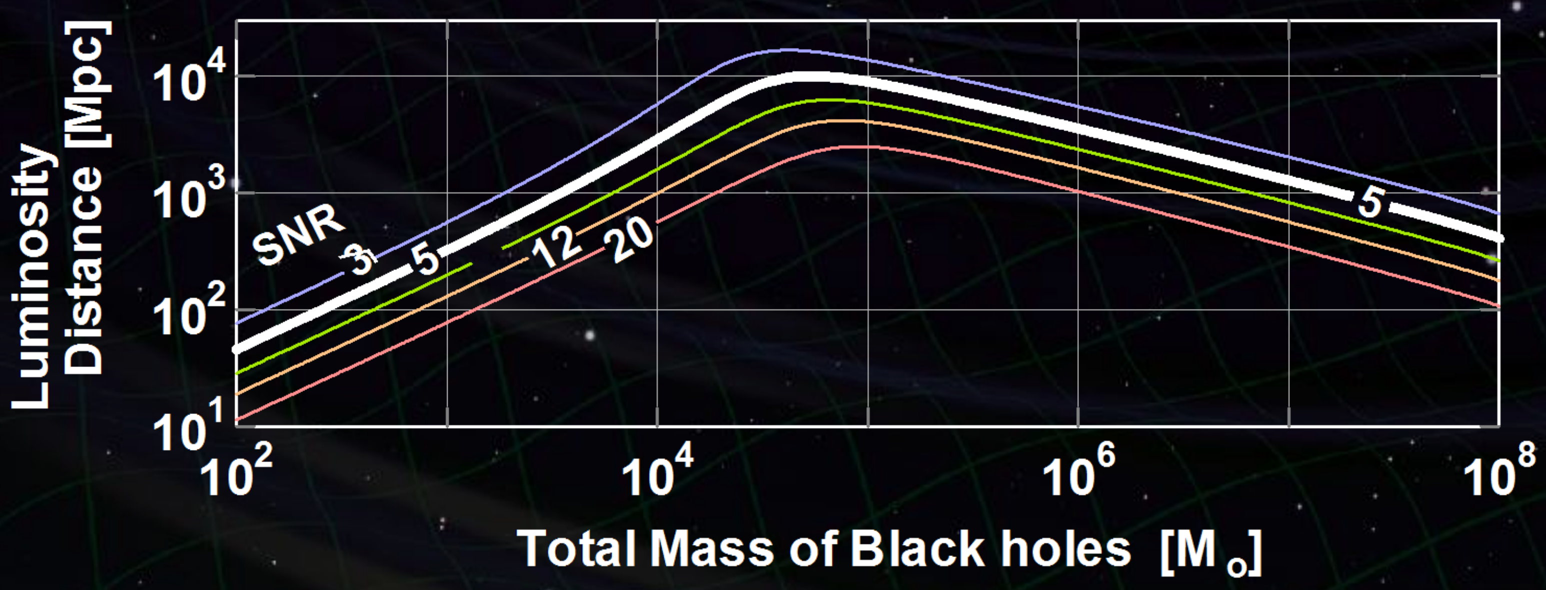


Characteristic amplitude : $h_c = \tilde{h} \times \sqrt{f_{\rm center}}$ (Dimensionless strain)

Observable range

GWs from binary BH mergers

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



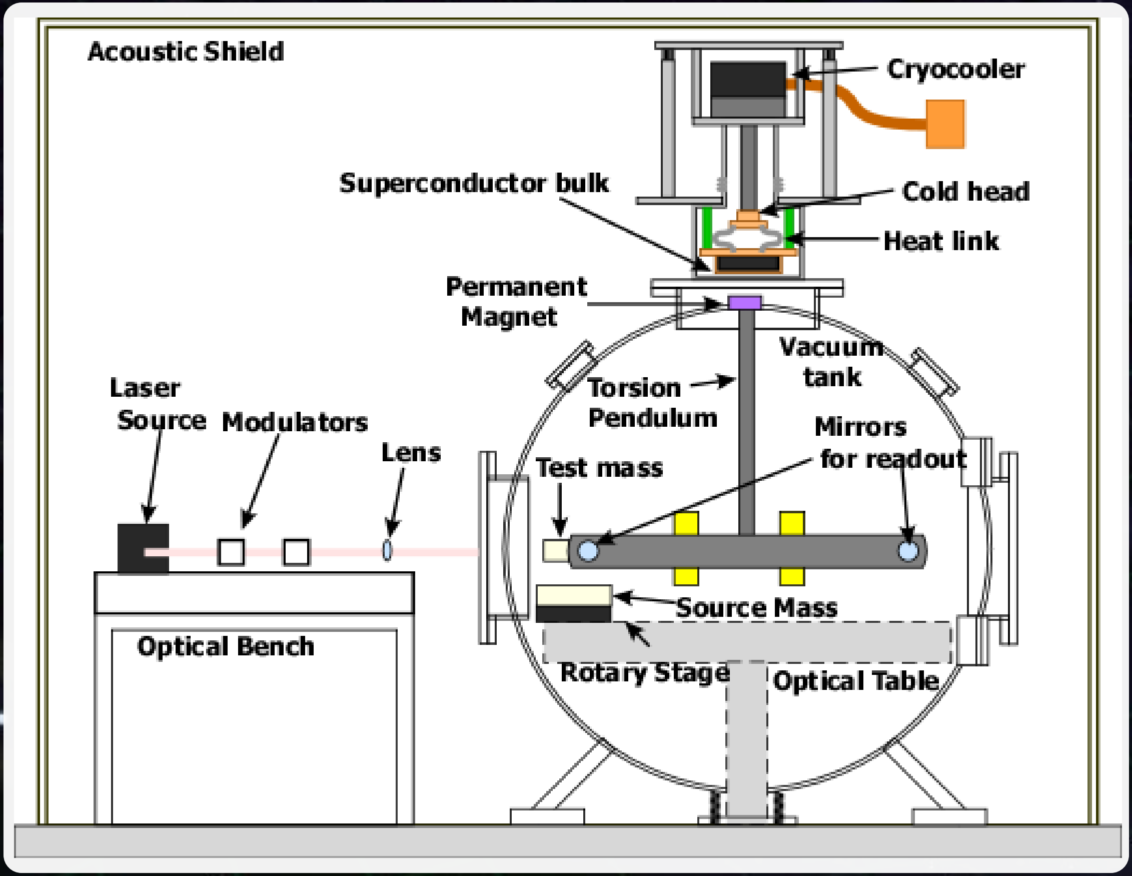
Calculation by K.Yagi

Prototype test

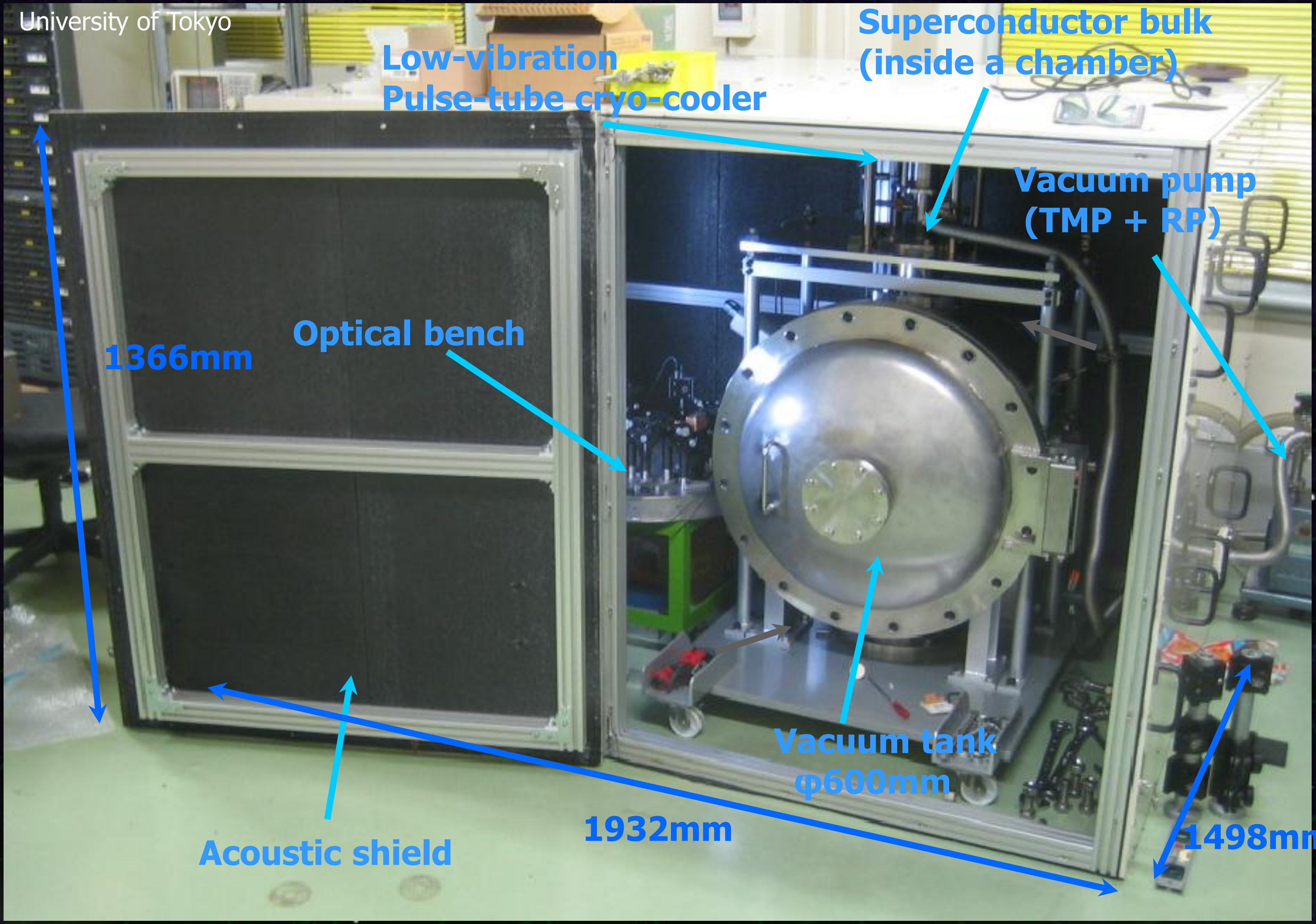
Reference:
- K.Ishidoshiro, et. al, Phys. Rev. Lett. 106, 161101 (2011)
- A. Shoda, presentation at GWPAW2011

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



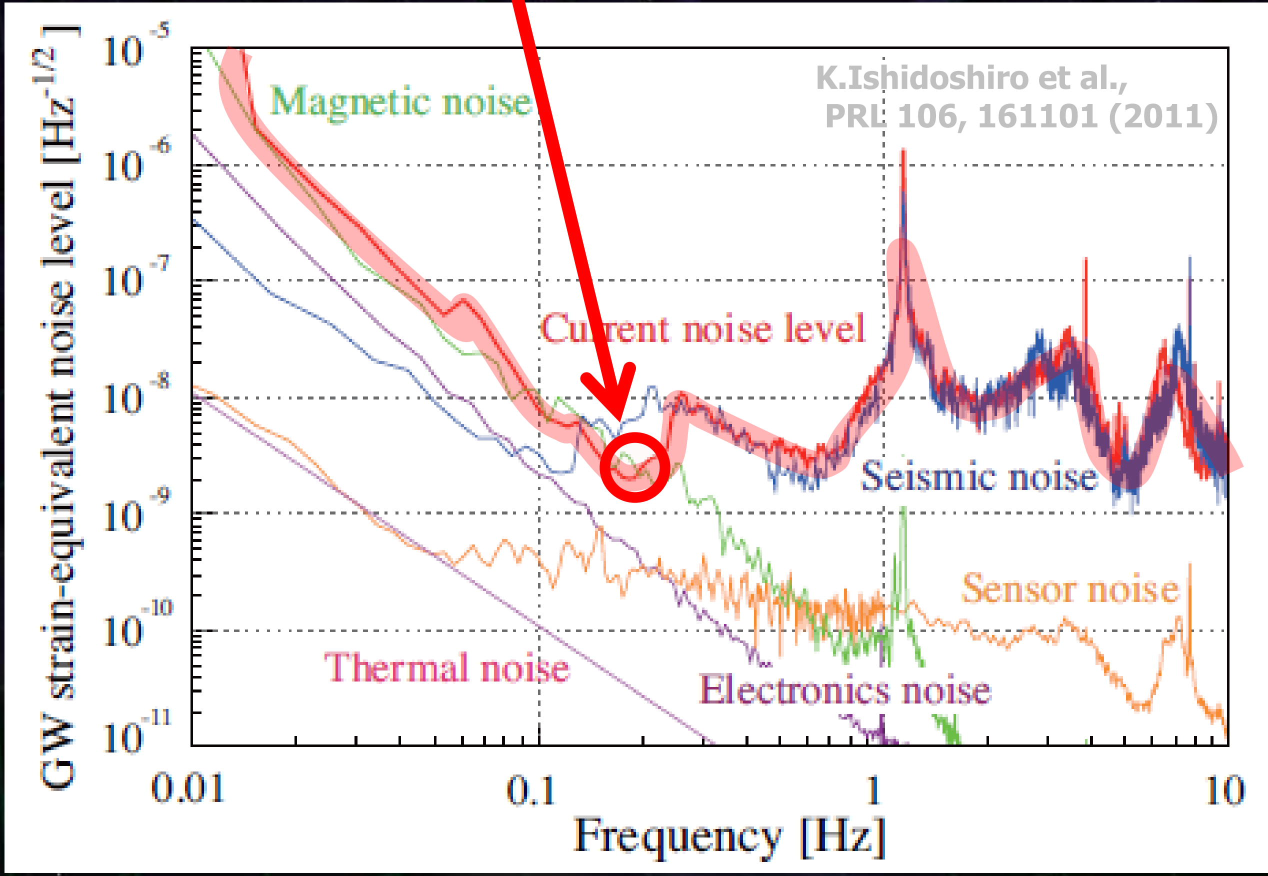
Small-scale TOBA at Tokyo



Sensitivity of small TOBA

Small-scale TOBA at University of Tokyo

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

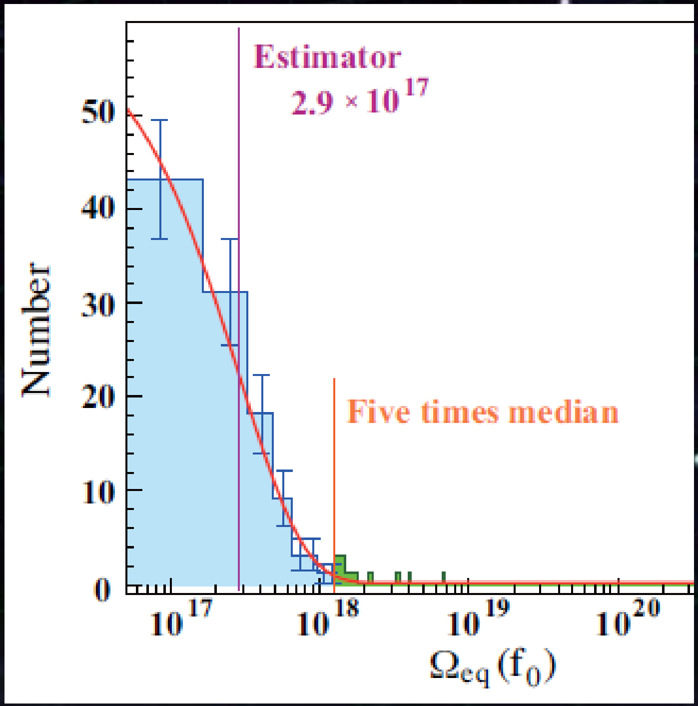
$$\Omega_{\rm eq}(f_0) = \frac{10\pi^2}{3H_0^2} f_0^3\, \tilde{h}^2(f_0)$$

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

Divide obs. data into 120 segments

→ Average and distribution

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



Upper limit on GWB

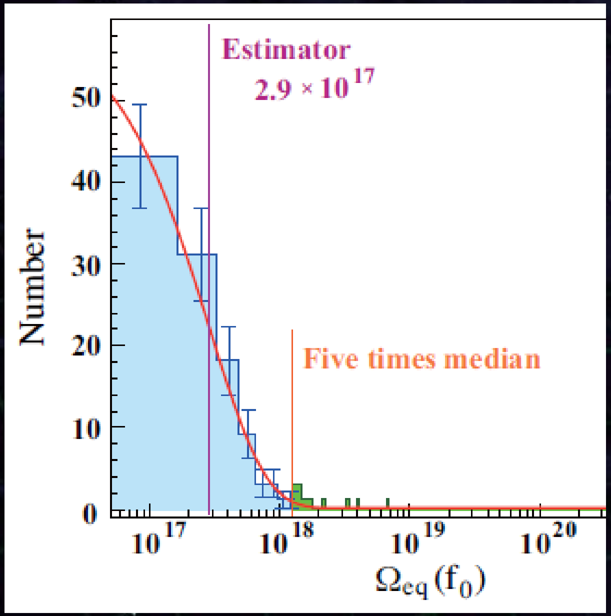
- Distribution → Averaged power at 0.2Hz

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

⇨ Upper limit on Ω_{gw}

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

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



Some details…

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

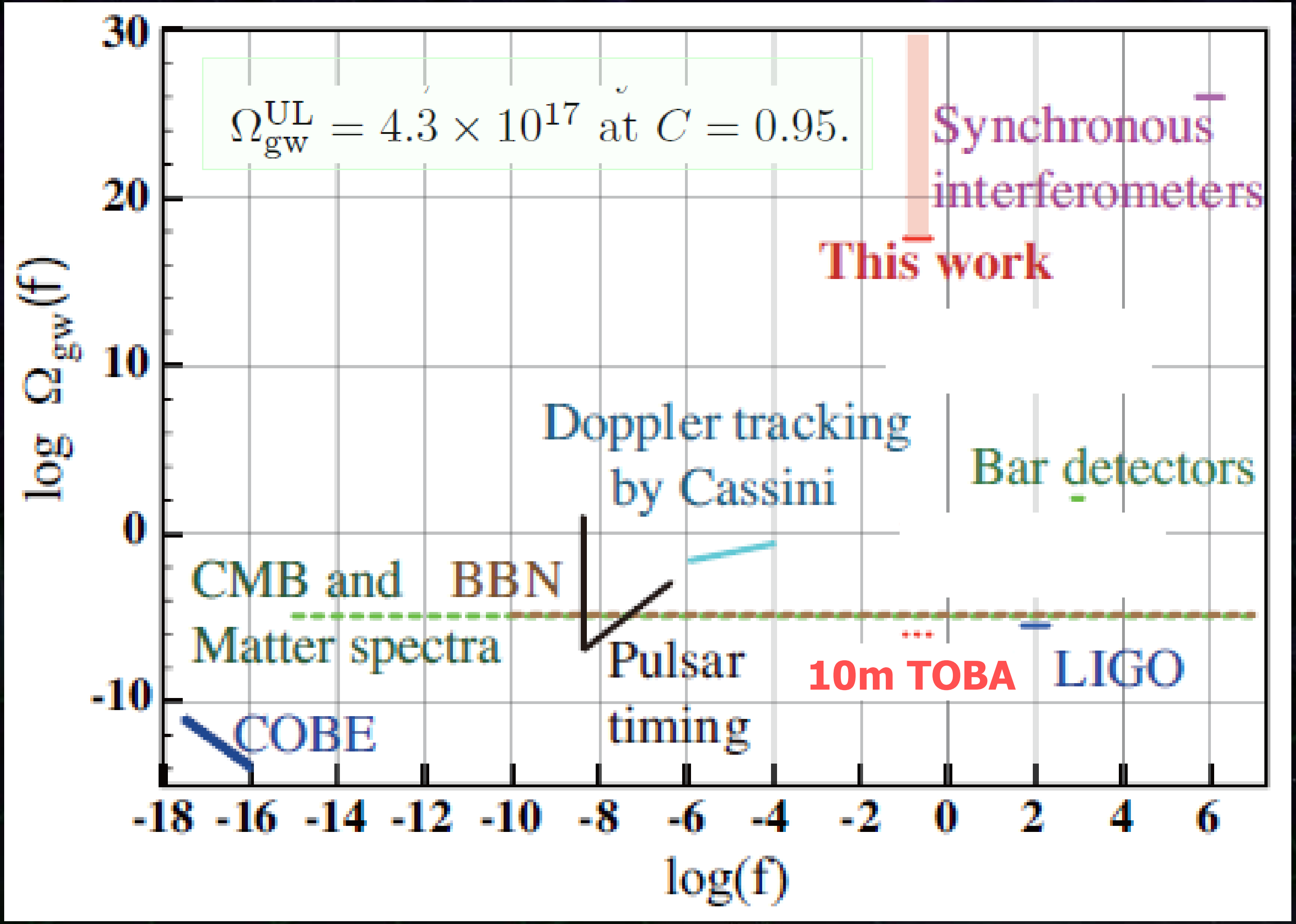
$$C = \int_{\overline{\Omega_{eq}}}^{\infty} P(\Omega_{es}|\Omega_{gw})\, d\Omega_{es}$$

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

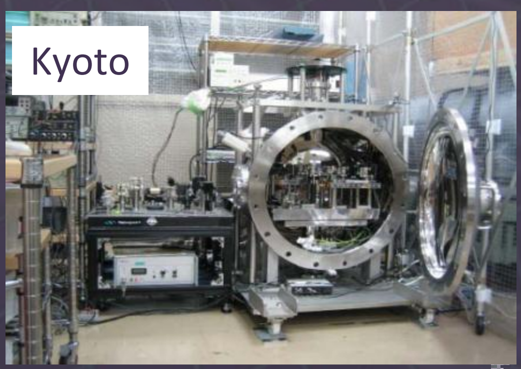


Observation with two detectors

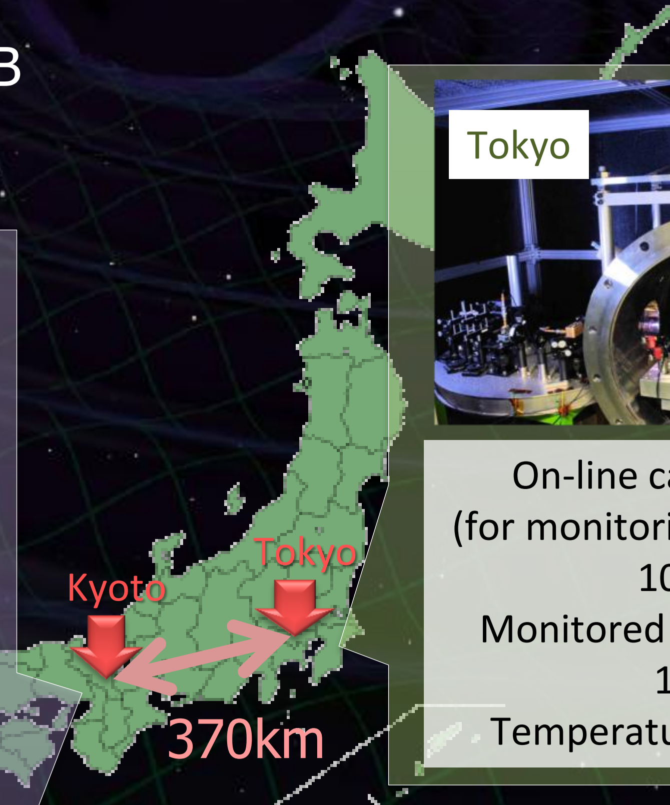
Observation with two detectors places at Tokyo and Kyoto, Japan.

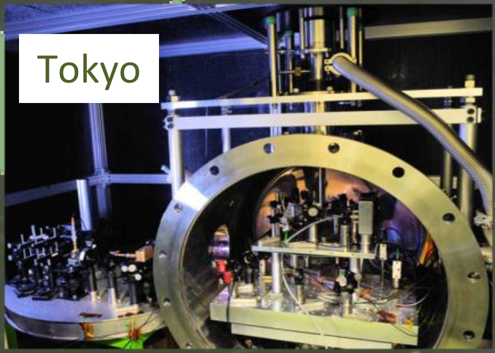
Comparable sensitivity, Separation : 370km

⇨ 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)

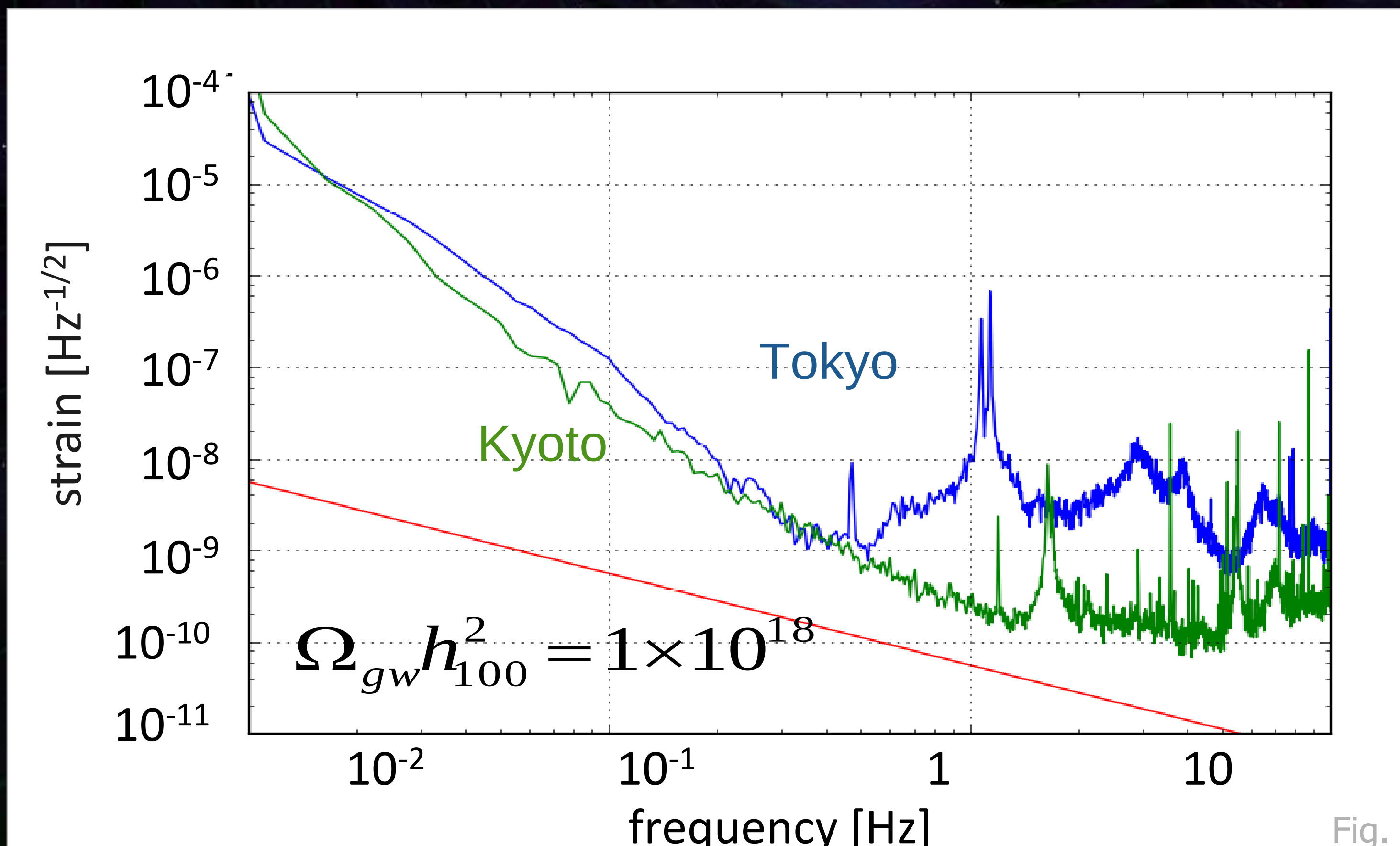


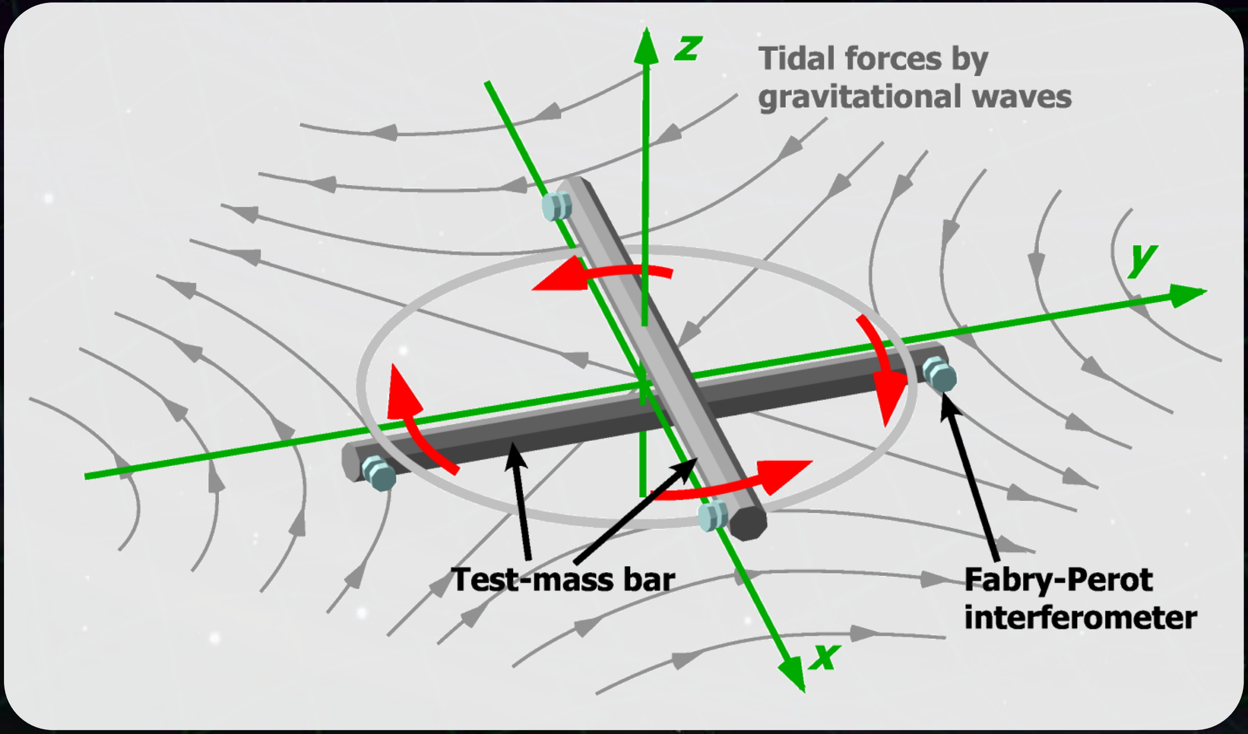
Fig. By A.Shoda

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 ⇒

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

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

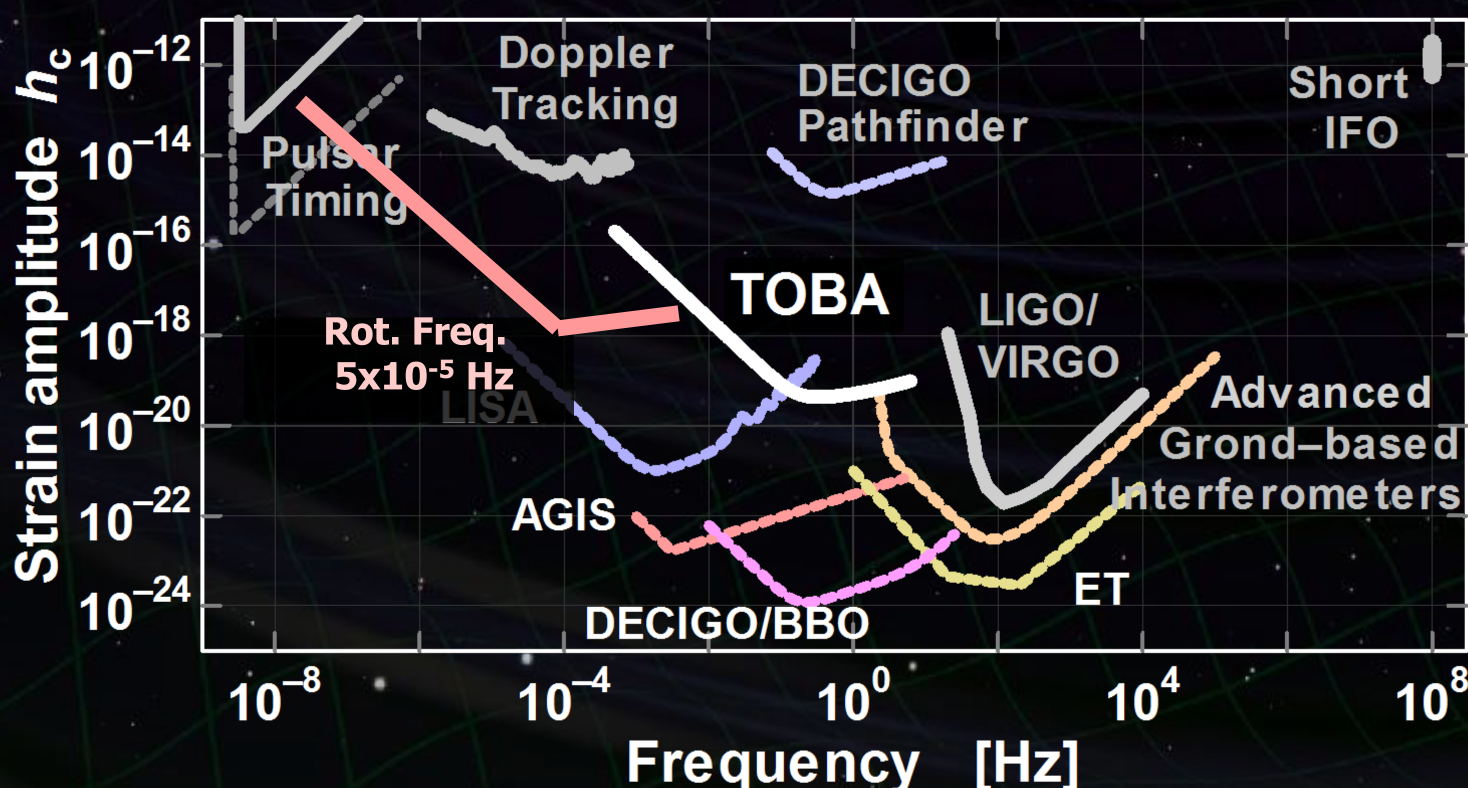
Sensitivity example

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

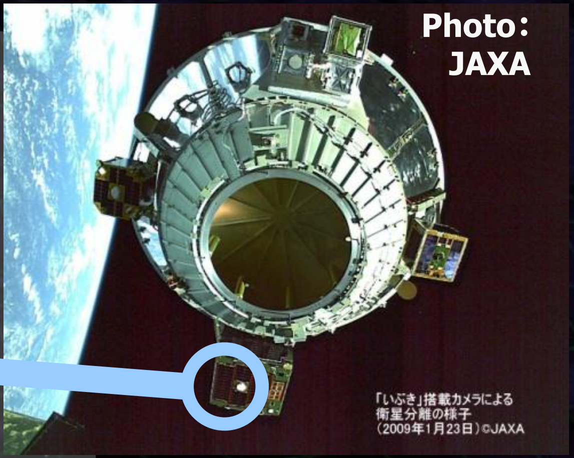
SWIM launch and operation

Tiny GW detector module

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

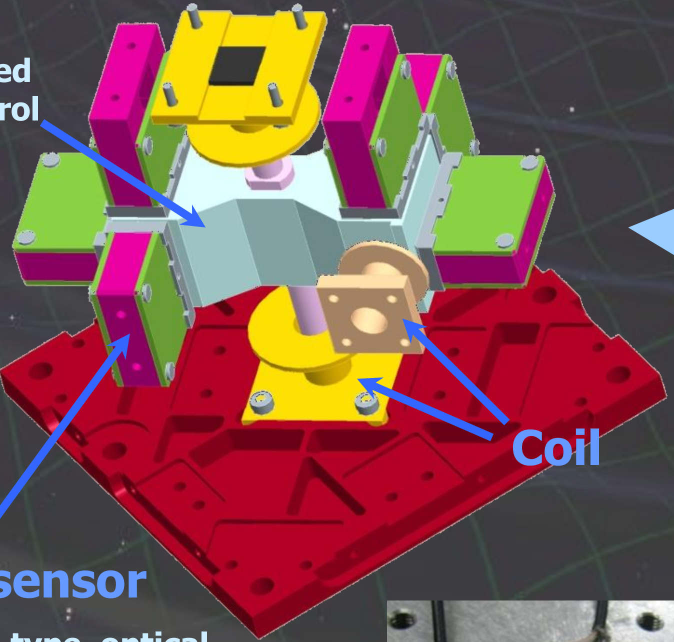
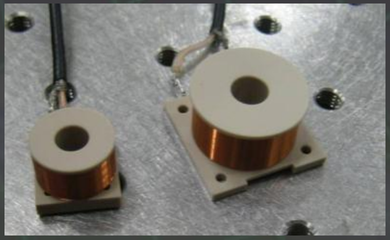
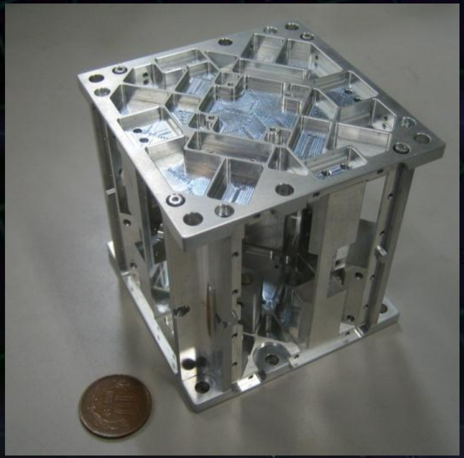


Photo sensor

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





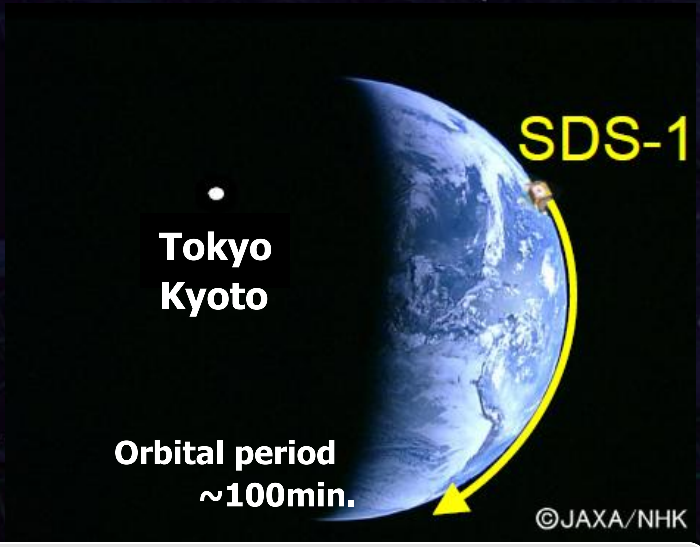
Observation by SWIM

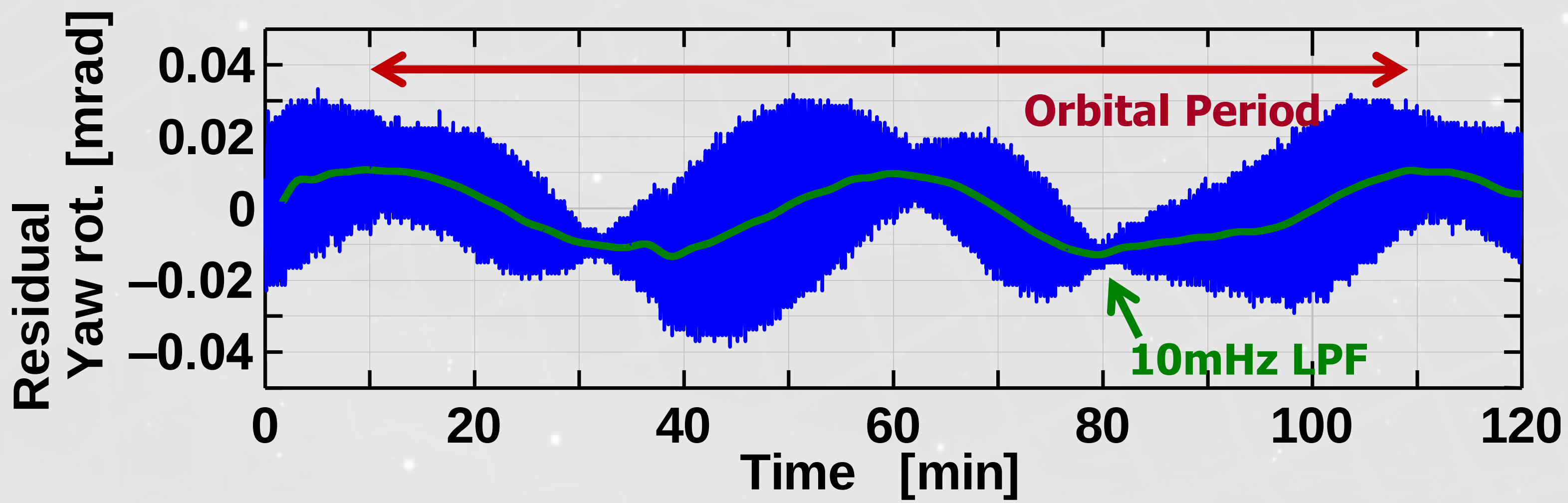
Continuous data taking

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

Simultaneous observation with ground-based detectors

⇨ Data analysis

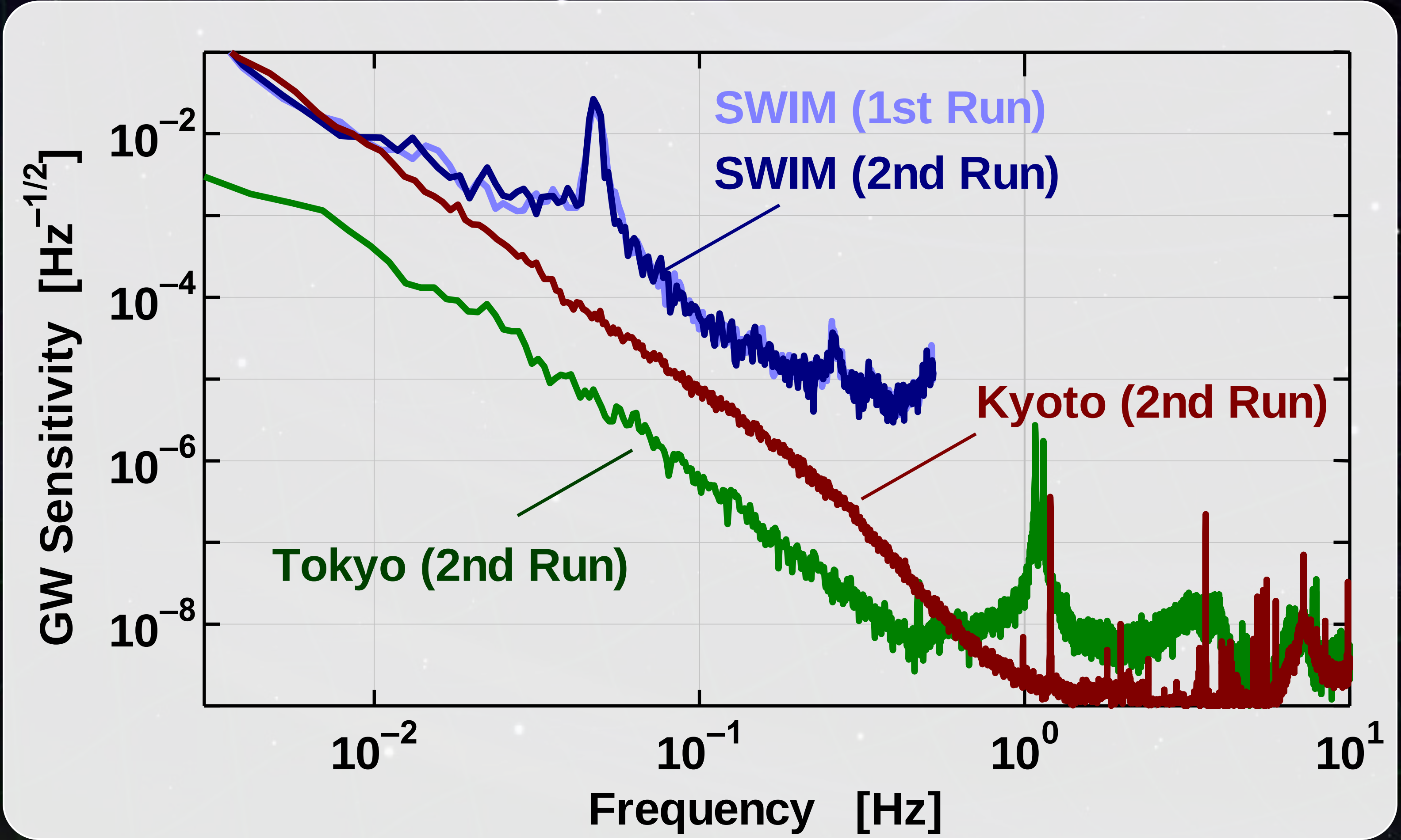




Sensitivity

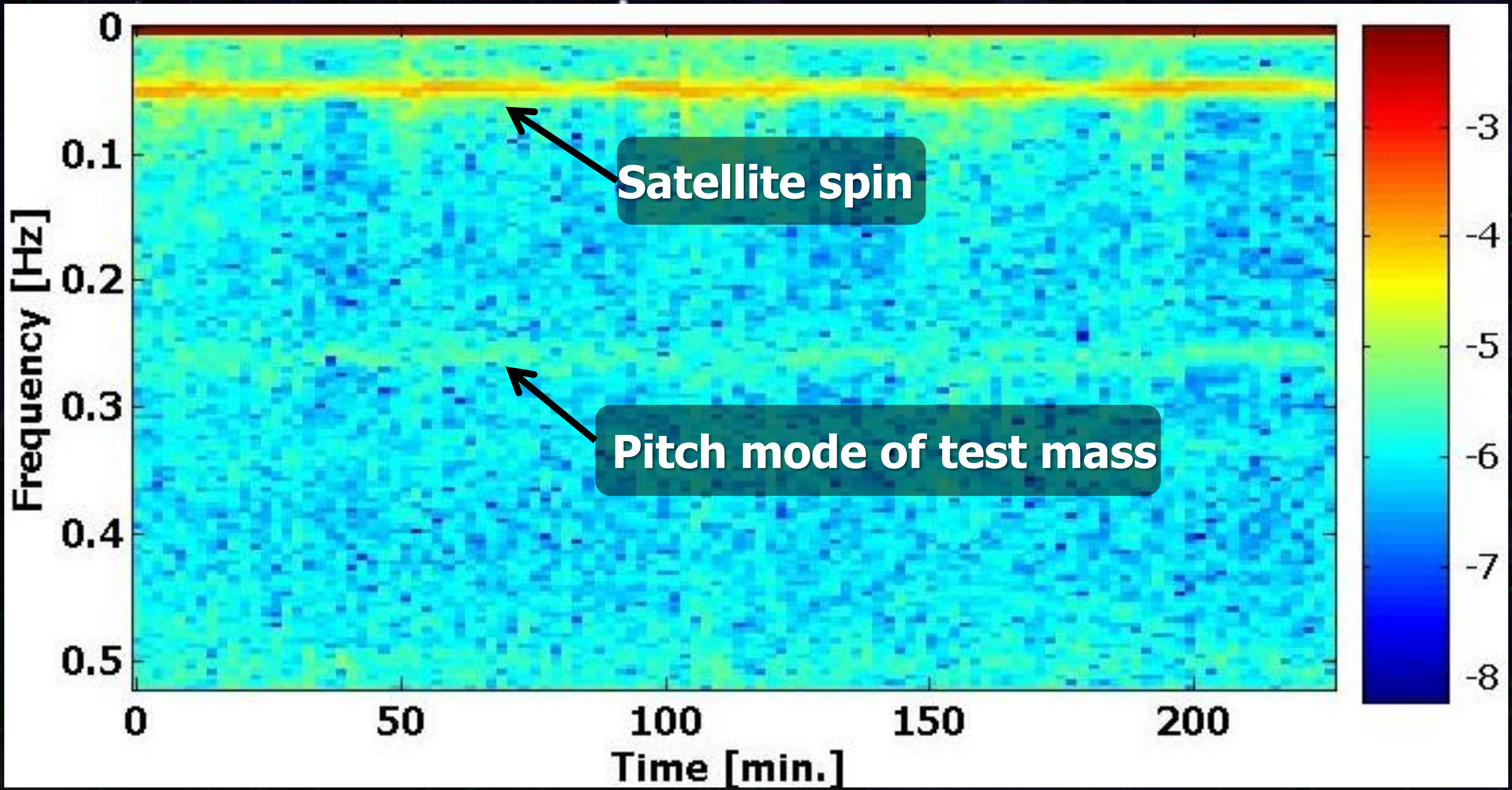
Observation by SWIM and ground-based detectors

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



SWIM observation

SWIM observation (July 15, 2010 ~240 min.)



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 SWIM$\mu\nu$, 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

References

- 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
  http://www.gravity.phys.uwm.edu/conferences/gwpaw/posters/shoda.pdf

- W.Kokuyama, presentation at GWADW2010
  http://gw.icrr.u-tokyo.ac.jp/gwadw2010/
  program/2010_GWADW_Kokuyama_2.ppt

End