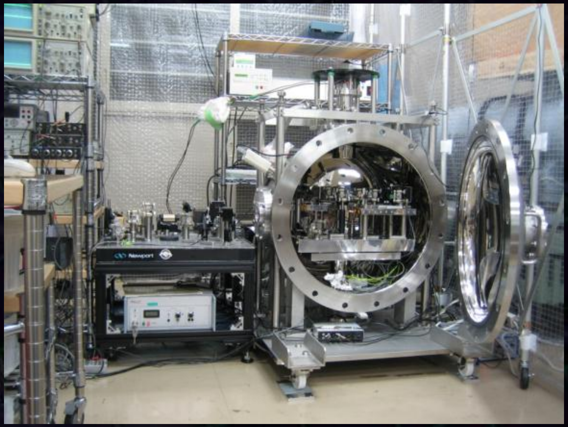
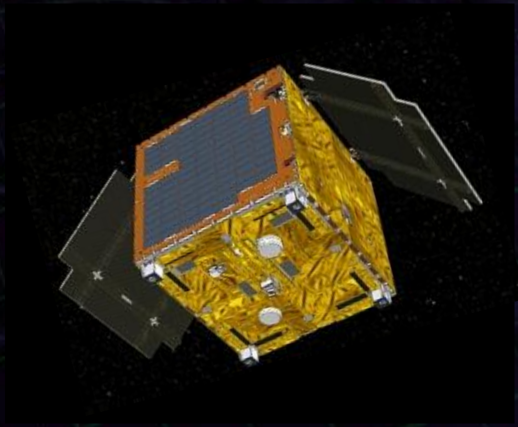
TOBA: Torsion-Bar Antenna

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

Low Frequency GW Antennae - Preliminary Meeting (3rd Oct 2011, Hawaii)

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

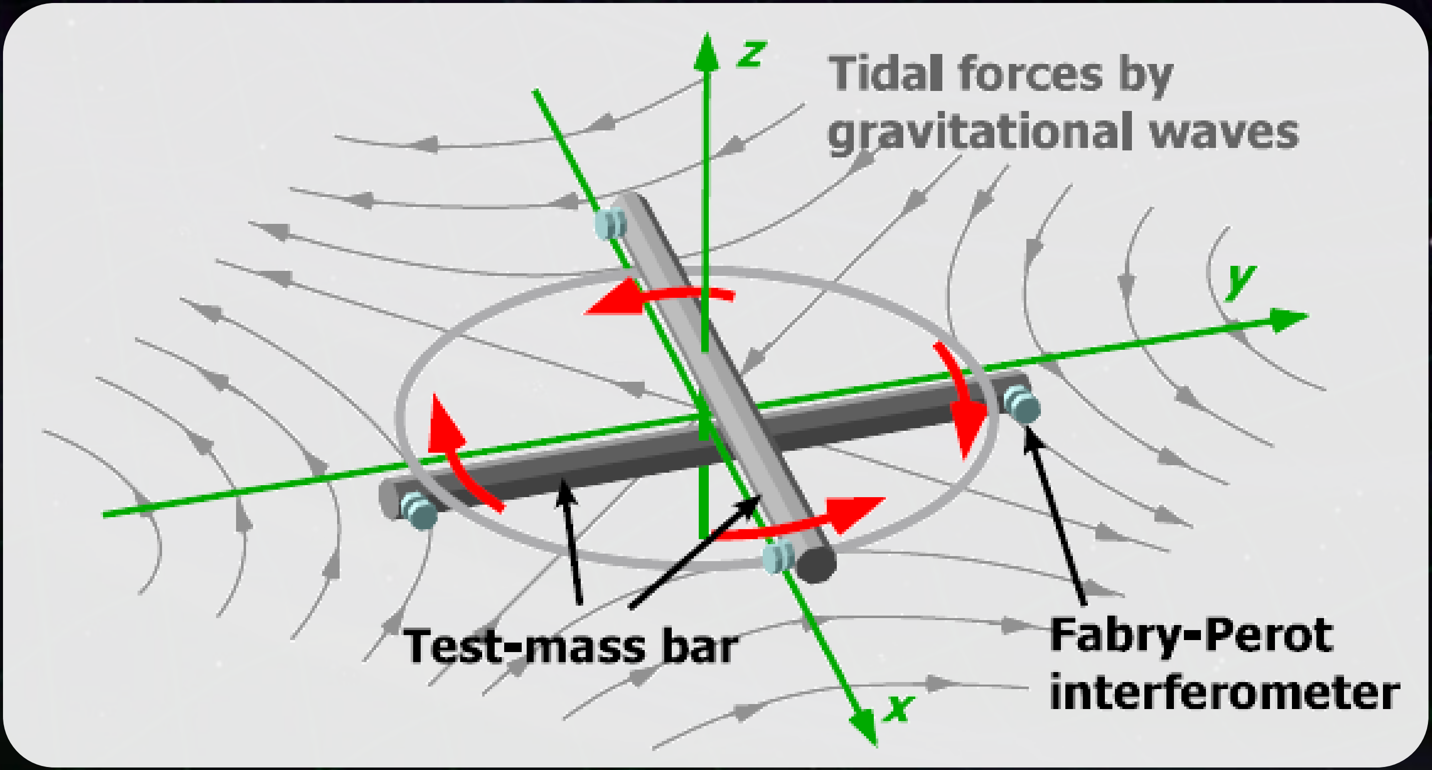
TOBA

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.

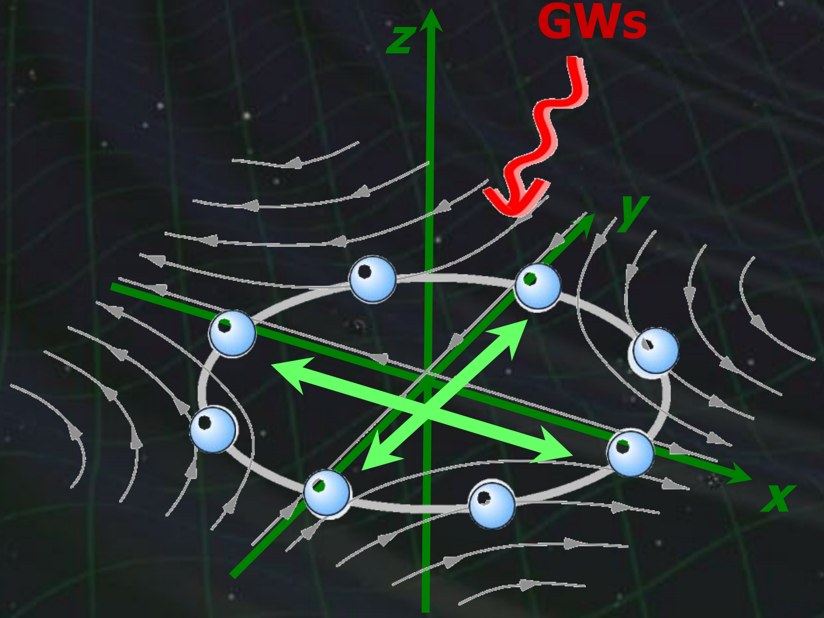


M.Ando, et. al, Phys. Rev. Lett. 105, 161101 (2010)

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)

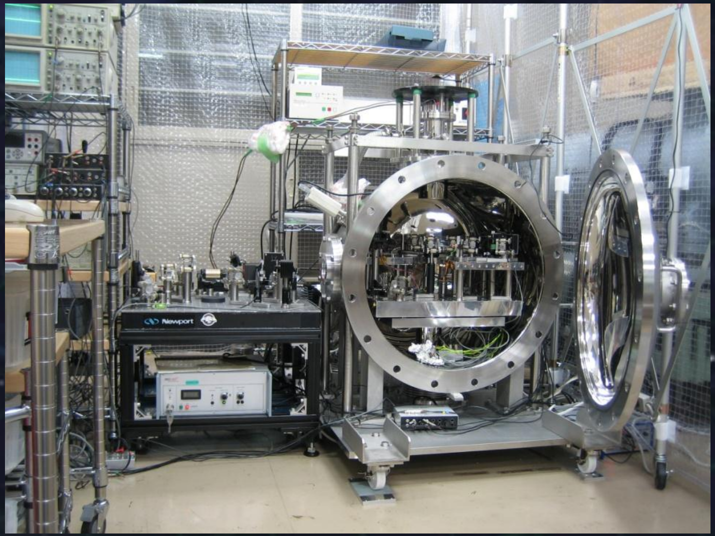
Long baseline

→ 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

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

Tidal force
by x-mode GW

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

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

Dynamic Quadrupole moment

Dynamic quadrupole moment

$$q^{ij} \equiv \int \rho \left(x^i w^j + w^i x^j - \frac{2}{3}\delta^{ij} x_k w^k \right) dV$$

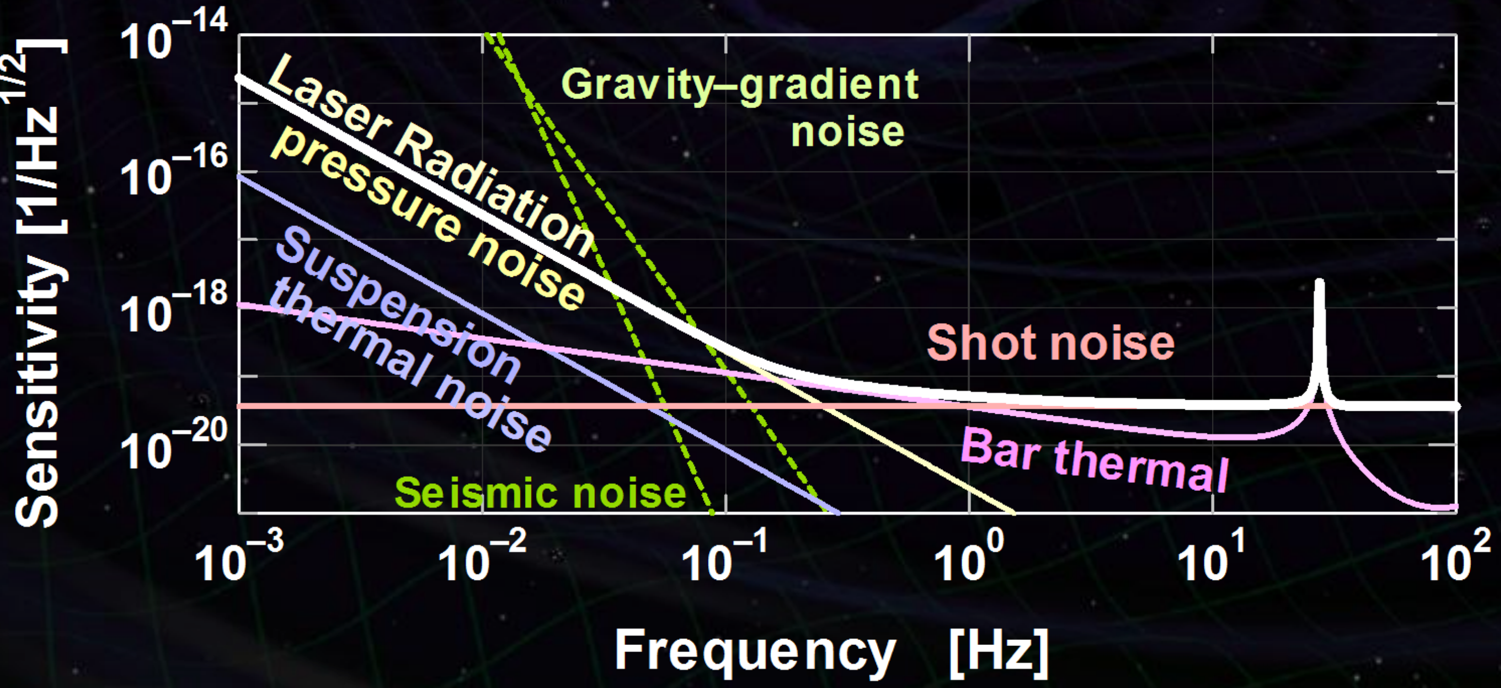
$\vec{w}(\mathbf{x})$: Mode pattern function

In case of bar rotation… $\vec{w}(\mathbf{x}) = (-y, x, 0)$

$$\begin{aligned}
q^{11} &= \int \rho(-2xy)\ dV \\
q^{22} &= \int \rho(2xy)\ dV \\
q^{12} &= \int \rho(x^2 - y^2)\ dV \\
q^{21} &= \int \rho(y^2 - x^2)\ dV
\end{aligned}$$

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}

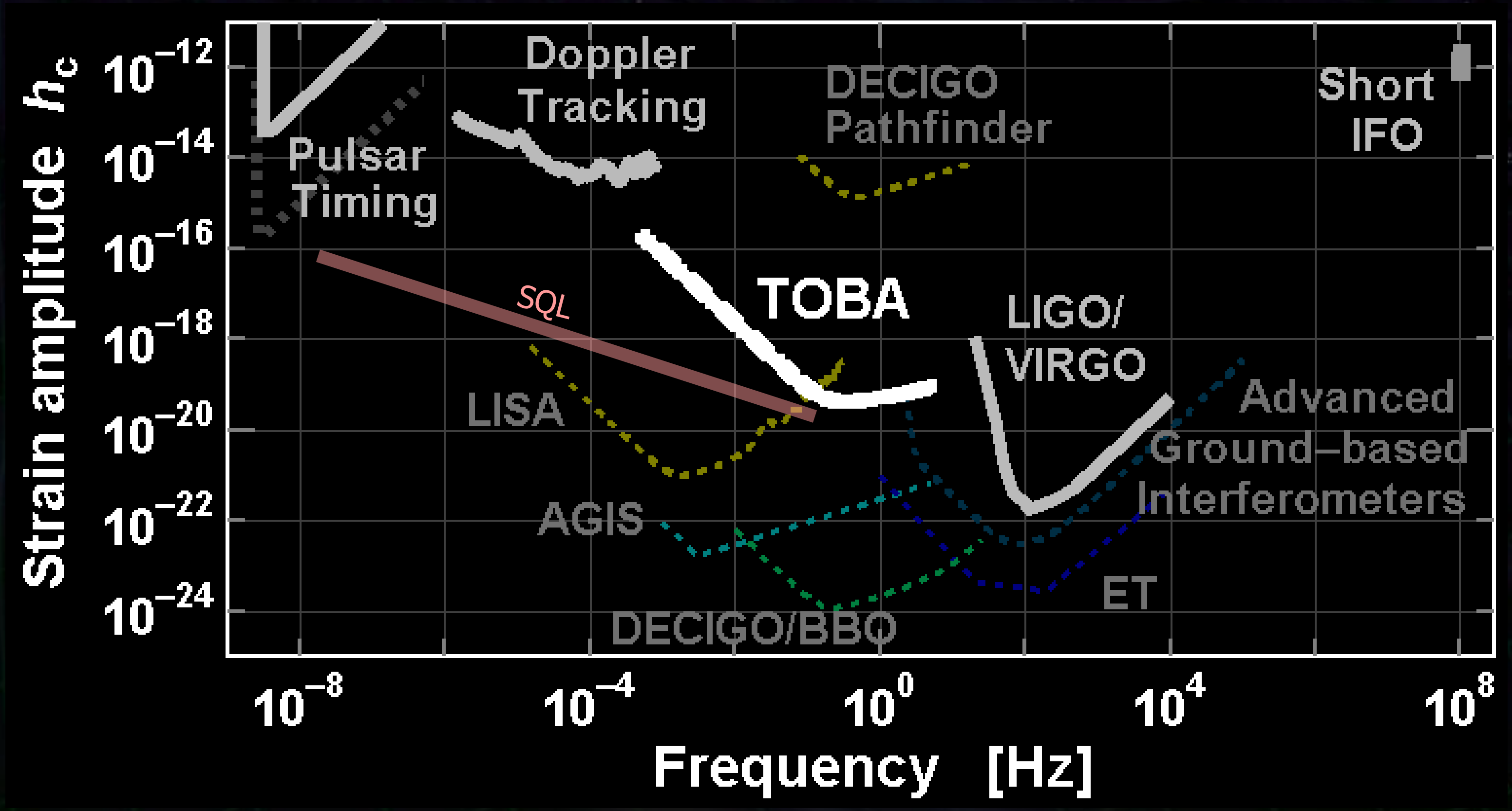
Laser Freq. noise < $10\mathrm{Hz/Hz}^{1/2}$,
Freq. Noise CMRR>100
Intensity noise < $10^{-7}/\mathrm{Hz}^{1/2}$,
Bar residual RMS motion < 10^{-12} m

TOBA Sensitivity

Comparison with the other detectors

DECIGO/BBO band:

Between ground-based detectors and LISA bands

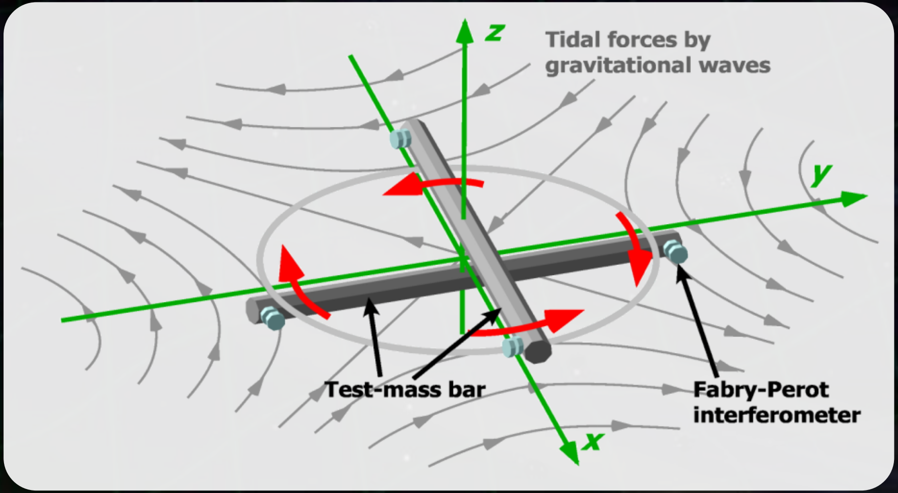


Characteristic amplitude : $h_c = \tilde{h} \times \sqrt{f_{\text{center}}}$ (Dimensionless strain)

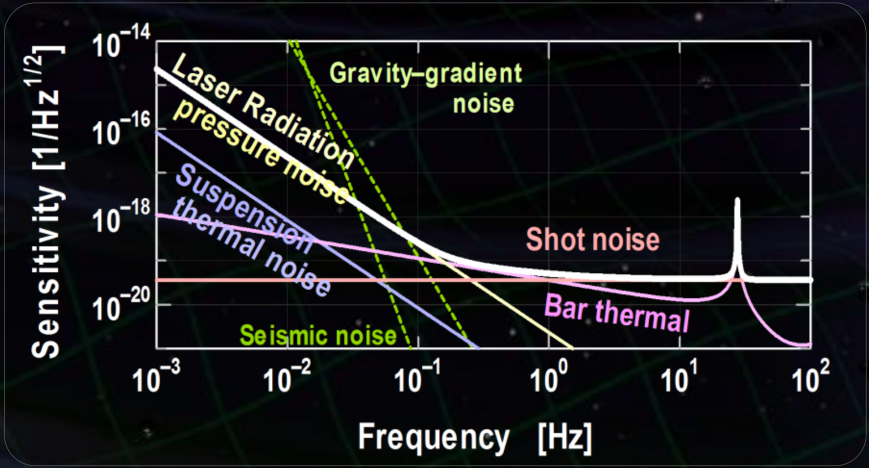
Optical readout noise

- Optical readout noise
  - Readout by short FP cavities at the bar edge.
  - Reference mirrors fixed to isolated base plate.

⇨ Shot noise + Rad. Pressure noise



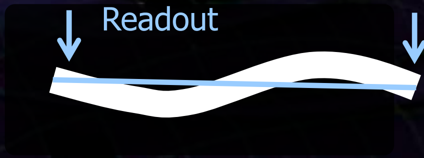
Nd:YAG 1064nm, Power 10W,
Short FP cavity, Finesse 100



Bar thermal noise

- Thermal noise of bar mode

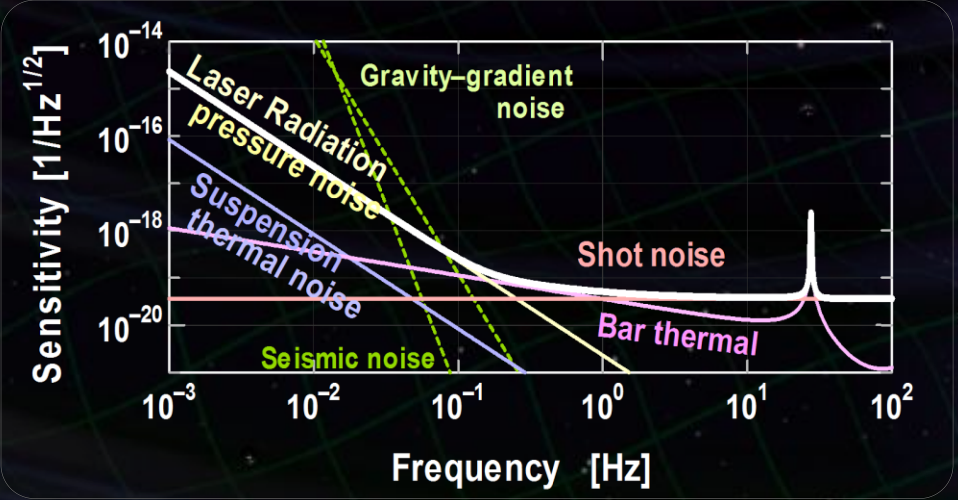
Differential readout at the edges
→Contribution of odd modes



Aluminum bar (7.6 ton)
length 10 m, ϕ0.3 m
Temp. 4K, Q 10^7

⇨ 8×10^{-20} $1/\mathrm{Hz}^{1/2}$ at 0.1Hz

By keeping the total mass,
- High Q and low T is better
- Shorter is better
- High Young's modulus is better



Suspension thermal noise

- Thermal noise of suspension system
  - Torque by dissipation (one bar)

$$T_{\rm ther} = \sqrt{4\gamma k_{\rm B} T} = \sqrt{4(I\omega_0/Q)k_{\rm B} T}$$

$$⇨ \quad h_{\rm ther} = \frac{4}{\alpha\omega^2}\cdot\sqrt{\frac{k_{\rm B} T\omega_0}{IQ}}$$

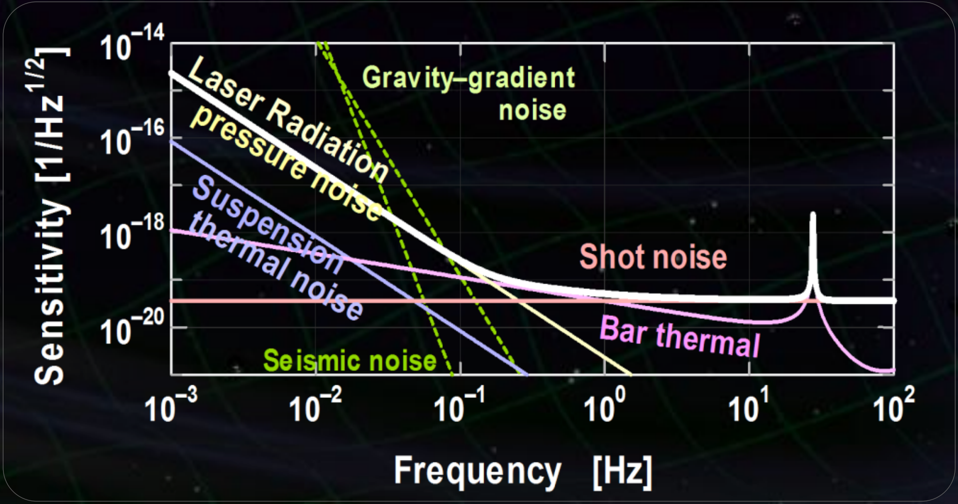
Detector response

$$I\ddot{\theta} + \gamma\dot{\theta} + \kappa\theta = \frac{1}{4}q^{ij}\cdot\ddot{h}_{ij}(t)$$

$$(\omega_0 = \sqrt{\kappa/I},\quad Q = I\omega_0/\gamma)$$

- Mechanical loss in suspension fiber
  - Steel wire
  - Tungsten wire
  - Silica fiber
  - Cryogenic sus.
  - Superconductor sus.

Cryogenic suspension, Temp. 4K, γ 10^{-10}



- Momentum of inertia

$$h_{\rm bar} \propto 1/I \propto 1/(M\cdot L^2)$$

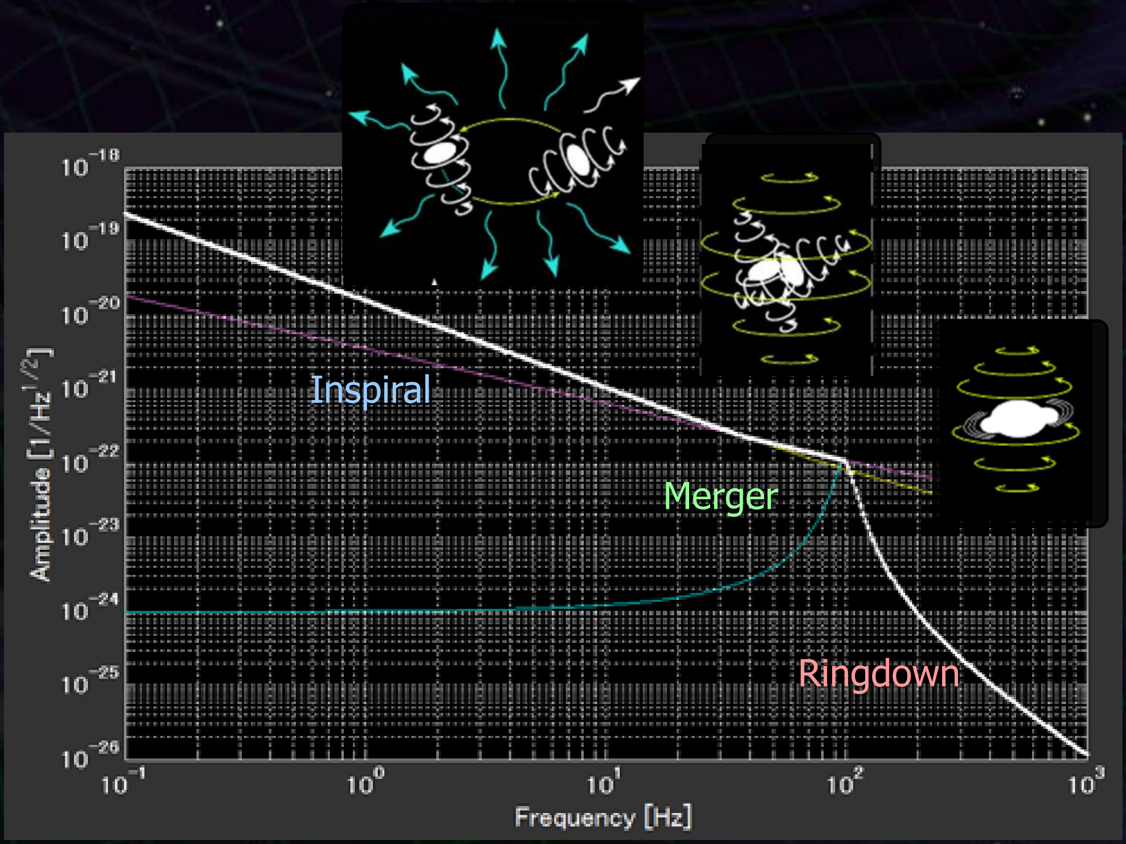
Chirp waveform

- Phenomenological waveform by numerical simulation

(Ajith+ arXiv 0909.2867)

  - For BH inspiral (no tidal deformation).
  - Include chirp, merger, and ring-down.
  - Include spin effect.

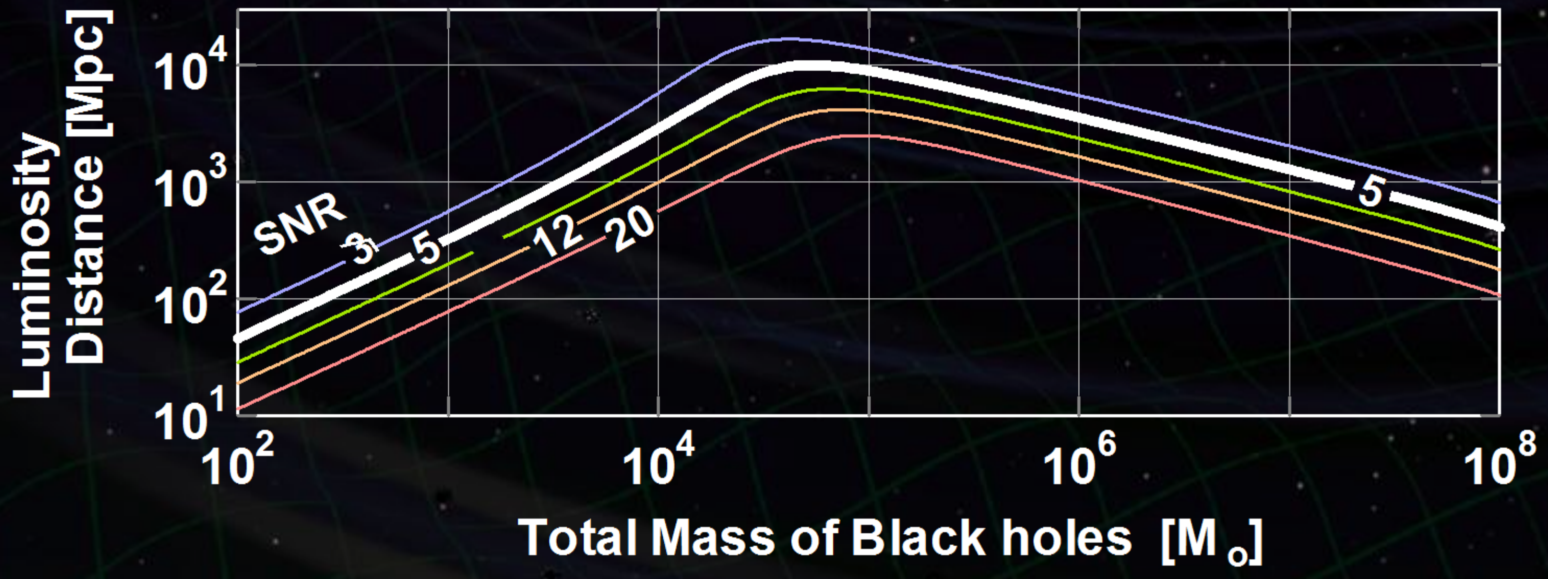
GW from BH merger
  - 100 Msolar equal mass
  - Spin parameter 0.5
  - Distance 100 Mpc



Observable range

GWs from binary BH mergers

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



Calculation by K.Yagi

Background GWs

Observable GW energy density ratio

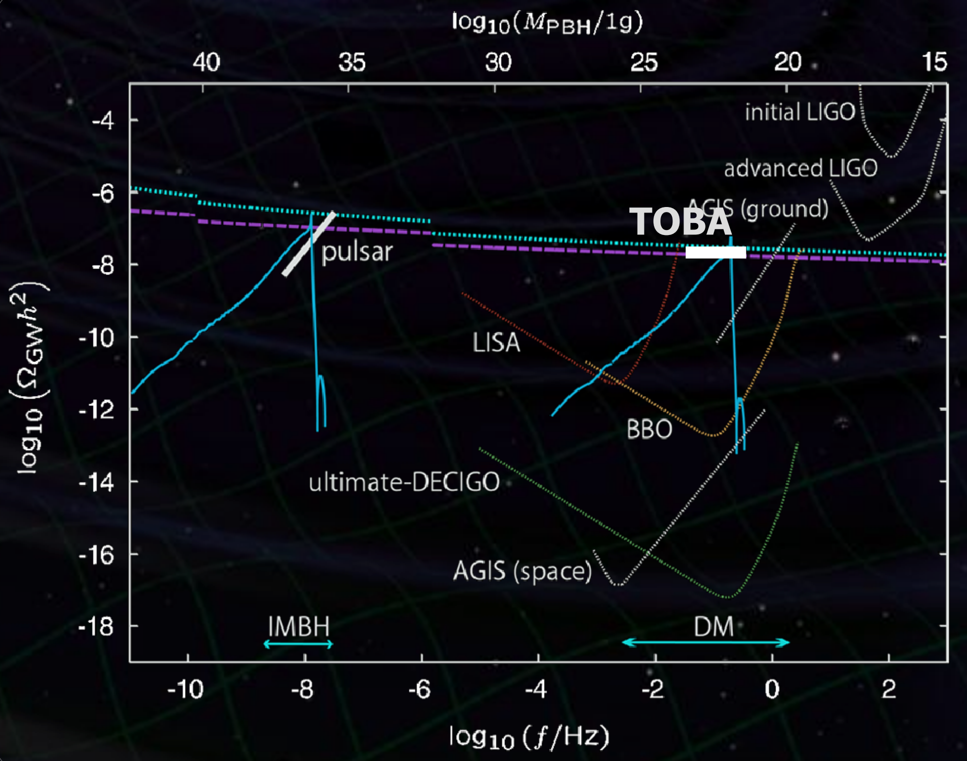
$$\Omega_{\rm gw} \sim 10^{-7}$$

(1-yr obs. by 2 TOBAs)

Beat BBN upper limit

GW by primordial tensor perturbation

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



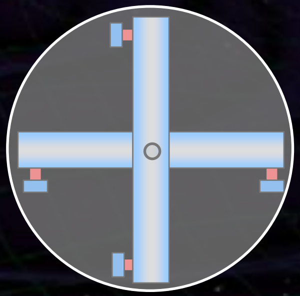
Discussions

Interferometer configuration

- Readout from reference plate

  - Readout by short FP cavities at the bar edge.
  - Reference mirrors fixed to isolated base plate.

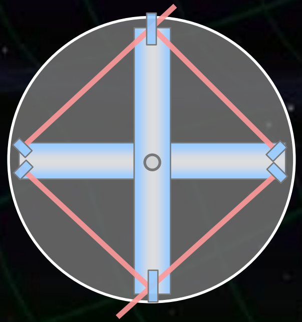
  - Independent measurement
    → Linear combination for GW signals.
  - Require a seismic-isolated reference plate.



- MI fixed at bar edges

  - Form Michelson interferometer at the bar edge.

  - Direct angular measurement
  - Do not need reference mirrors.
  - Coupling from bar displacements.
    → Room for improvements



Bar material

- Selection of bar material
  - Bar thermal noise
  - Electro-magnetic properties
  - Availability (production, cost)

⇨ Silicon is promising.

	Q-factor	Young's modulus	Density	Availability	Thermal noise
Aluminum	$<10^7$	72 GPa	2700 kg/m^3	○	8×10^{-20} Hz$^{-1/2}$
Sapphire	10^8	335 GPa	3970 kg/m^3	△	1×10^{-20} Hz$^{-1/2}$
Silicon	10^9	185GPa	2329 kg/m^3	○	5×10^{-21} Hz$^{-1/2}$

(L=10m, ϕ=0.3m)

Bar shape

- Design of bar shape

- Detector response to GW $\tilde{\theta}(\omega) = \frac{1}{2}\alpha\tilde{h}_\times(\omega)$

Shape factor $\alpha = \frac{\int (x^2 - y^2)\, dV}{\int (x^2 + y^2)\, dV}$ ⇨ Thin bar or dumb-bell along x-axis → $\alpha=1$

- Standard quantum limit $h_{\mathrm{SQL}} \propto 1/\sqrt{I} \propto 1/L$

Moment of Inertia $I = \int \rho(x^2 + y^2)\, dV$ ⇨

Cylindrical bar $I = M \cdot L^2/12$

Dumb-bell $I = M \cdot L^2/4$

- Bar thermal noise

When mass is kept, $h_{\mathrm{bar}} \propto L^2$ ⇨ Shorter is better.

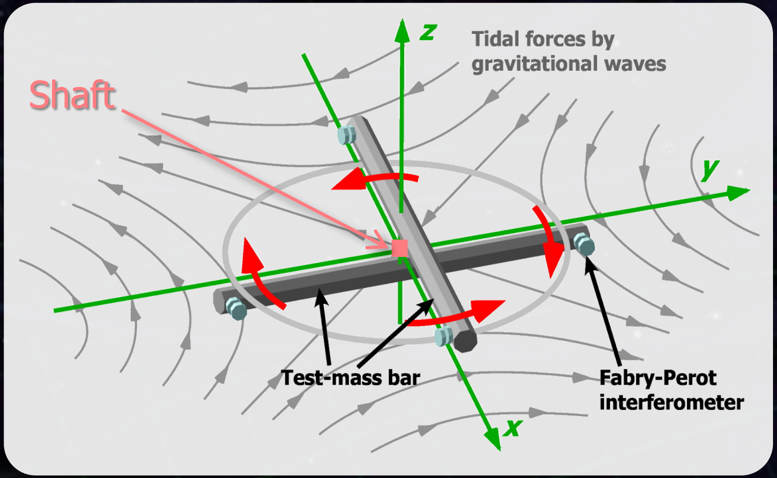
- Suspension thermal noise

When mass is kept, $h_{\mathrm{bar}} \propto 1/I \propto 1/L^2$ ⇨ Longer is better.

Resonant detector

- Connect two bars by a shaft
  → resonant torsion detector

  - GW signal is enhanced at resonant frequency by Q.
  - Requirements for readout and bar-thermal noise are relaxed.
  - Detector noise is mainly limited by thermal noise of the shaft.



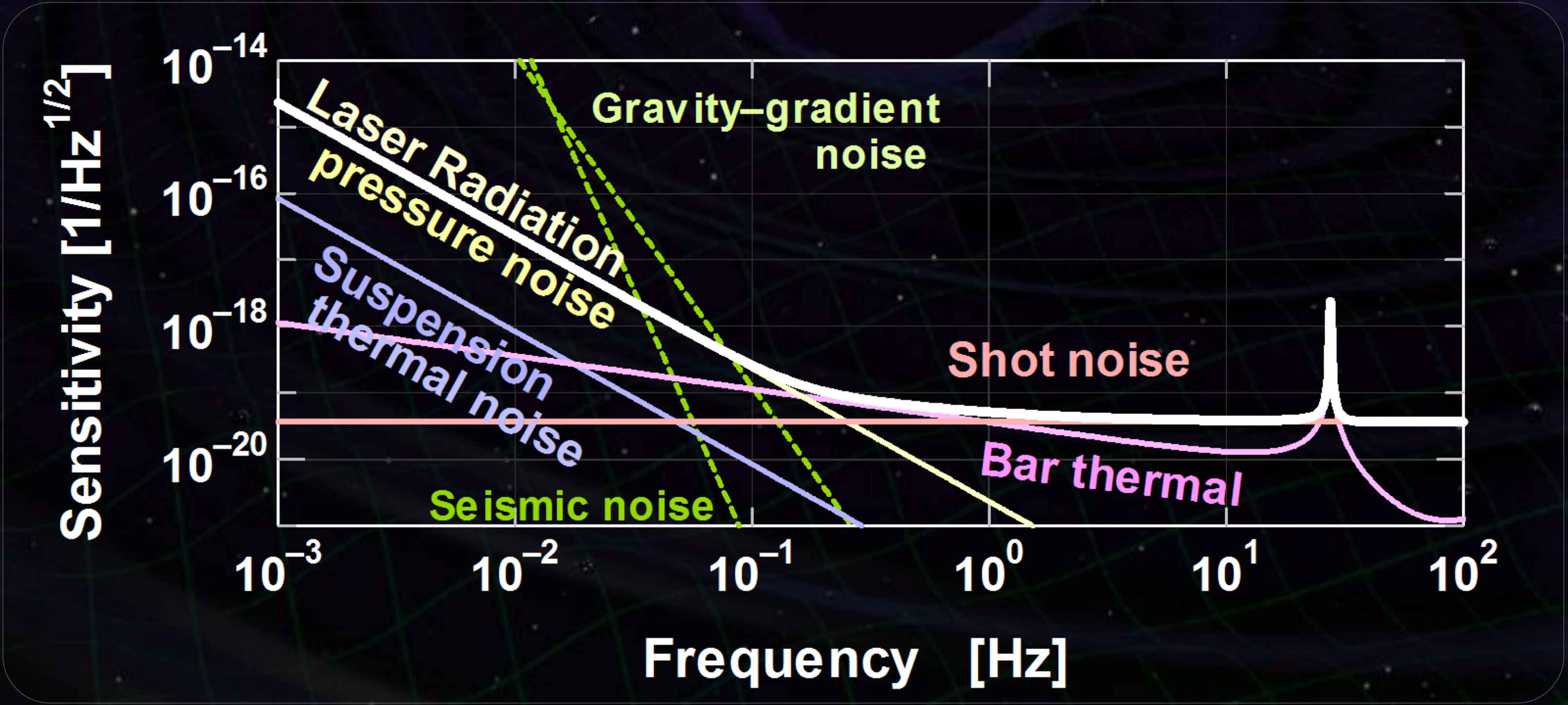
- Thermal noise level

At resonant freq. $h_{\rm ther} = \frac{4}{\alpha} \cdot \sqrt{\frac{k_{\rm B}T}{I\omega_0^3 Q}}$

f_0=0.1Hz, Q=10^9, T=4K, M=7600kg, L=10m ⇨ 7.5x10^{-18} [1/Hz$^{1/2}$]

Fundamental noise level of TOBA

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



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

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

Gravity gradient noise (1/2)

- Gravity gradient noise by point-like source.

- Assume a dumb-bell mass
  and a point-like source mass

⇨ DC torque $T_{\mathrm{tidal}} \simeq \frac{2GM_{\mathrm{S}}I}{r^3}\sin(2\phi)$

Equivalent noise $\delta h_{\mathrm{tidal}} \simeq \frac{12GaM_{\mathrm{S}}}{r^4\omega^2}$

(Radial motion, Max. direction, a: amplitude, a, L << r)

(Ex.) Human activity

$M_s = 100$ kg, $r = 10$ m,
$\phi = \pi/2$, $f = 0.1$ Hz, $a = 0.1$ m ⇨ $\delta h \sim 2\times10^{-12}$

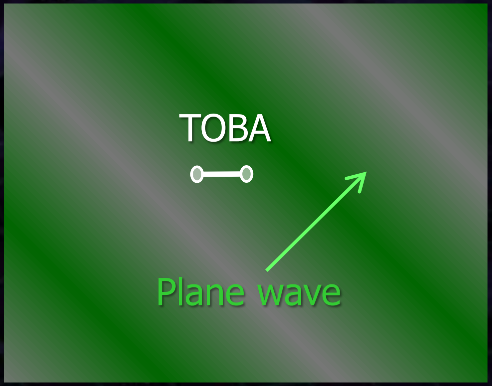
Gravity gradient noise (2/2)

- Gravity gradient noise by ground motion.

  - Coherent plane wave with long wavelength

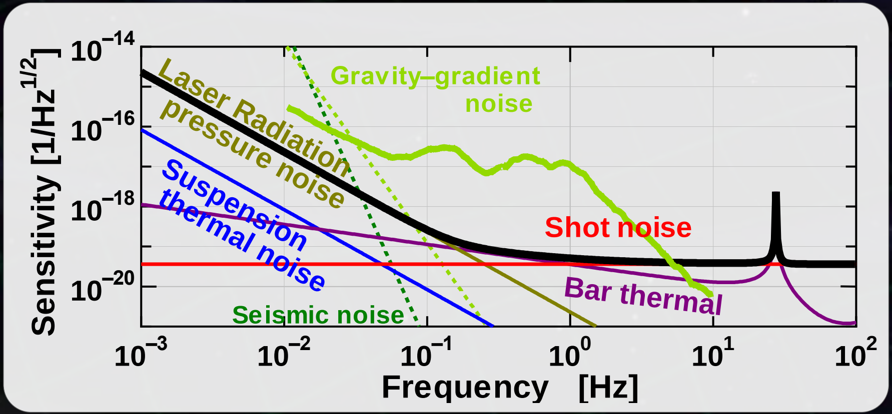
    Velocity 5km/s, Frequency 0.1Hz
    → wavelength ~ 50km

    ⇨ Same effect as km-scale interferometer



  - GG noise estimation (by Jan Harms)

    Assumption:
    Infinite plane wave
    Homestake mine seismic level



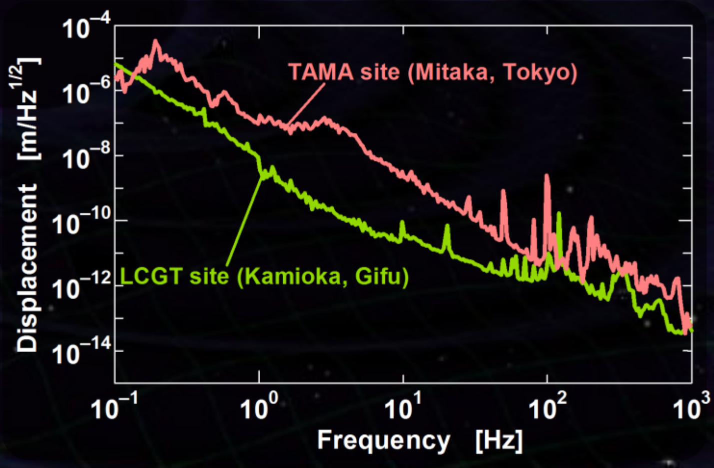
Gravity gradient noise will be critical for ground-based TOBA

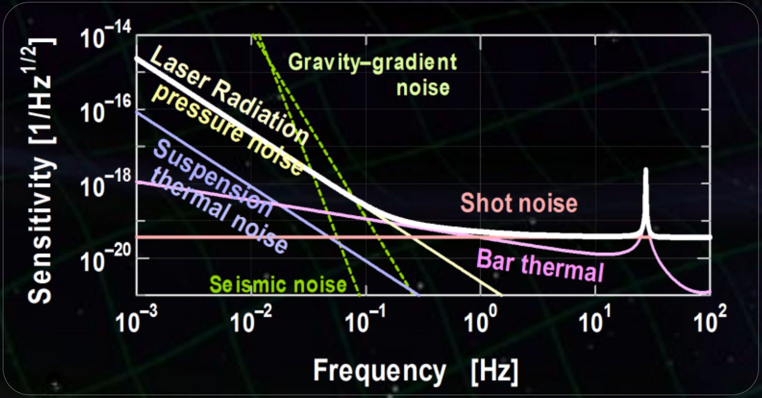
Seismic noise

- Rotational ground motion
- Coupling from displacement DoF

Coupling 10^{-3} or CMRR 10^{-3}
→ $<10^{-9}$ isolation is required
at 0.1Hz freq. band.

Horizontal : IP (10mHz) x 5 stages
Vertical : GASF ???





Other noise sources

- Magnetic noise
- Thermal radiation
- Residual gas noise
- Electronics noise

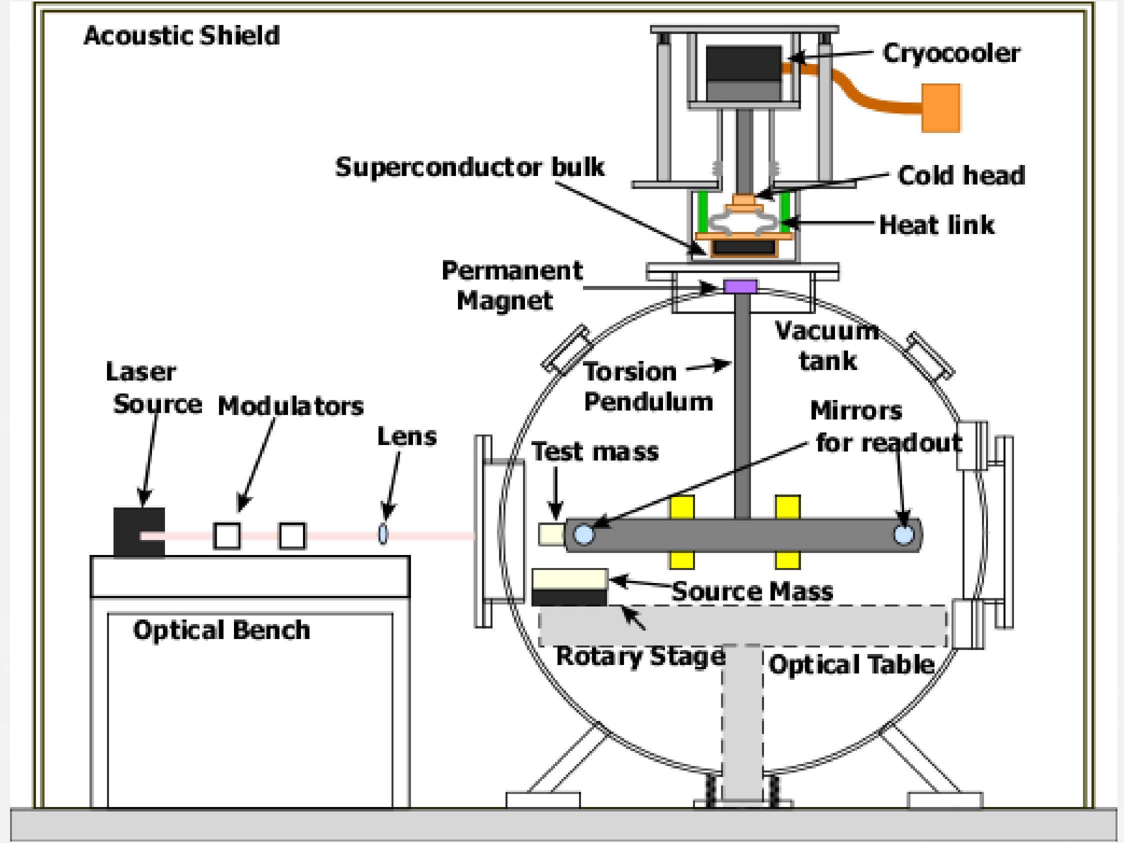
Prototype test

Reference:

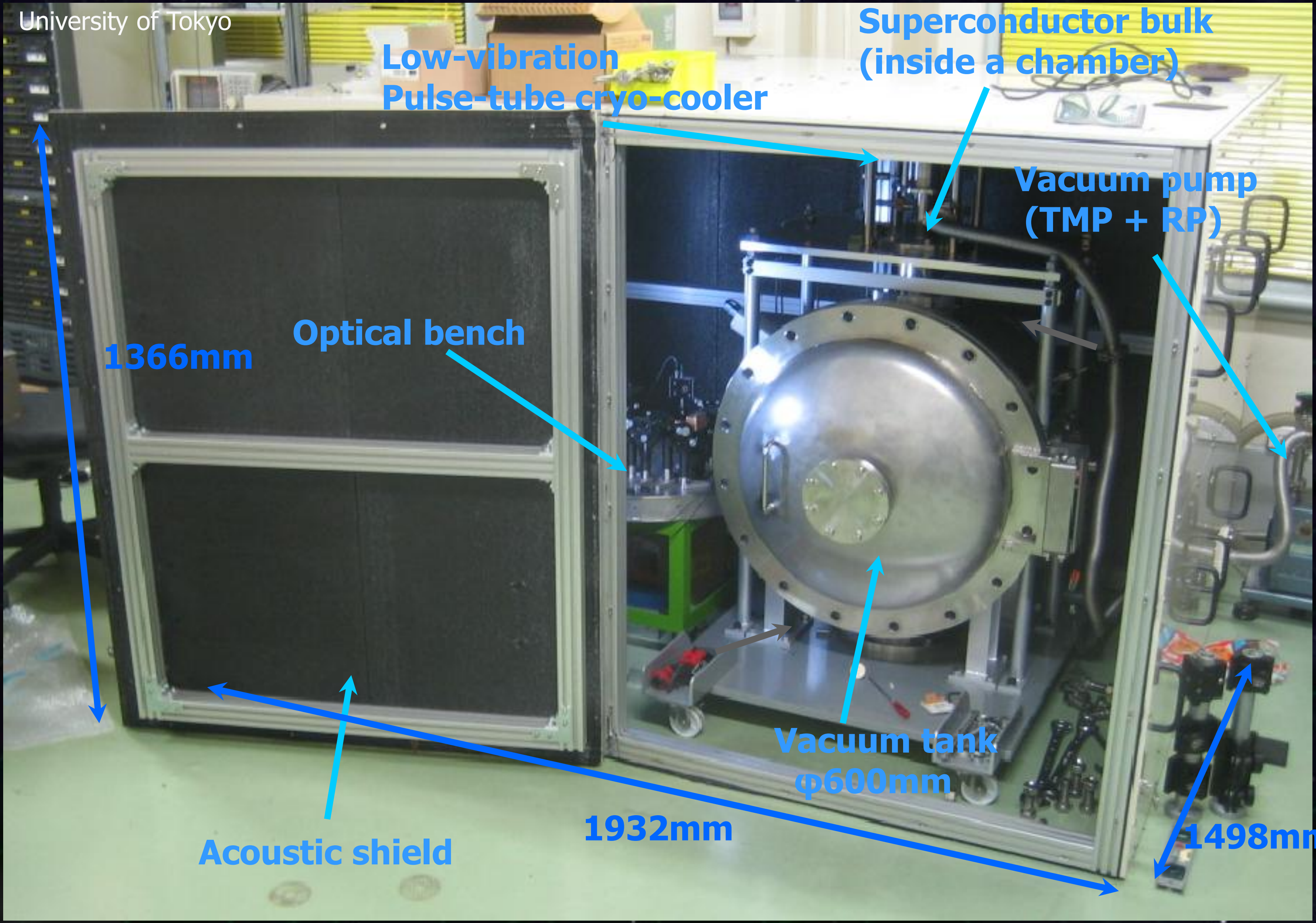
- **K.Ishidoshiro, et. al, Phys. Rev. Lett. 106, 161101 (2011)**
- **A. Shoda, presentation at GWPAW2011**

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



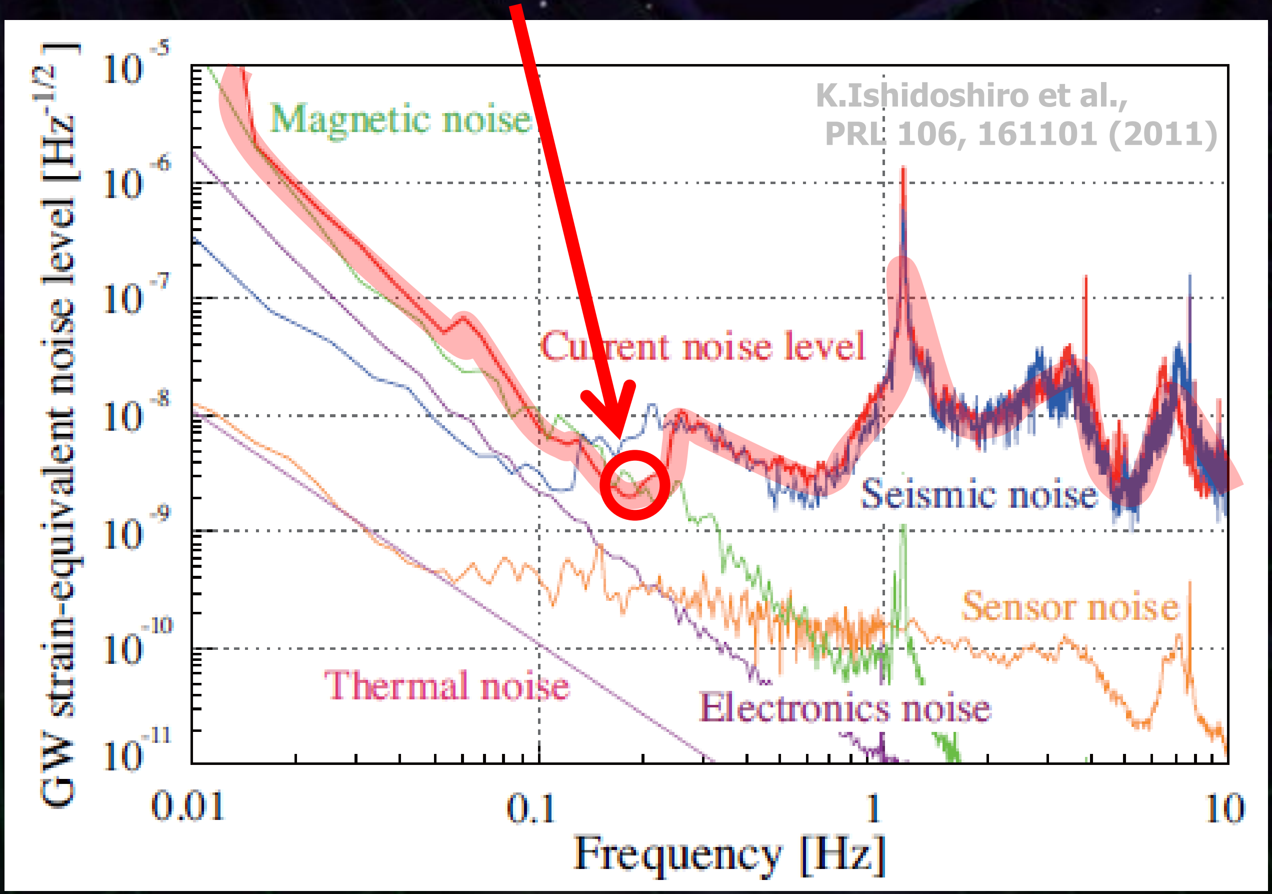
Small-scale TOBA at Tokyo



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



K.Ishidoshiro et al., PRL 106, 161101 (2011)

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

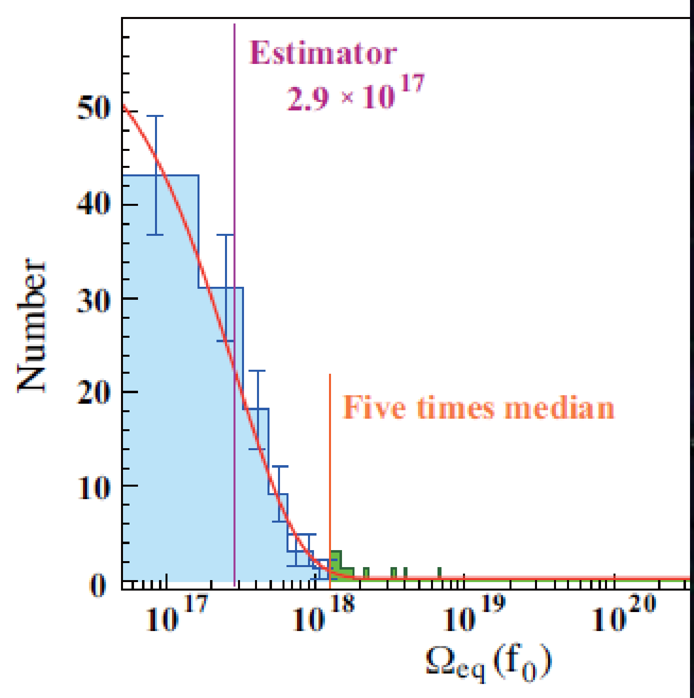
$$\Omega_{\rm eq}(f_0) = \frac{10\pi^2}{3H_0^2} f_0^3\,\tilde{h}^2(f_0)$$

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

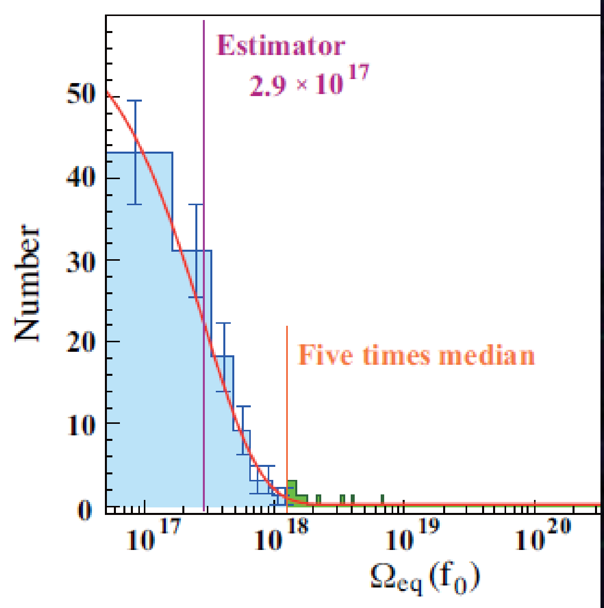
- Distribution → Averaged power at 0.2Hz

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

⇨ Upper limit on Ω_{gw}

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

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



Some details…

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

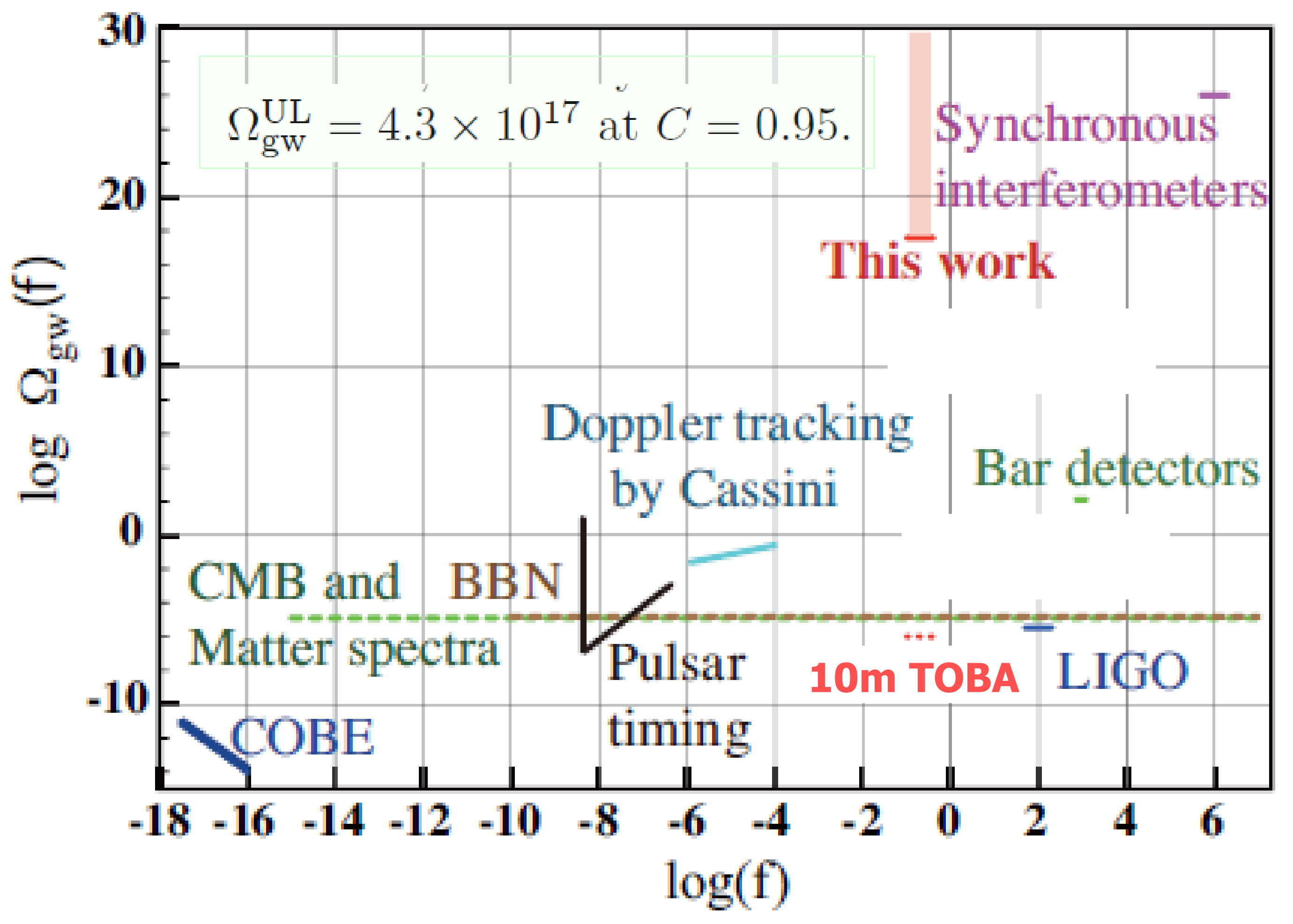
$$C = \int_{\overline{\Omega_{\mathrm{eq}}}}^{\infty} P(\Omega_{\mathrm{es}}|\Omega_{\mathrm{gw}})\, d\Omega_{\mathrm{es}}$$

Distribution with Ω_{gw} assuming Gaussian dist.

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

Comparison with previous results

New upper limit at unexplored frequency band of 0.2Hz



Observation with two detectors

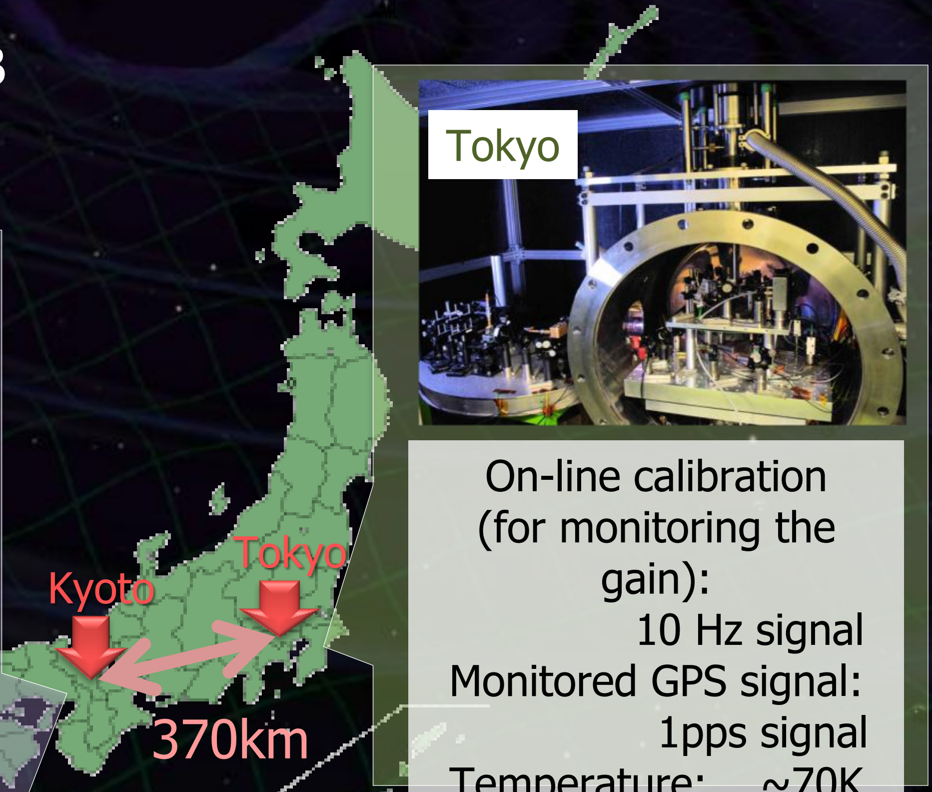
Observation with two detectors places at Tokyo and Kyoto, Japan.

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)

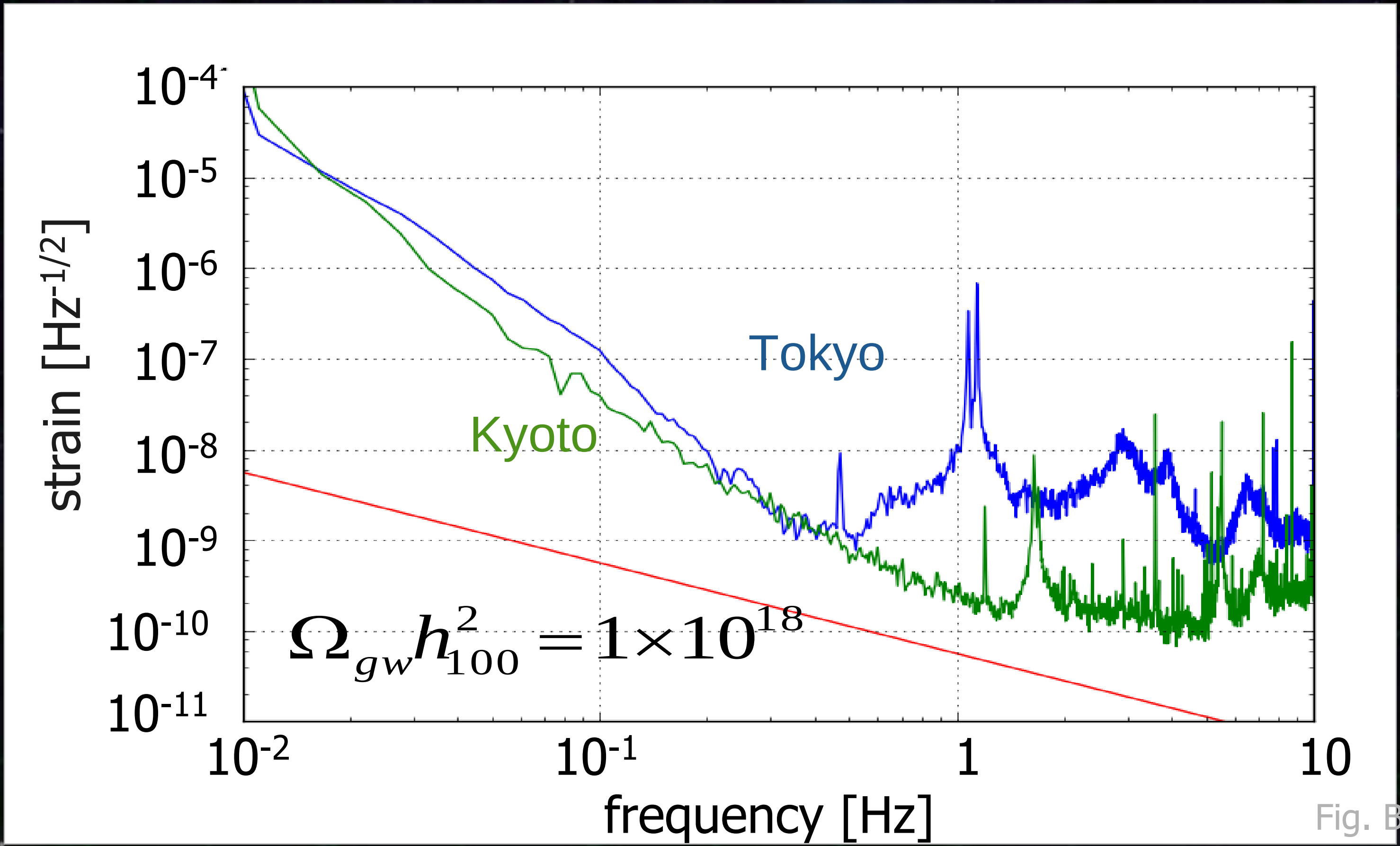
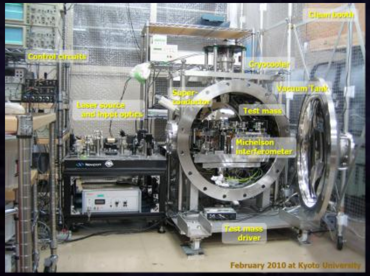


Fig. By A.Shoda

Prototype plan

TOBA prototype plan

- We have two small-scale TOBAs at Tokyo and Kyoto.
  - Aluminum test mass, length ~20cm, mass ~300g.
  - Room temperature, poor seismic isolation.
  - Magnetic levitation using superconductor bulk.



February 2010 at Kyoto University

- Next plan concepts

(A) Medium-scale TOBA at room temperature.
- Silicon test mass, length ~1m, mass ~100kg.
- Differential measurement using two orthogonal bars.
- Better isolation system.

(B) Medium/small-scale TOBA at cryogenic temperature.
- Similar configuration to (A), but with a cryogenic system.
- Resonant detector configuration???

(C) Medium-scale TOBA development for a space mission.
- Low-freq. observation by a rotation configuration.
- Several options:
  Resonant?, Cryogenic?, Orbit?

TOBA prototype example (1)

- Medium-scale TOBA
  - Realistic configuration with current technology.
  - Also works as a gravity-gradient noise monitor, or a test bench for quantum noise investigation.

※ Gravity-gradient noise : ~10^{-17} [$1/\mathrm{Hz}^{1/2}$] at 0.1Hz

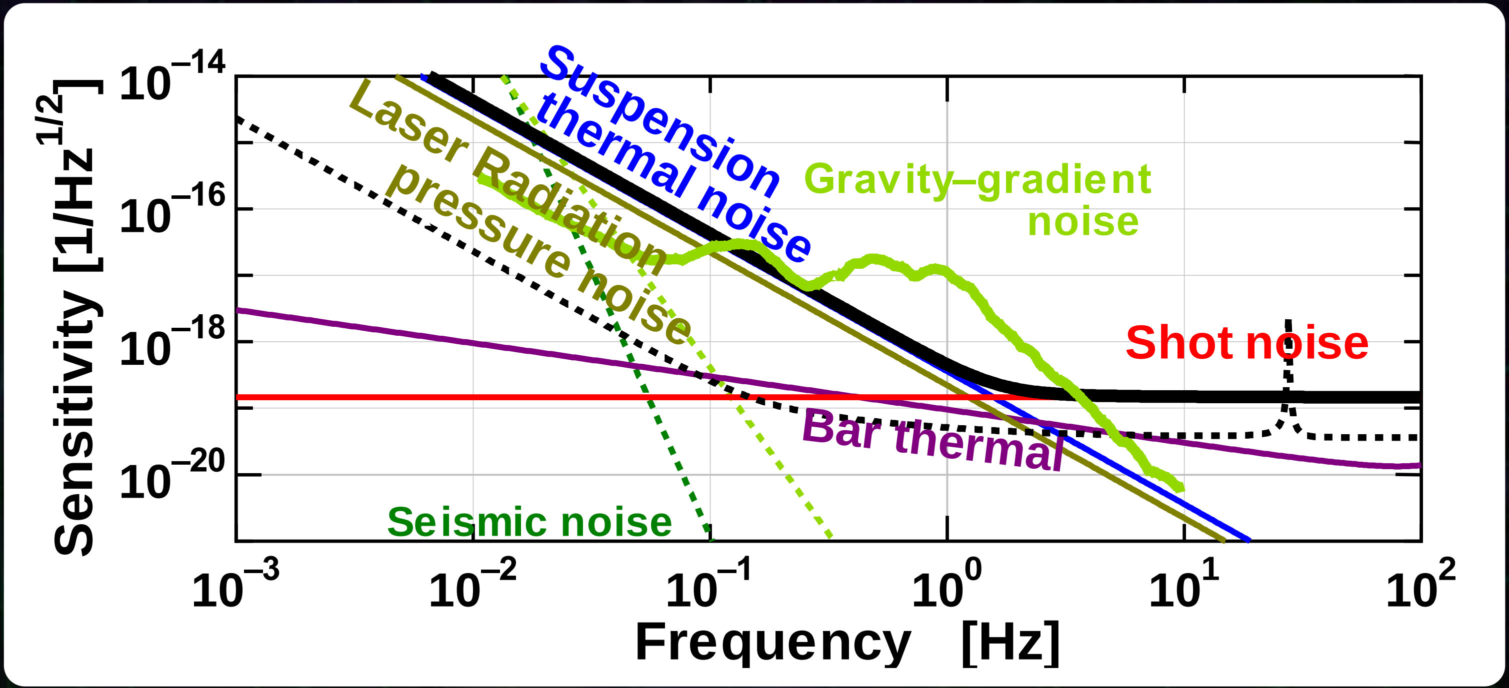
⇨ - Silicon test mass,
- Differential measurement using two orthogonal bars.
- Isolation system : LCGT type-B SUS, placed at an under ground site.

	Length	diameter	mass	MoI	Sensitivity	Max IR
Room temp. (300K)	10	0.3	1646	1.37×10^{4}	3×10^{-18}	800
	3	0.2	219	164	3×10^{-17}	150
	1	0.15	41	3.4	3×10^{-16}	20
Cryogenic (4K)	10	0.3	1646	1.37×10^{4}	4×10^{-19}	3500
	3	0.2	219	164	6×10^{-18}	350
	1	0.15	41	3.4	3×10^{-17}	50
	[m]	[m]	[kg]	[kg•m^2]	[$1/\mathrm{Hz}^{1/2}$ @0.1Hz]	[Mpc]

Sensitivity estimation

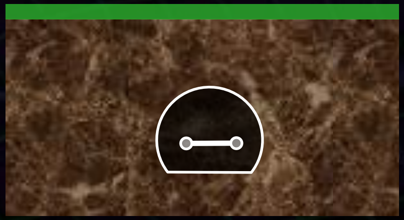
Bar length : 3m, Mass : 219kg
Laser source : 1550nm, 10W
Cavity length : 1cm, Finesse : 100

Silicon bar, Q-value : 10^9 , Temp: 300K
Pendulum Q-value : 10^{10}
Pendulum resonance 0.1mHz



Open questions…

- Readout scheme
  - Better setup to reduce couplings from the other DoF?
  - Non-optical readout, such as SQUID?
- Gravity gradient noise
  - What happens at an underground site?
  - Propagation of seismic waves?
    (Cancelation, Scattering, Diffraction)



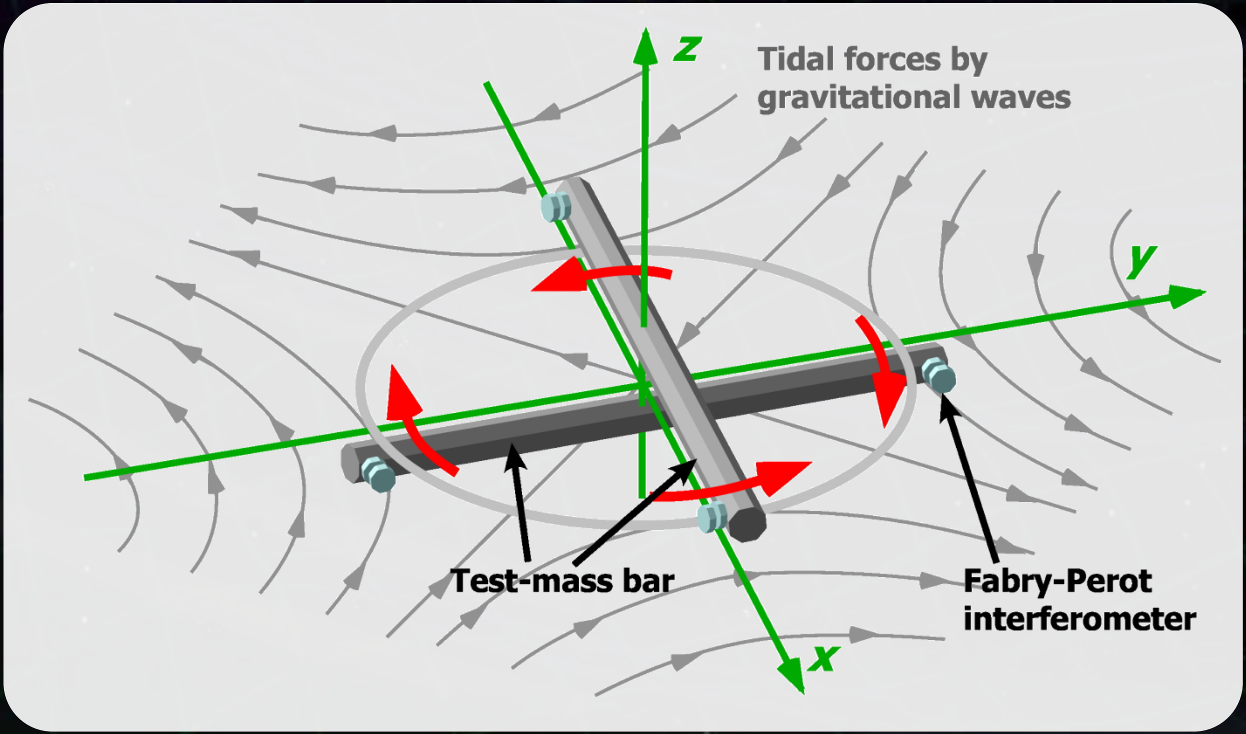
- Seismic noise
  - Design of isolation system.
  - Active controls.
- Other fancy ideas….
  - Detector configuration.
  - QND measurement.

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

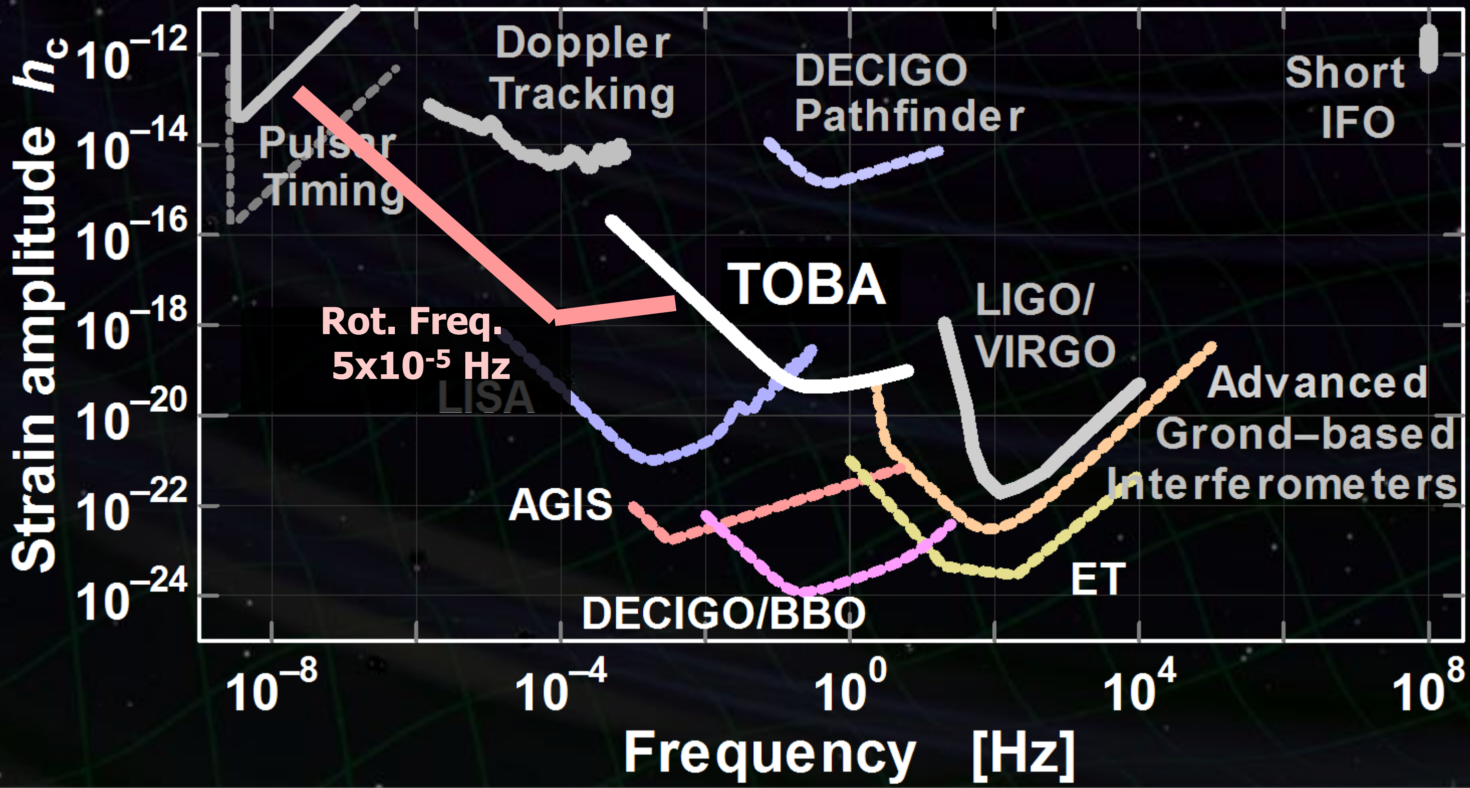
Sensitivity example

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}



Rotation of interferometer?

Usual free-mass interferometric detector cannot be rotated

Rotation freq. > Resonant freq. of the suspension

→ Not stable with linear spring model.

TOBA in space

TOBA prototype example (2)

- Space TOBA

- Silicon test mass, tune at 1mHz.
- Differential measurement using two orthogonal bars.

	Length	diameter	mass	MoI	Sensitivity	Max IR
Room temp. (300K)	10	0.3	1646	1.37×10^{4}	2×10^{-17}	70
	3	0.2	219	164	2×10^{-16}	7
	1	0.15	41	3.4	1×10^{-15}	1
	[m]	[m]	[kg]	[kg•m^{2}]	[1/Hz$^{1/2}$ @1mHz]	[Gpc]

※ Acceleration noise is not included.

Noise estimation for space TOBA

- Magnetic noise
  (Divergence of the magnetic field) x (magnetic noise)

- Thermal radiation noise
  Differential thermal radiation change in time.

- Residual gas noise
  Brownian noise on the bar.

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

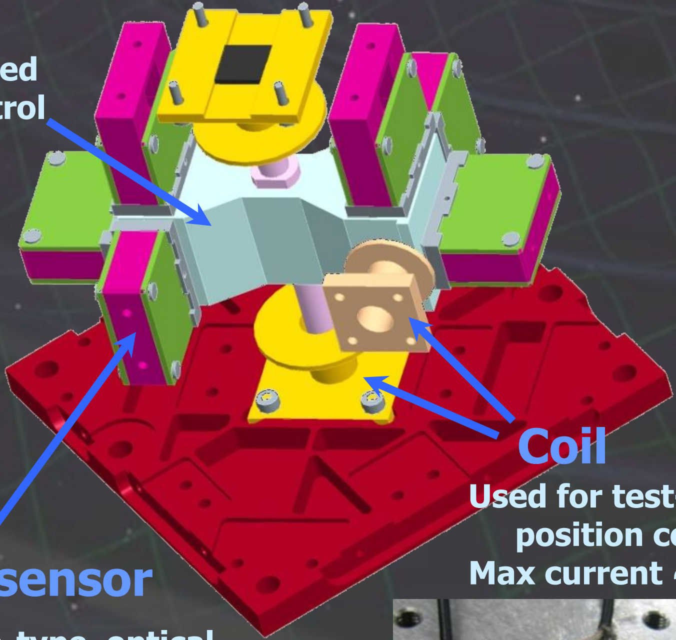
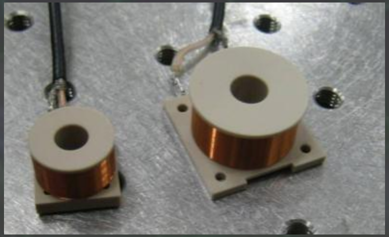


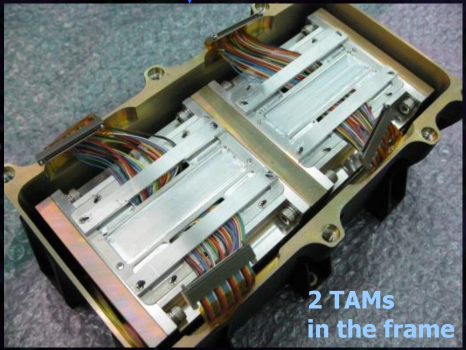
Photo sensor

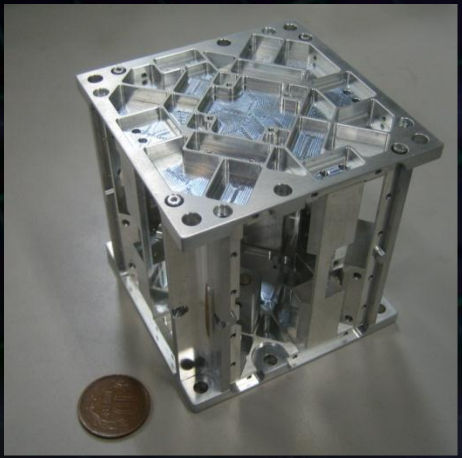
Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion

Coil

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







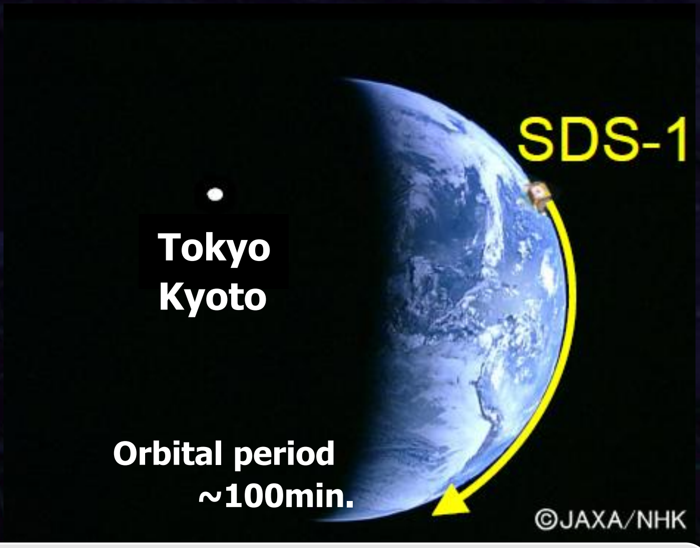
Observation by SWIM

Continuous data taking

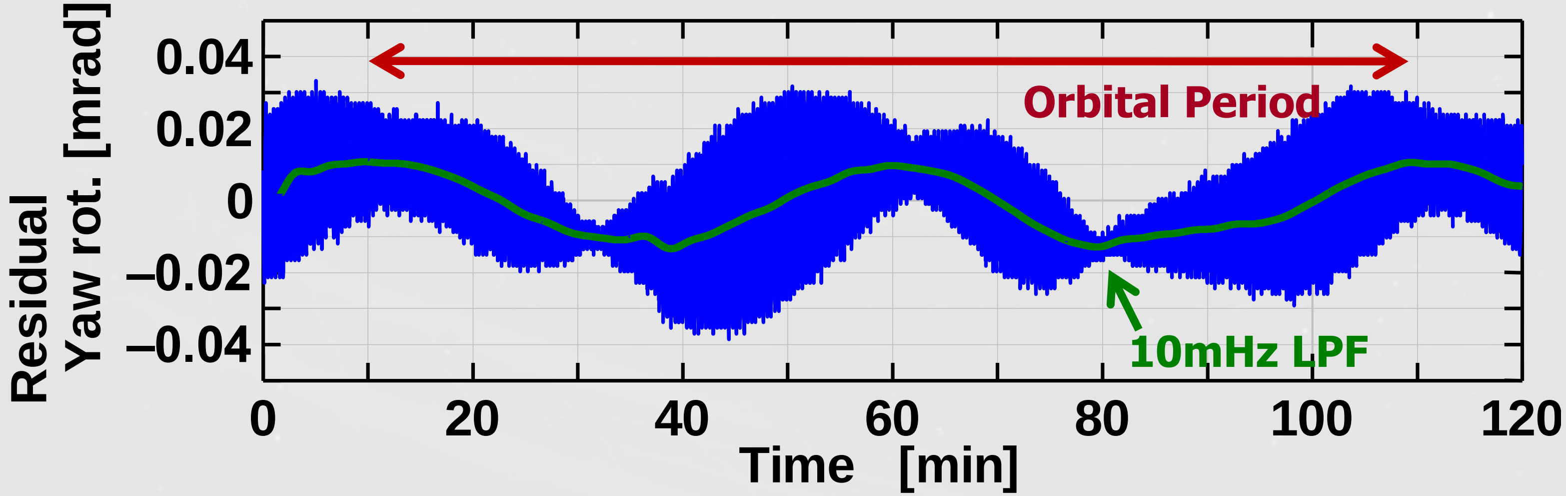
Jun 17, 2010 ~120 min.
July 15, 2010 ~240 min.

Simultaneous observation
with ground-based detectors

⇨ Data analysis

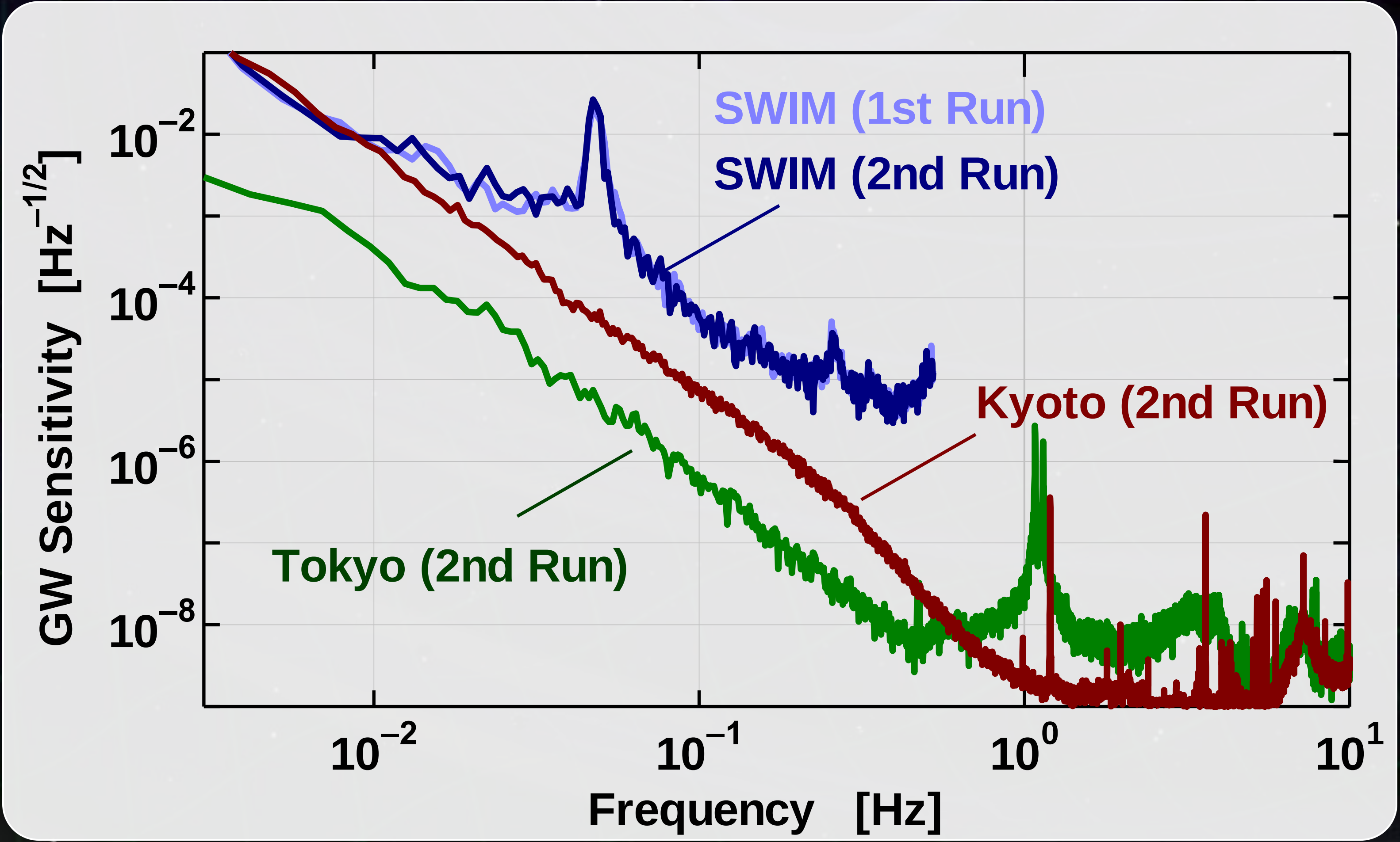


©JAXA/NHK



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 (~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

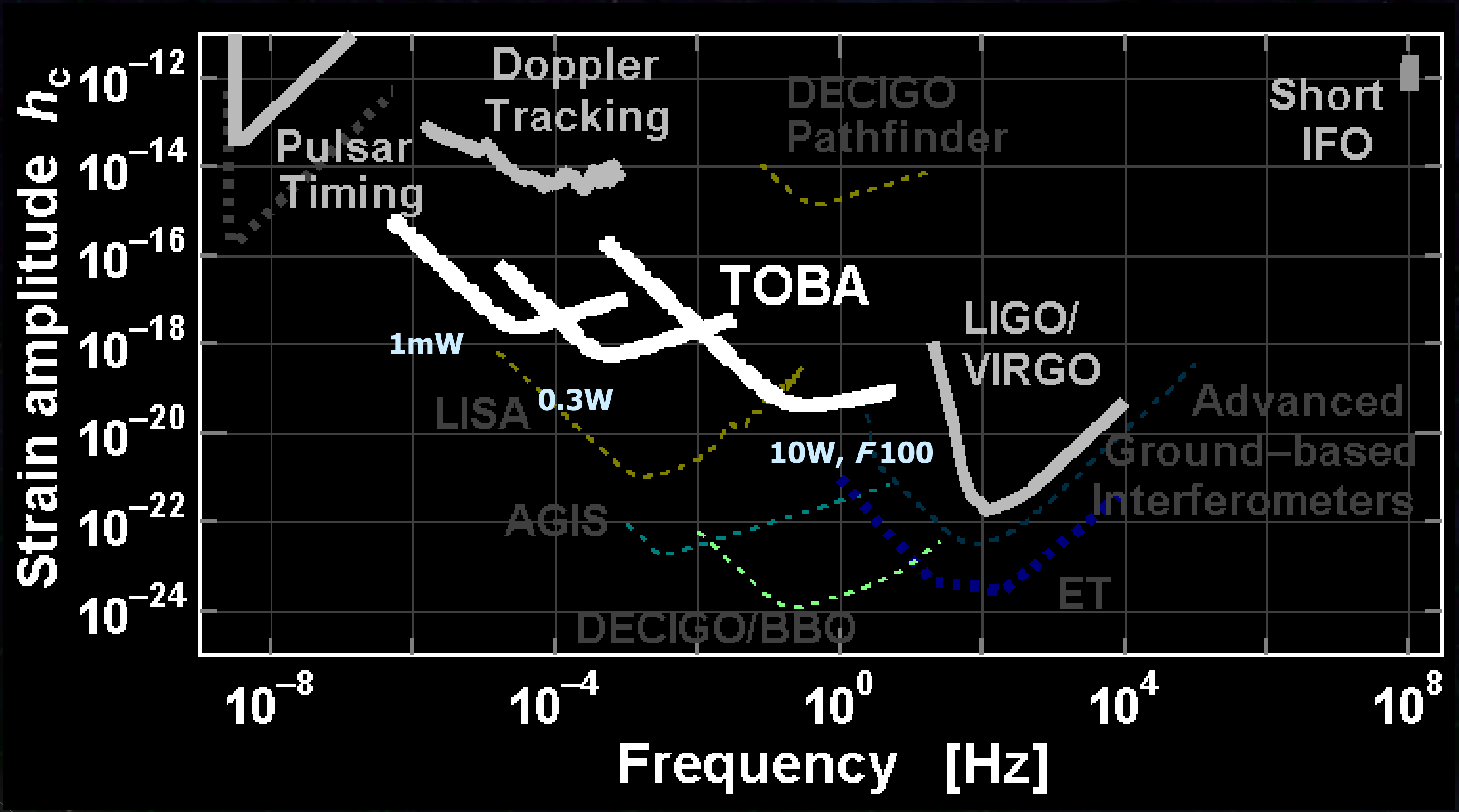
End

Backups

TOBA Sensitivity

Sensitivity example

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



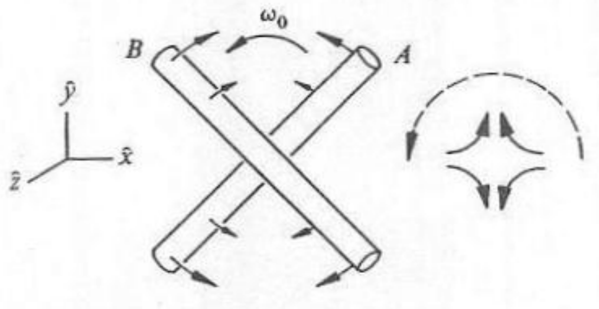
Topic

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.

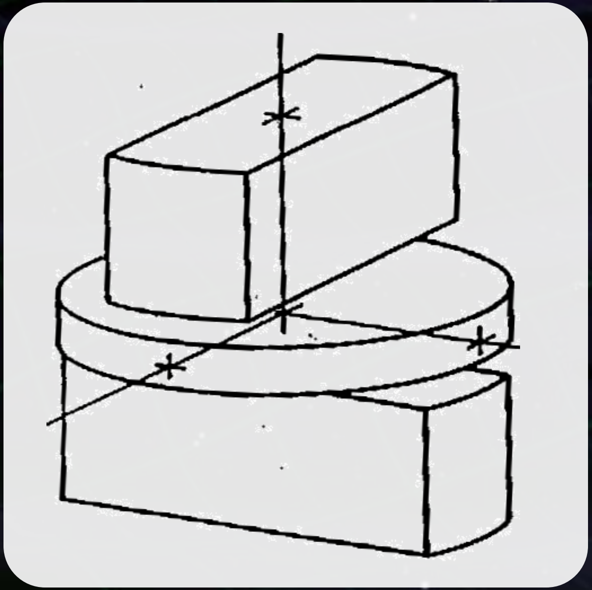


(f) Angular accelerations of rotating bars ["Heterodyne detector"; see Braginsky, Zel'dovich, and Rudenko (1969)]

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).

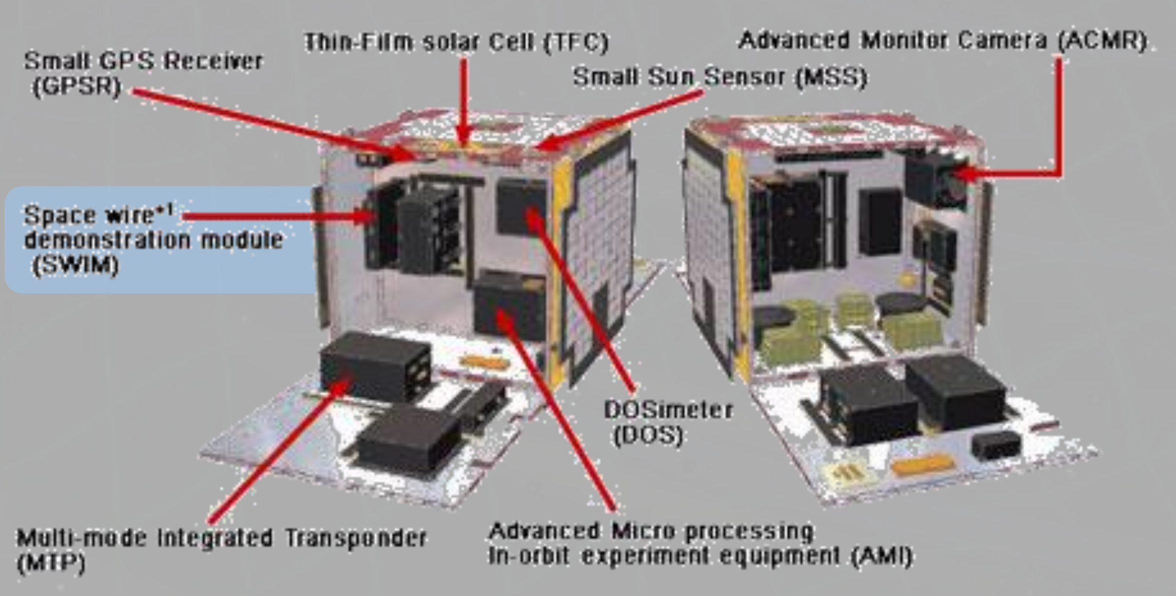


SDS-1衛星での実証

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)



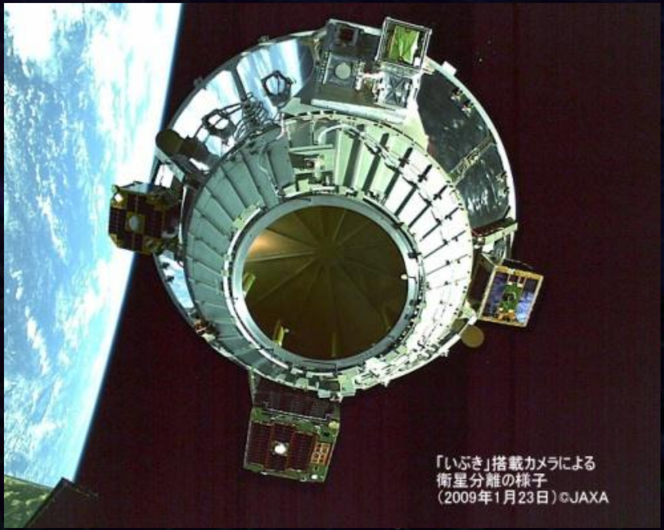
http://www.iat.jaxa.jp/info/prm/2007/019/01.html

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.



「いぶき」搭載カメラによる
衛星分離の様子
（2009年1月23日）©JAXA

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

Photo by JAXA

SWIMμν : User Module

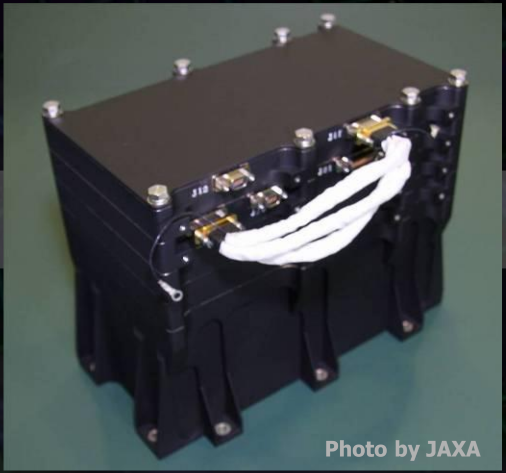


Photo by JAXA

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

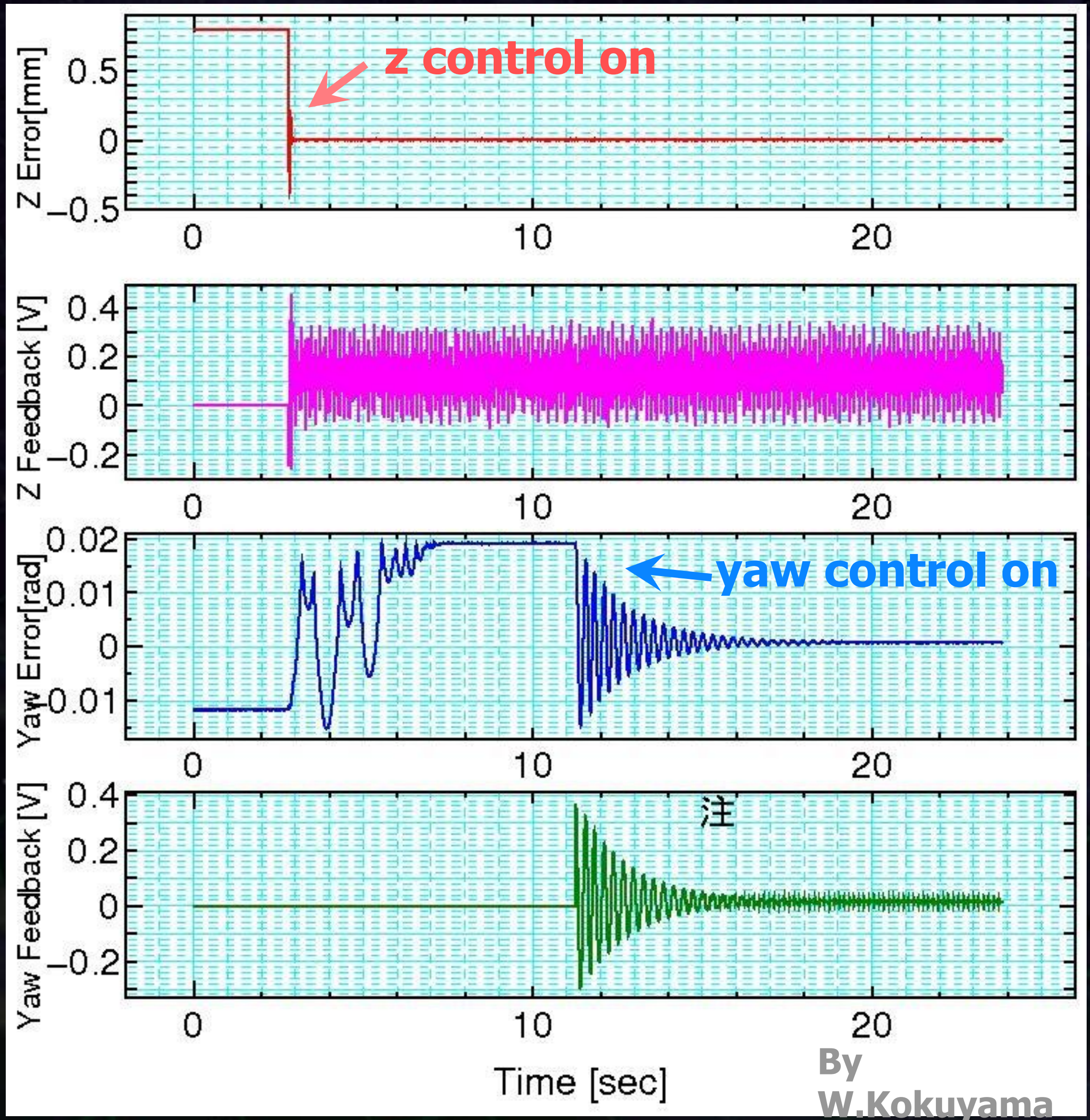
Damped oscillation
    (in pitch DoF)

Free oscillation
    in x and y DoF

Signal injection
    → OL trans. Fn.

Operation: May 12, 2009

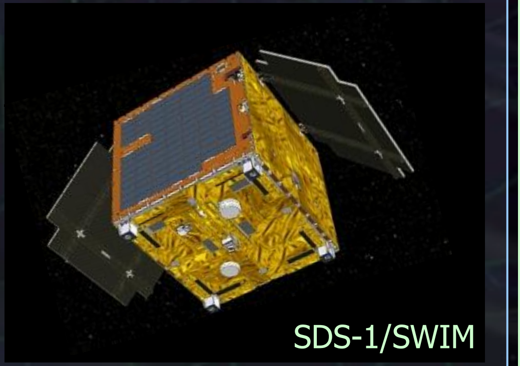
Downlink: ~ a week

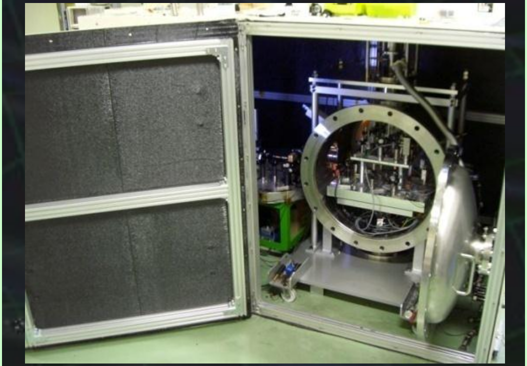


By W.Kokuyama

プロトタイプ

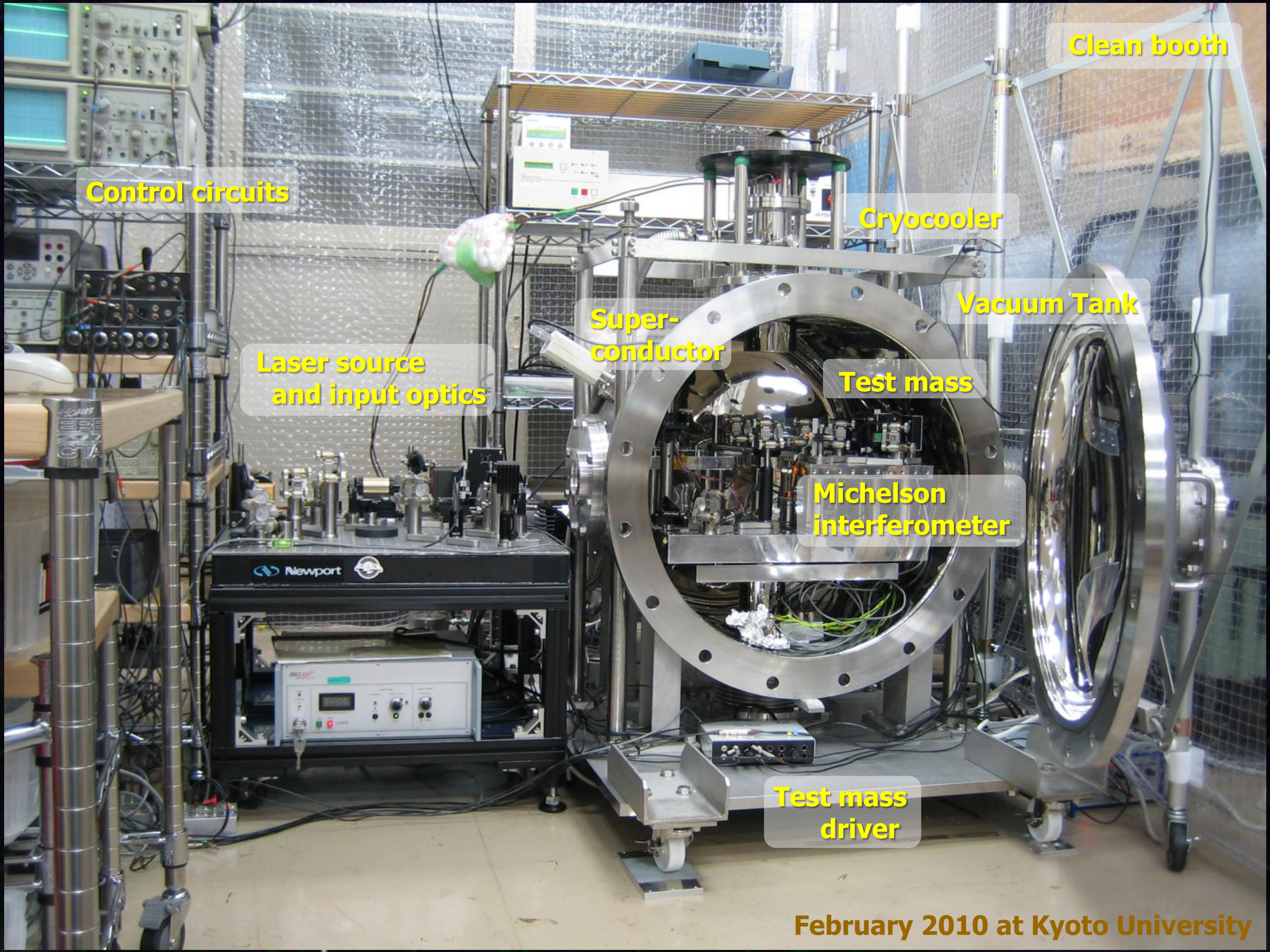
2つの地上装置, 1つの衛星搭載モジュール





	ねじれ型重力波検出器A (地球周回軌道, 2009年-)	**ねじれ型重力波検出器B** (東京大学, 2008年-)	**ねじれ型重力波検出器C** (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



February 2010 at Kyoto University

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.

複数台での

同時観測，相関解析を行う.

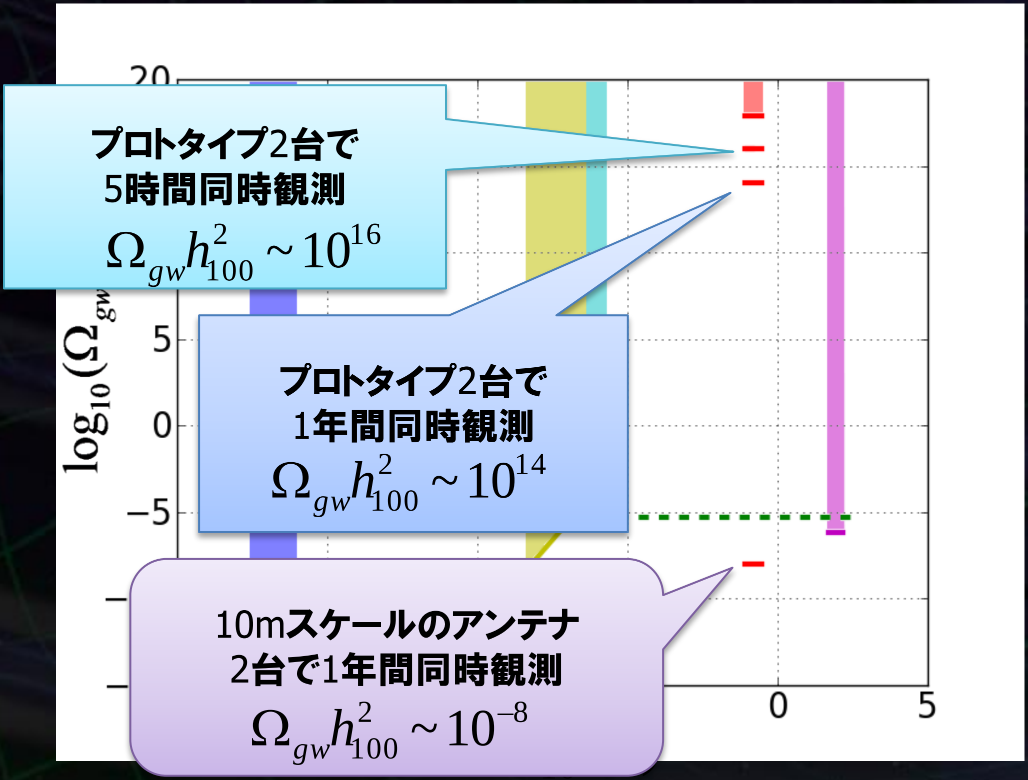
信号と雑音を区別できる.

感度を向上できる.

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

程度の向上.

Fig. By A.Shoda



プロトタイプ2台で
5時間同時観測
$\Omega_{gw}h_{100}^2 \sim 10^{16}$

プロトタイプ2台で
1年間同時観測
$\Omega_{gw}h_{100}^2 \sim 10^{14}$

10mスケールのアンテナ
2台で1年間同時観測
$\Omega_{gw}h_{100}^2 \sim 10^{-8}$

結果の見通し

観測データ (2010年7月) 解析の暫定結果.

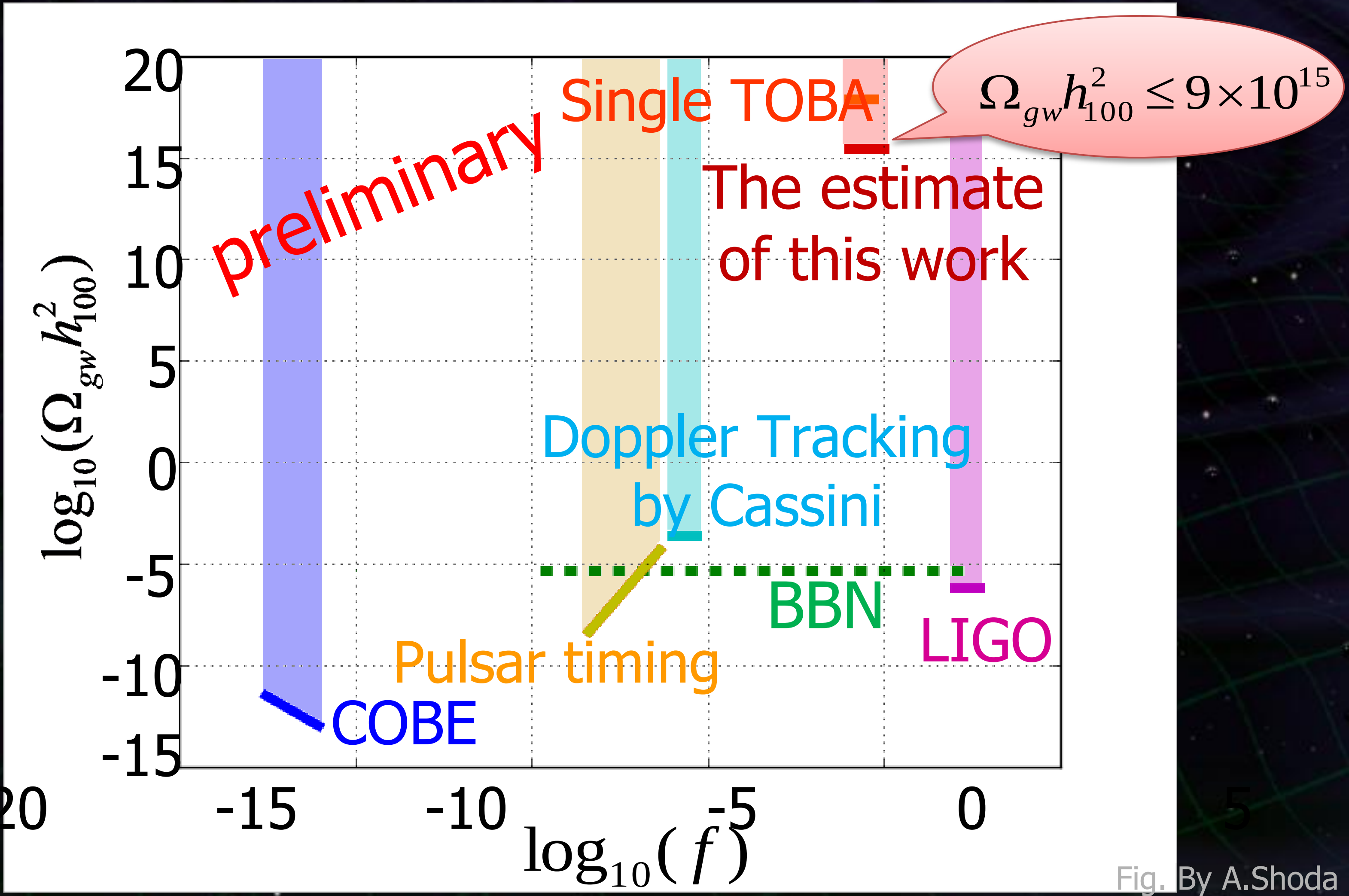


Fig. By A.Shoda