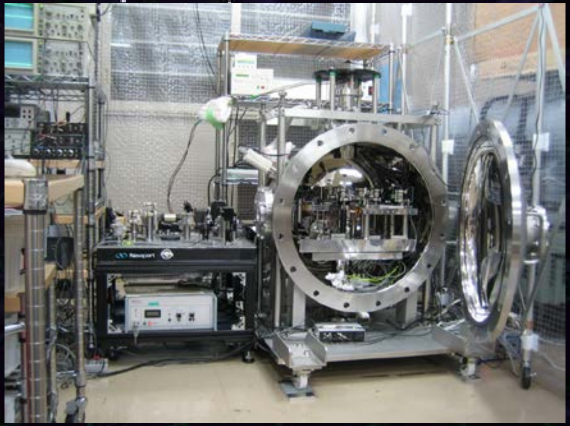
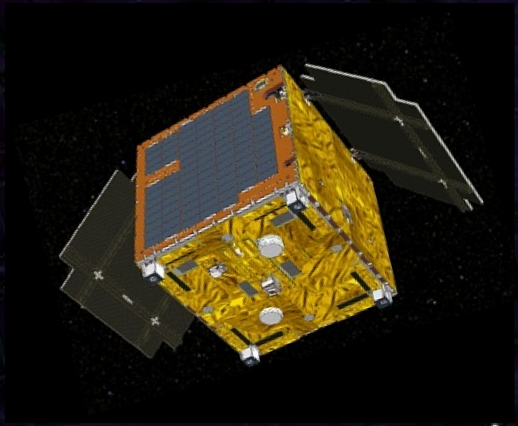
TOBA: Torsion-Bar Antenna

Small-scale TOBA at Tokyo



Small-scale TOBA at Kyoto



SWIM on SDS-1 satellite

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Special thanks to the MANGO members

GWADW2012 (May 17, 2012, Hawaii, USA)

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 fundamental 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.

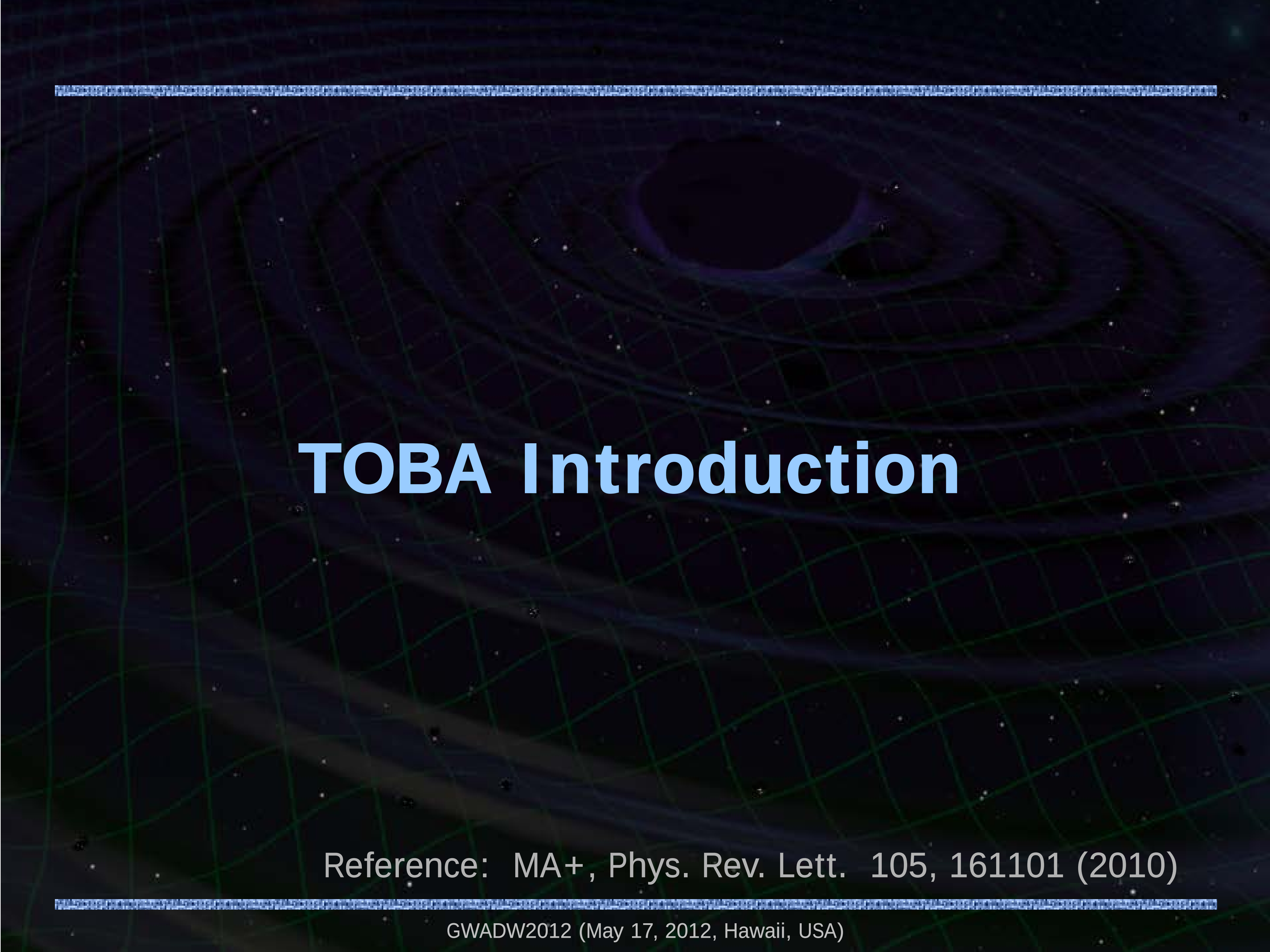
Introduction

Prototype results

- **Ground-based TOBA** **(A. Shoda)**
- **Rotating TOBA in space**

Next steps

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
- W.Kokuyama, in preparation



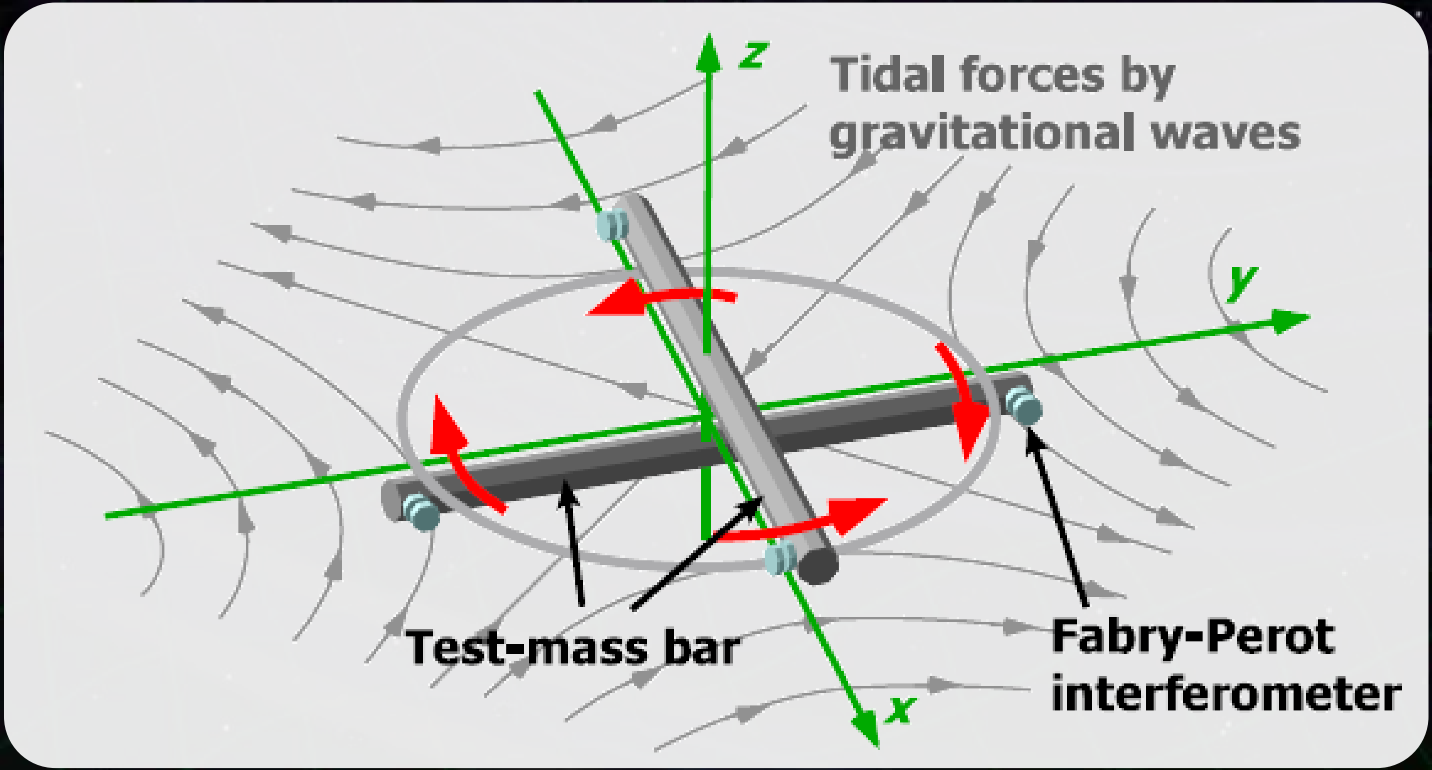
TOBA Introduction

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

TOBA

TOBA : Torsion-Bar Antenna

Monitors tidal-force fluctuation caused by GWs.

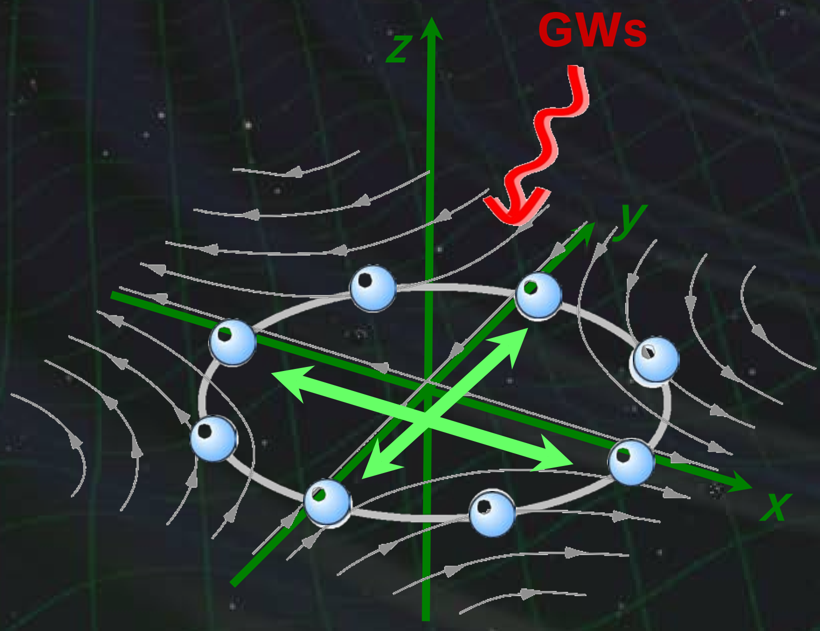


MA+, Phys. Rev. Lett. 105, 161101 (2010)

Detection principle

Conventional IFO antenna

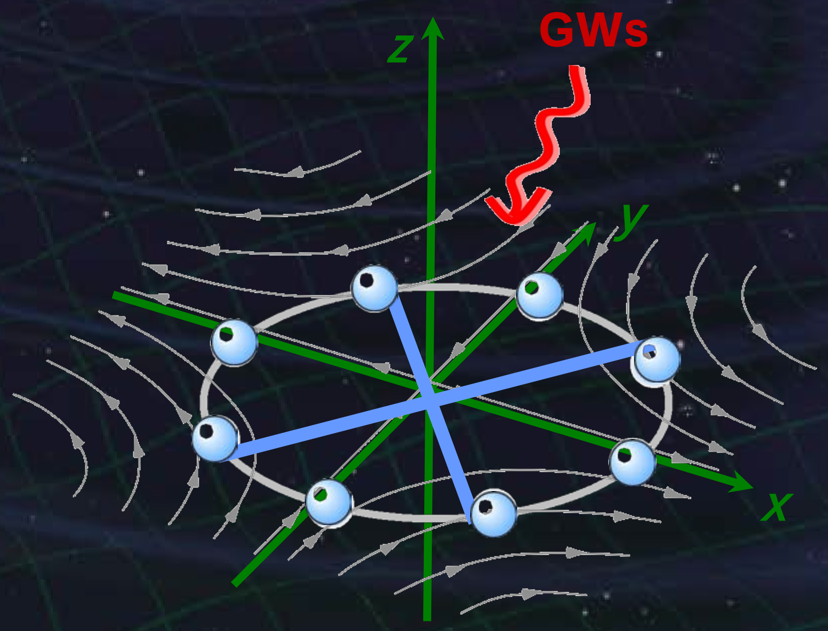
Detect differential length change



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

Comparison

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)

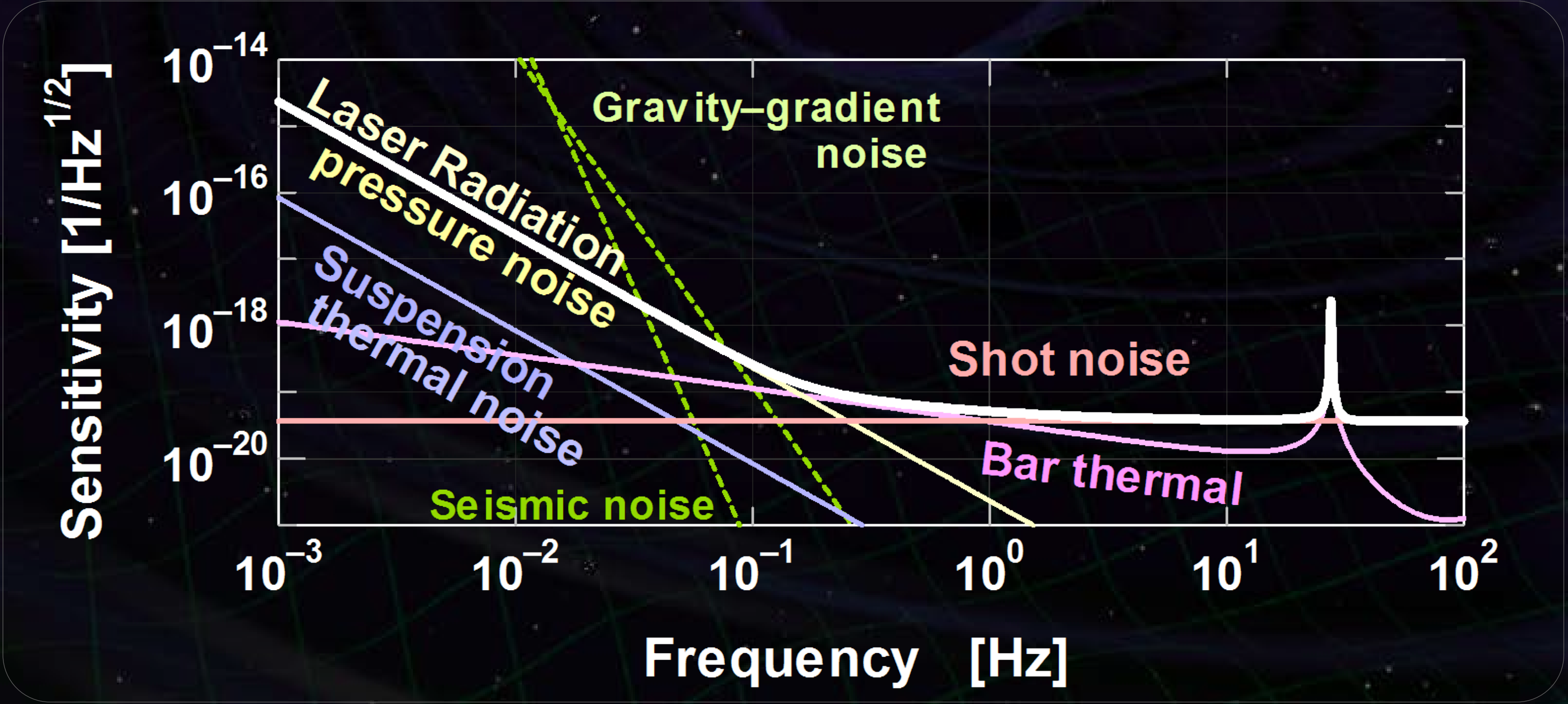
Shorter length

→ 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)



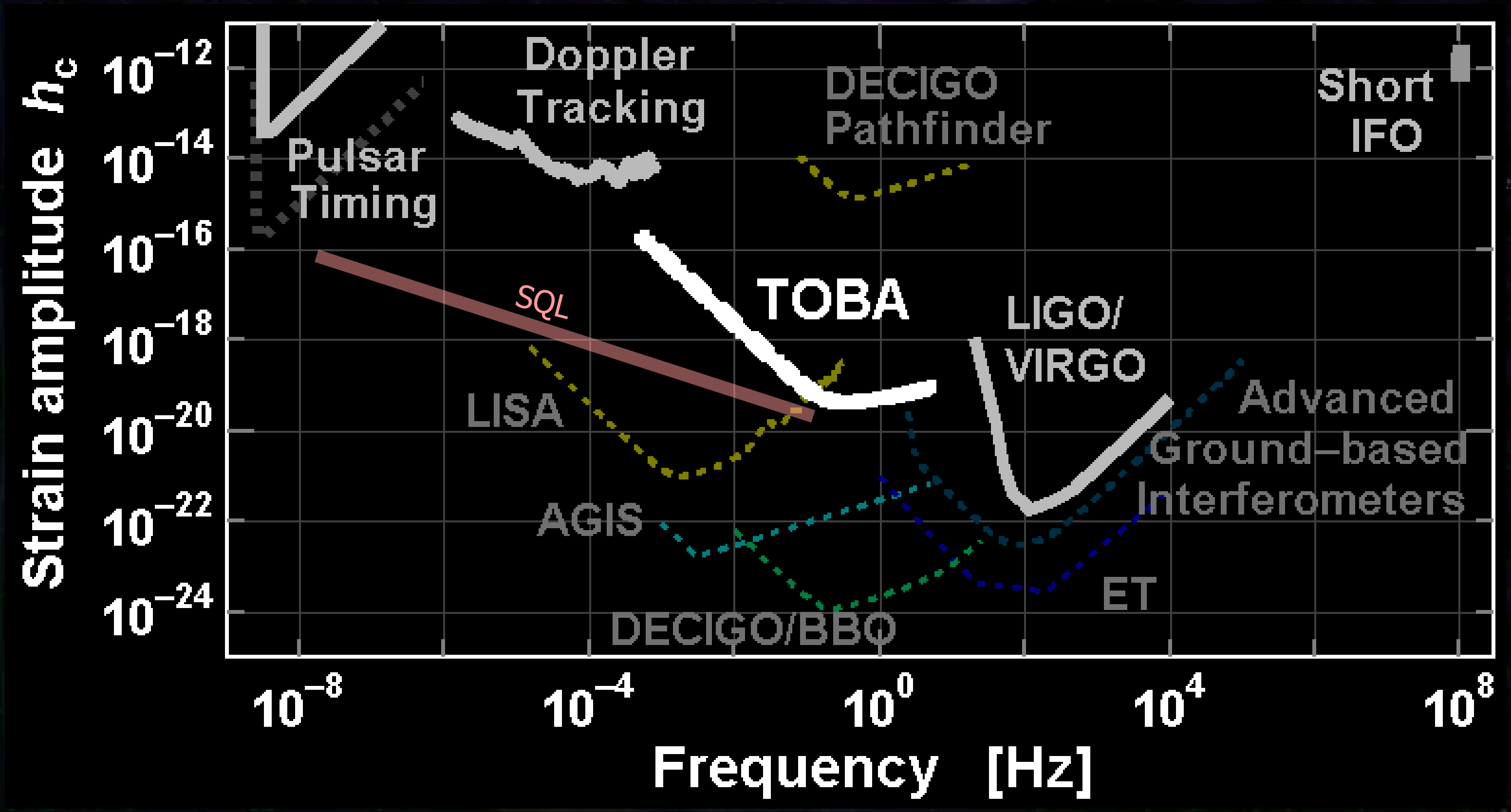
Bar length : 10m, Mass : 7600kg
Laser source : 1064nm, 10W
Cavity length : 1cm, Finesse : 100
Bar Q-value : 10^5 , Temp: 4K
Support Loss : 10^{-10}

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

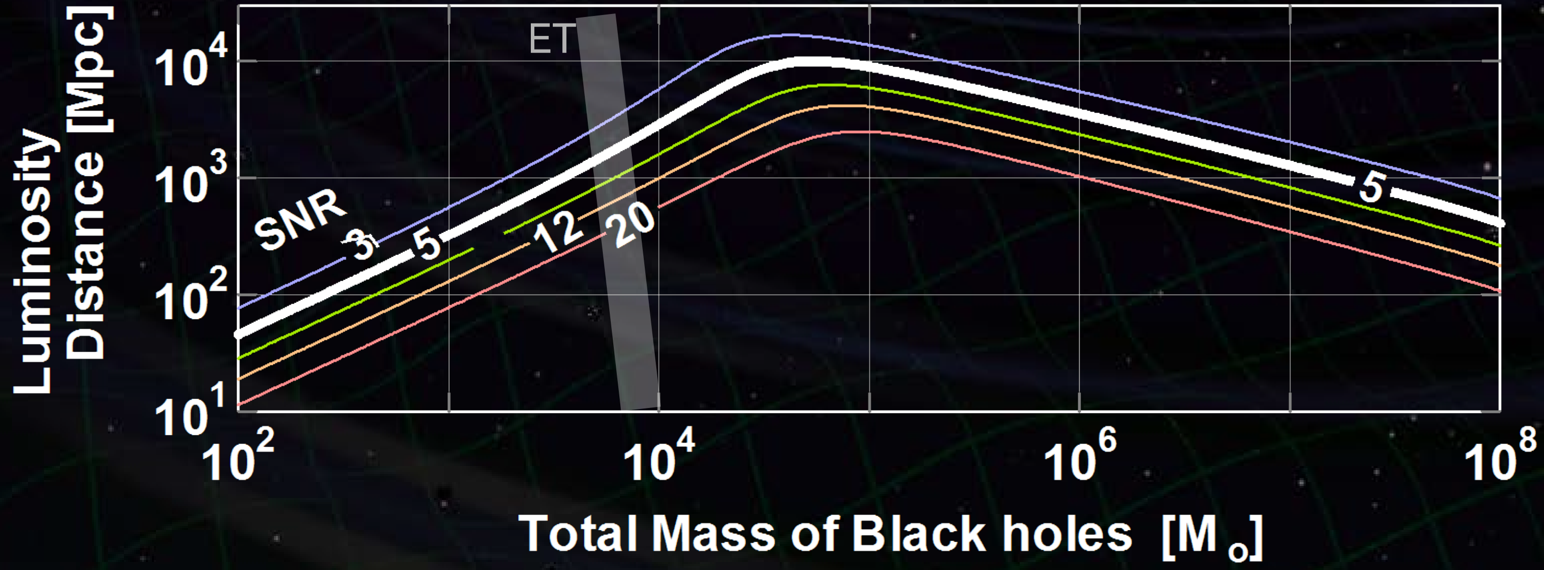


Characteristic amplitude : $h_c = \tilde{h} \times \sqrt{f_{\mathrm{center}}}$ (Dimensionless strain)

Observable range

GWs from binary BH mergers

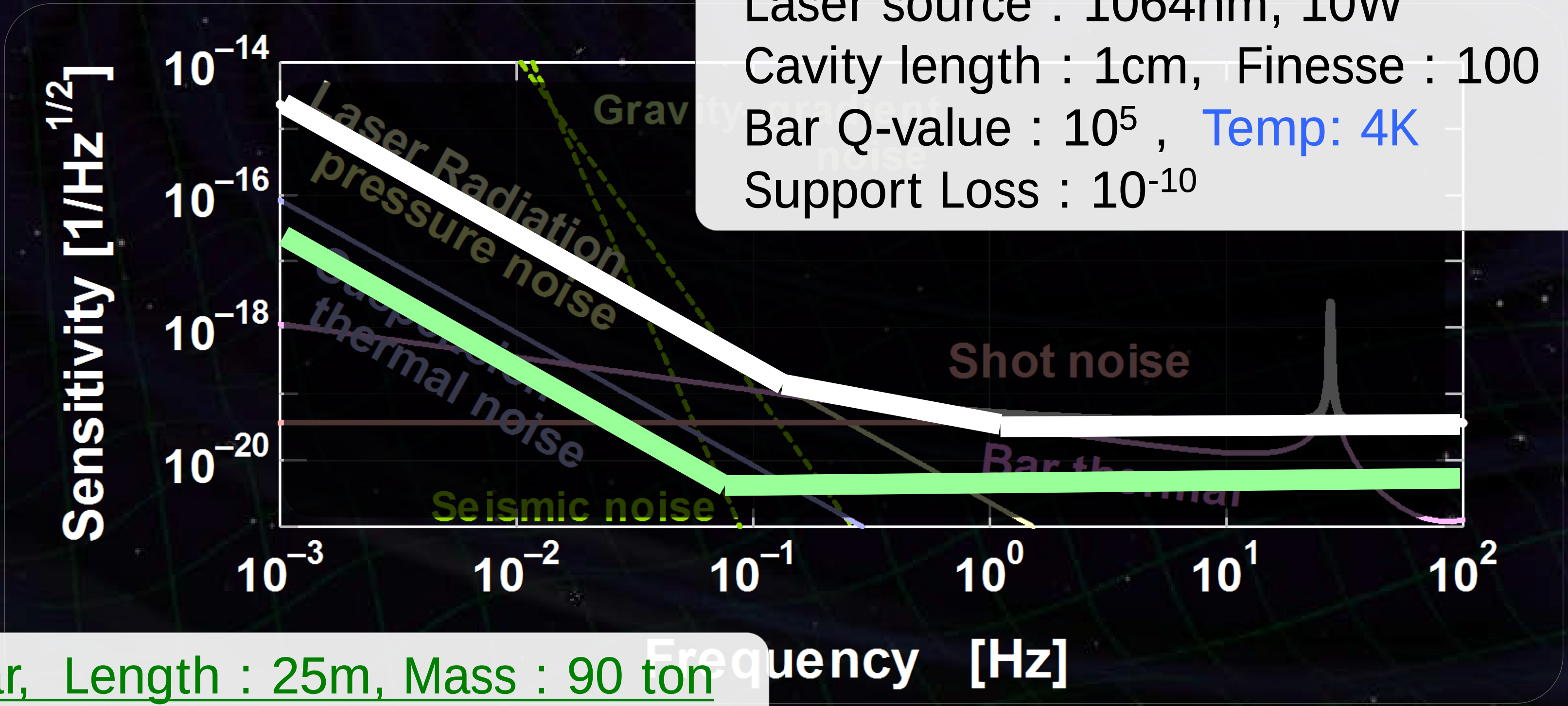
⇨ Obs. Range ~10Gpc ($\sim 10^5 M_\odot$, SNR $= 5$)



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

And more...

Al bar, Length : 10m, Mass : 7.6 ton
Laser source : 1064nm, 10W
Cavity length : 1cm, Finesse : 100
Bar Q-value : 10^5 , Temp: 4K
Support Loss : 10^{-10}

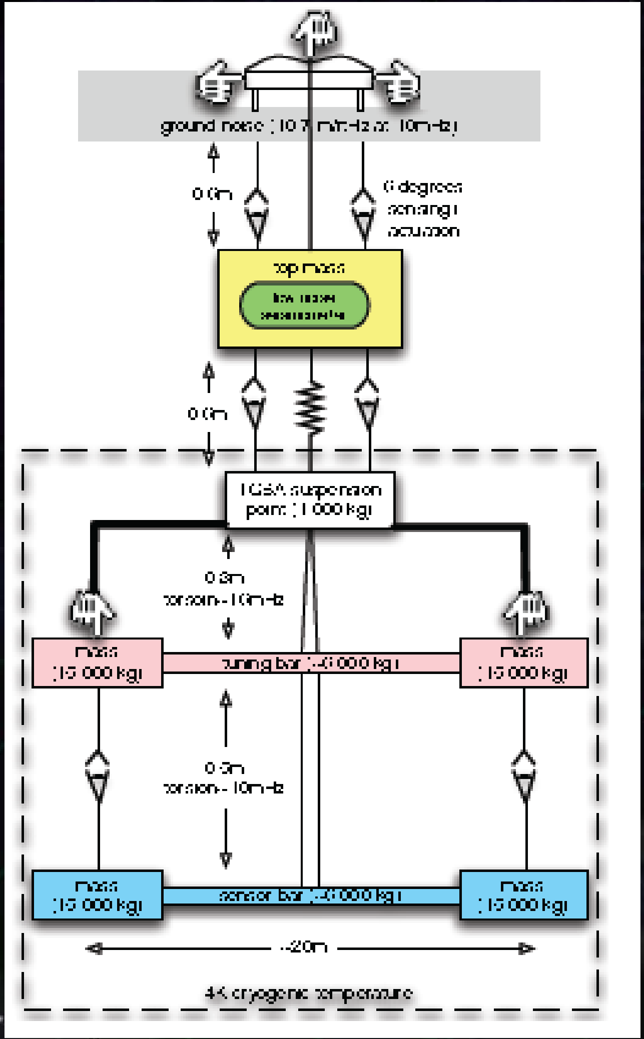


Si bar, Length : 25m, Mass : 90 ton
Laser source : 1550nm, 10W
Squeezing 10dB, Finesse : 100
Bar Q-value : 10^9 , Temp: 4K
Support Loss : 10^{-9}

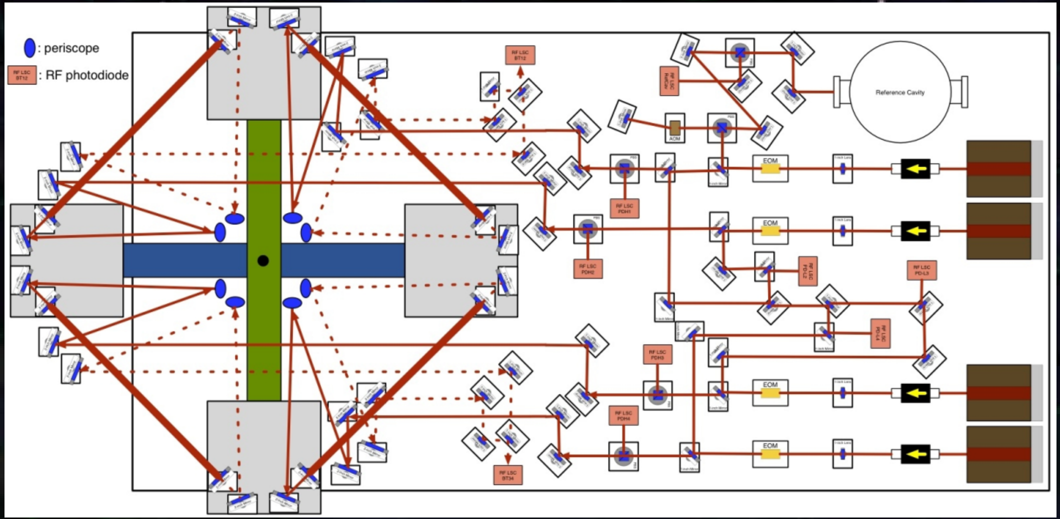
>10 times better!

Schematic design

- Example of extreme design (By Bram Slagmolen)



Si bar, Length : 10m, Mass : 11 ton
Laser source : 1550nm, 100mW
Squeezing 10dB, Finesse : 300
Bar Q-value : 10^9 , Temp: 4K
Support Loss : 10^{-9}



Rotating TOBA

Rotate the detector along its axis

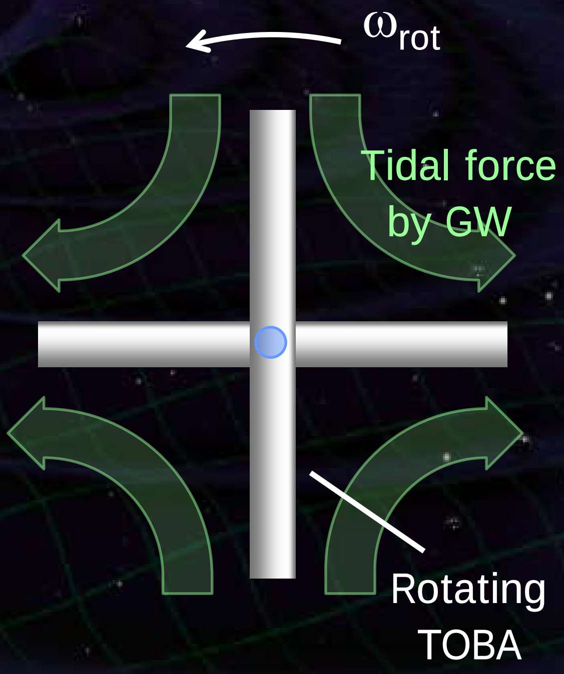
- Up-conversion of low-freq. GWs

  Low-freq. GW appears at $2\ \omega_{rot}$

- Avoid low-freq. noises

  Observer rotates with the detector

  Noises at ω_{rot} : not important



・Two independent polarization of GW.

□Allow intermitted observation.

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.

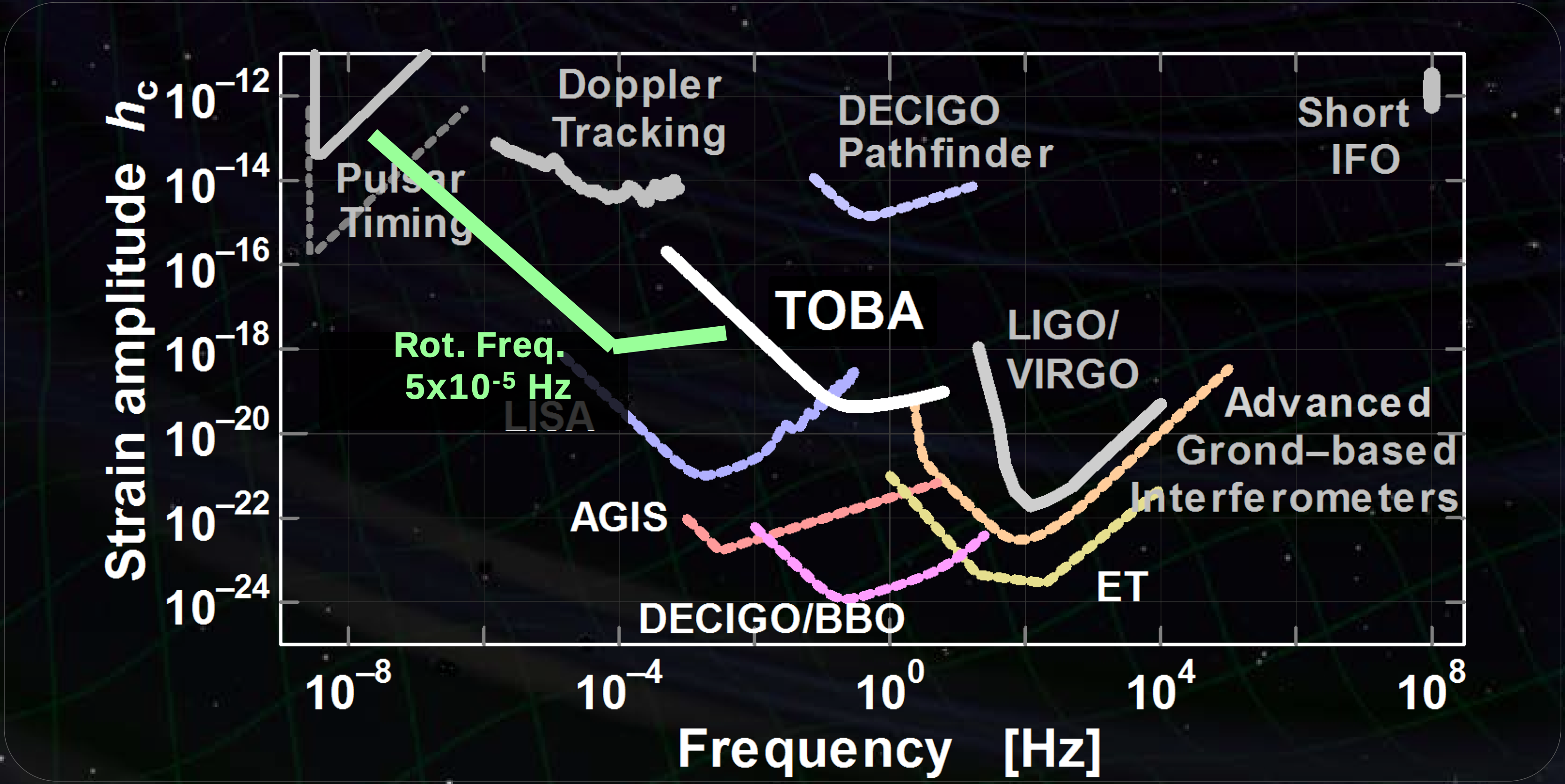
Sensitivity by R-TOBA

Sensitivity example

(Rotation freq. 5×10^{-5} Hz, Laser power 1mW)

⇨ 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}



Results from Prototypes

→ A.Shoda's file

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

Rotating TOBA prototype

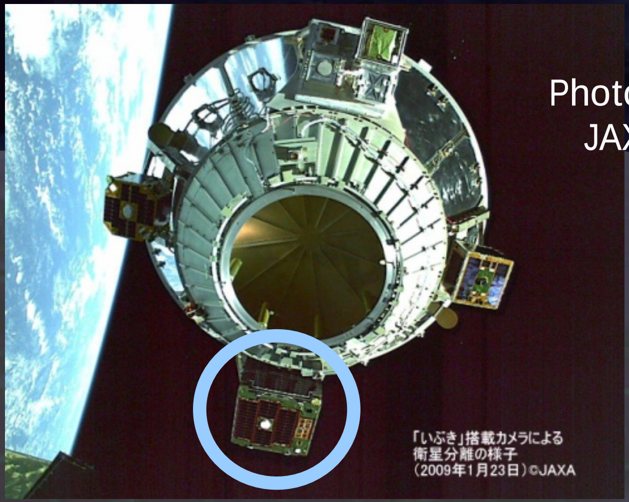
(SWIM on SDS-1 satellite)

Reference: W. Kokuyama, Ph.D thesis

Rotating TOBA : SWIMμν

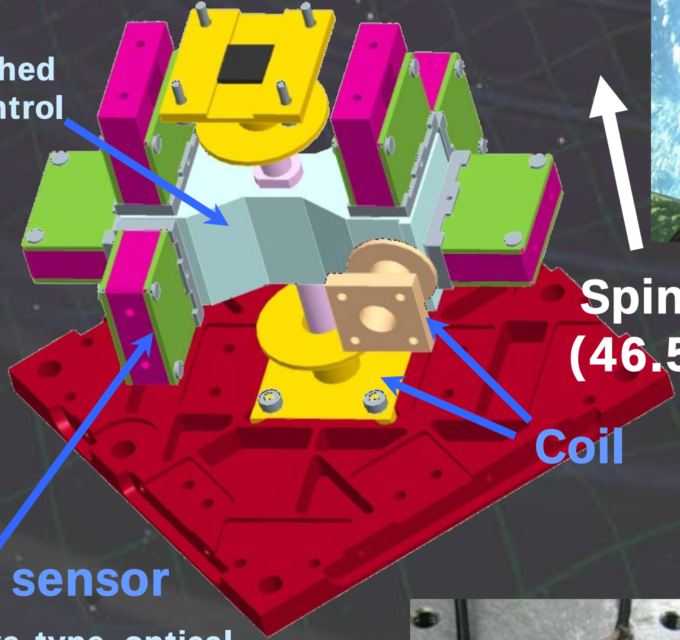
Small Module SWIMμν on SDS-1

Launched Jan. 2009, Terminated Sept. 2010



Photo：
JAXA

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



Spin Axis (46.5mHz)

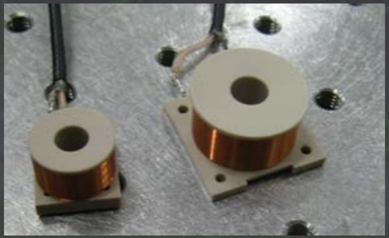
Test mass

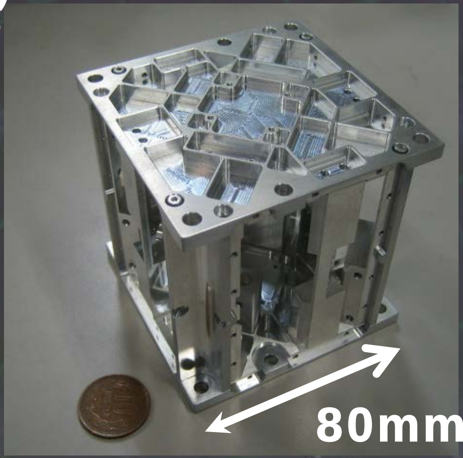
~47g Aluminum, Surface polished
Small magnets for position control

Coil

Photo sensor

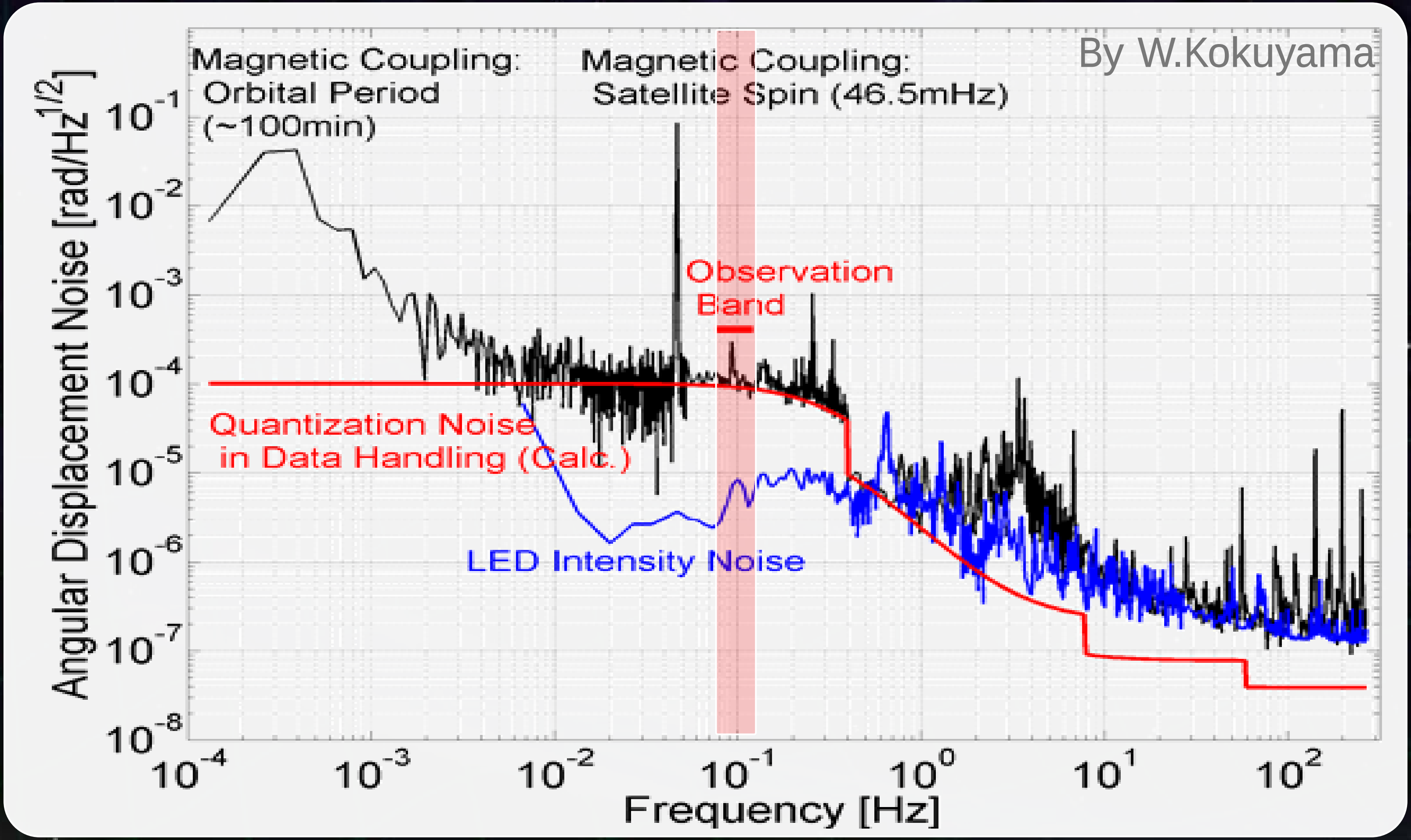
Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion





Sensitivity

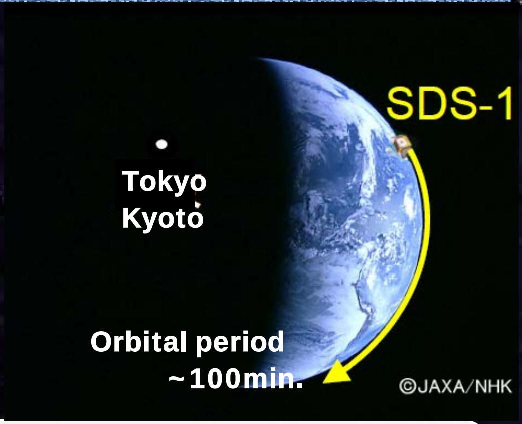
Though limited by non-fundamental noises, best as a space-borne GW detector.

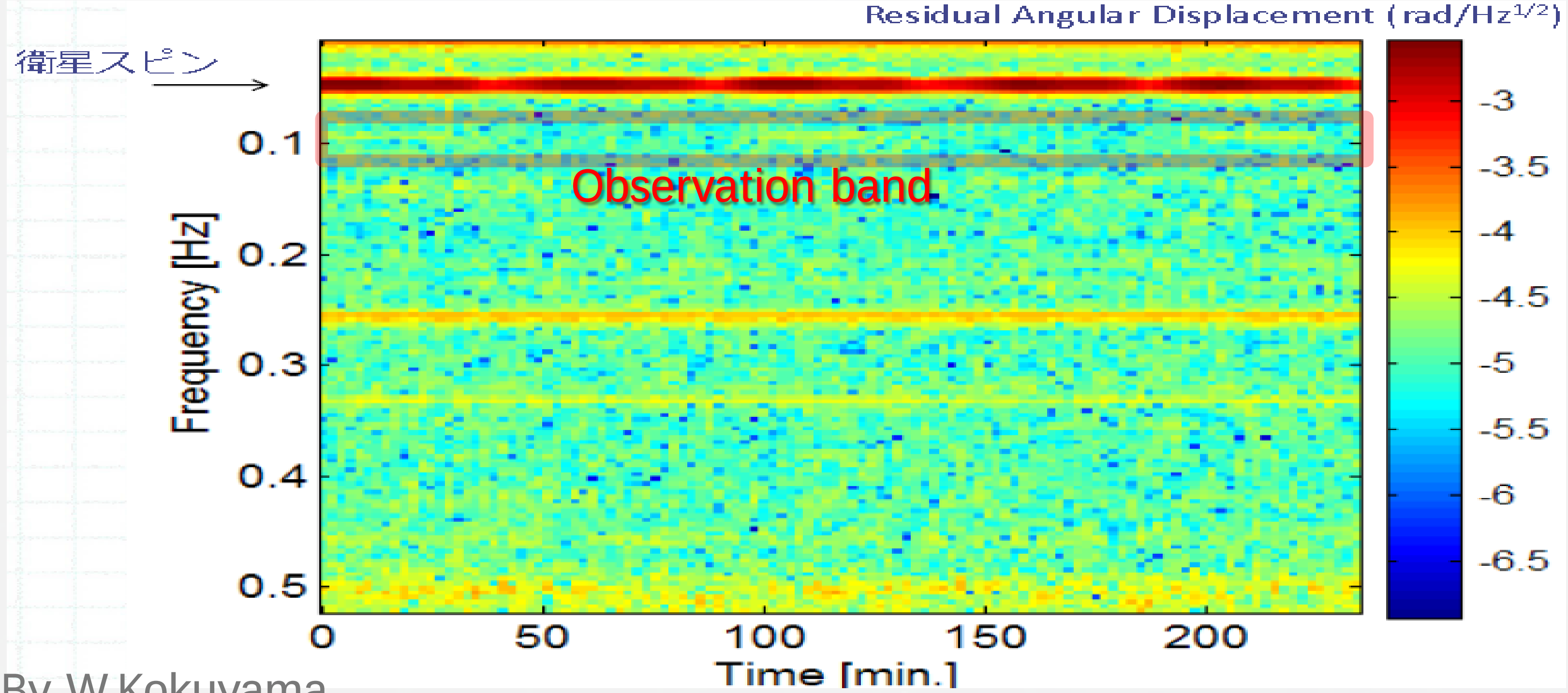


Observation by SWIM

Continuous data taking

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





By W.Kokuyama

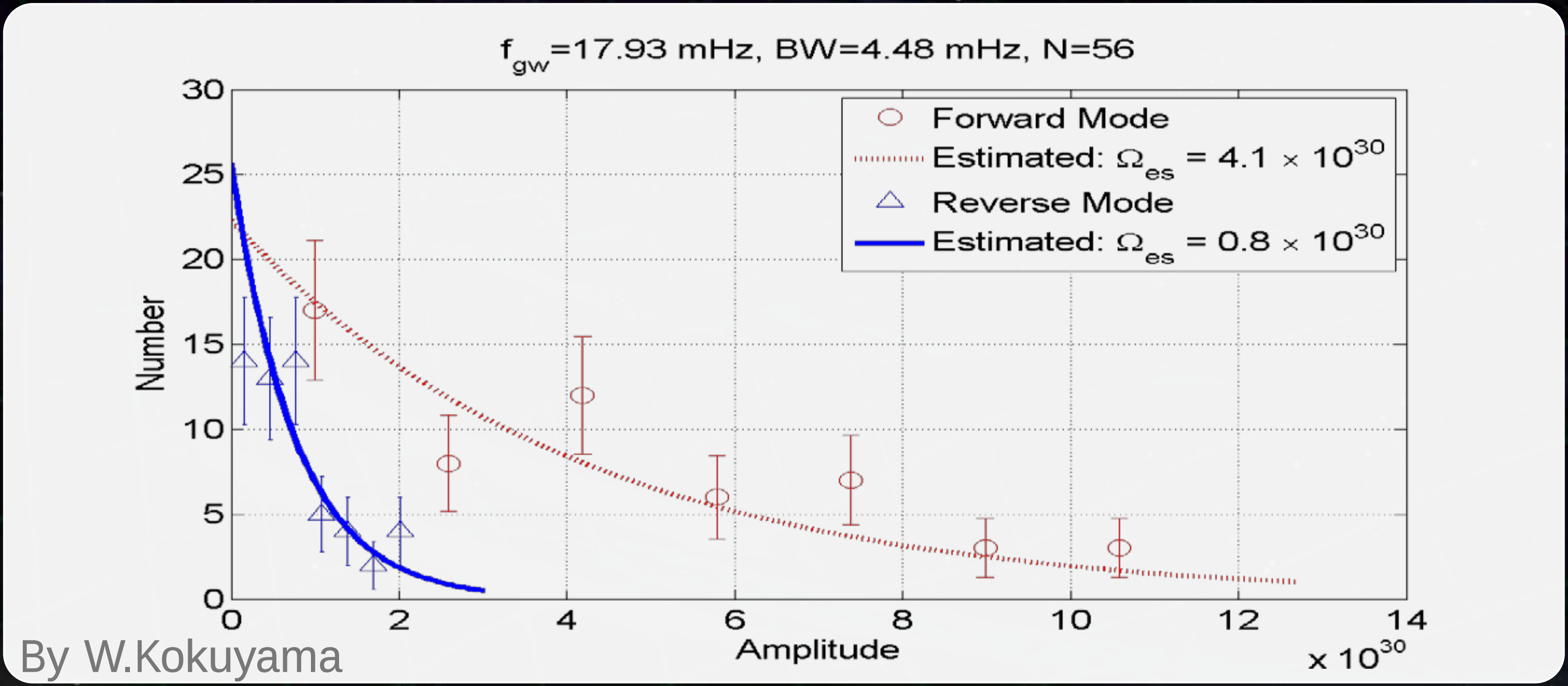
Upper Limit on GWB

Upper Limit at two frequencies (two polarizations)

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

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

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

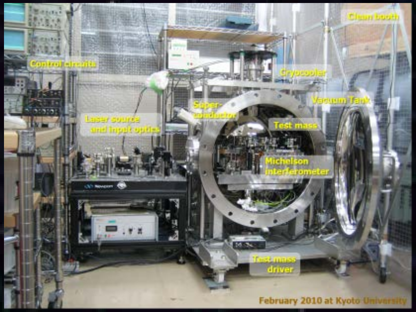


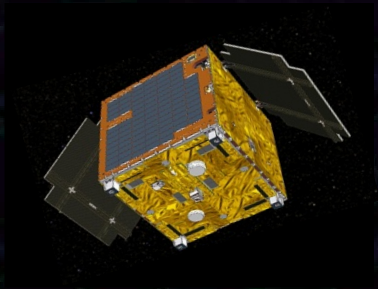
By W.Kokuyama

Next Prototype plan

TOBA next plan

- Results from two small-scale TOBAs at Tokyo and Kyoto, and rotating TOBA in space.





⇨ One more prototype step before the 10-m scale TOBA.

Concepts

- Design concepts
  - Should be intermediate step for the 10-m scale TOBA.
  - Scientific outcomes.
  - Common techniques with KAGRA, ET, ...
  - Realistic both in technology and the budget.

⇩

Medium-scale TOBA for Newtonian noise observation.

- NN monitor sensor
- Take the most advantages of R&Ds
  for the next generation detectors.

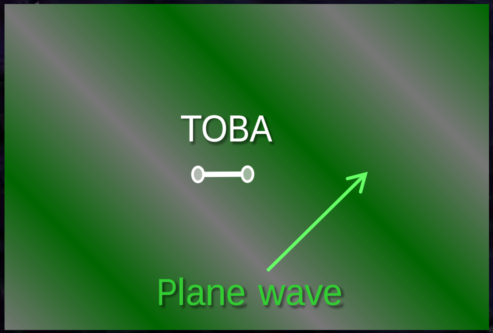
Gravity gradient noise

- Newtonian noise by ground motion.

- Coherent plane wave with long wavelength

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

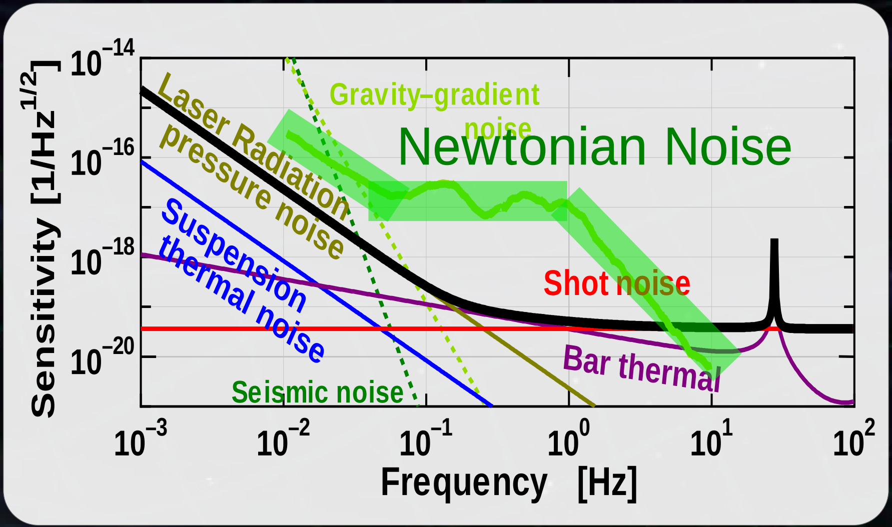
⇨ Same effect as km-scale interferometer



- NN estimation (by Jan Harms)

$$\boxed{h_{\mathrm{gw}} \sim 10^{-17}\ \mathrm{Hz}^{-1/2}}$$

Assumption:
Infinite plane wave
Homestake mine seismic level



Atmospheric NN may be larger; should be considered.

Medium-scale TOBA candidates

- Sensitivity estimation (only with fundamental noises)
  - Silicon test mass, room-temp. or cryogenic
  - Laser 1550nm for two orthogonal bars.
  - Readout by interferometers.
  - Isolation system : KAGRA technology.

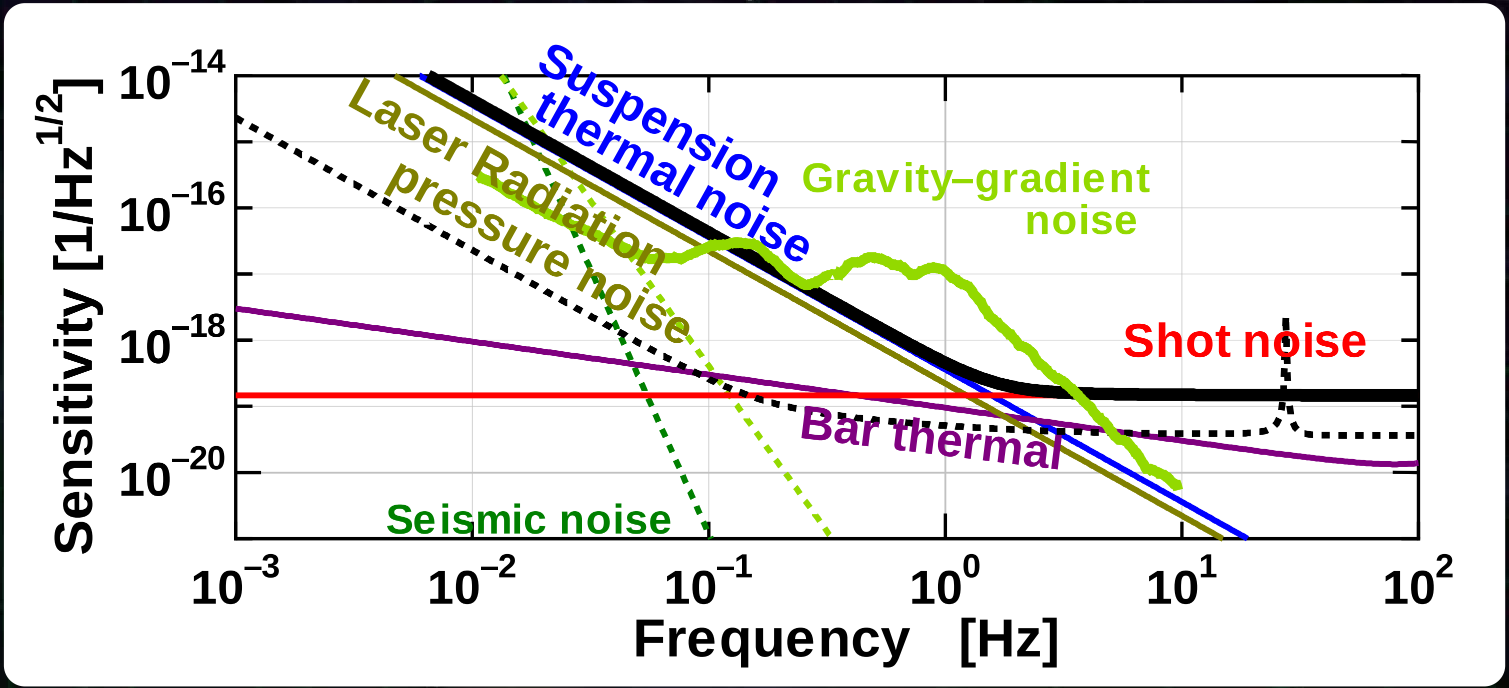
	Length	Diameter	Mass	MoI	Sensitivity	Max IR
Room temp. (300K)	10	0.3	1646	1.37×10^{4}	3×10^{-18}	800
	3	0.2	219	164	3×10^{-17}	150
	1	0.15	41	3.4	3×10^{-16}	20
Cryogenic (4K)	10	0.3	1646	1.37×10^{4}	4×10^{-19}	3500
	3	0.2	219	164	6×10^{-18}	350
	1	0.15	41	3.4	3×10^{-17}	50
	[m]	[m]	[kg]	[kg·m^2]	[1/Hz$^{1/2}$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

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

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



Medium-scale TOBA design

- Under discussion, but may be ... Cryo. with 1-m scale

  - Same direction as KAGRA, ET, ...
    → Effective use of resources and technologies.

    (Cryo-system, Suspension, Isolators, Materials)

	Length	Diameter	Mass	MoI	Sensitivity	Max IR
Room temp. (300K)	10	0.3	1646	1.37x10^{4}	3x10^{-18}	800
	3	0.2	219	164	3x10^{-17}	150
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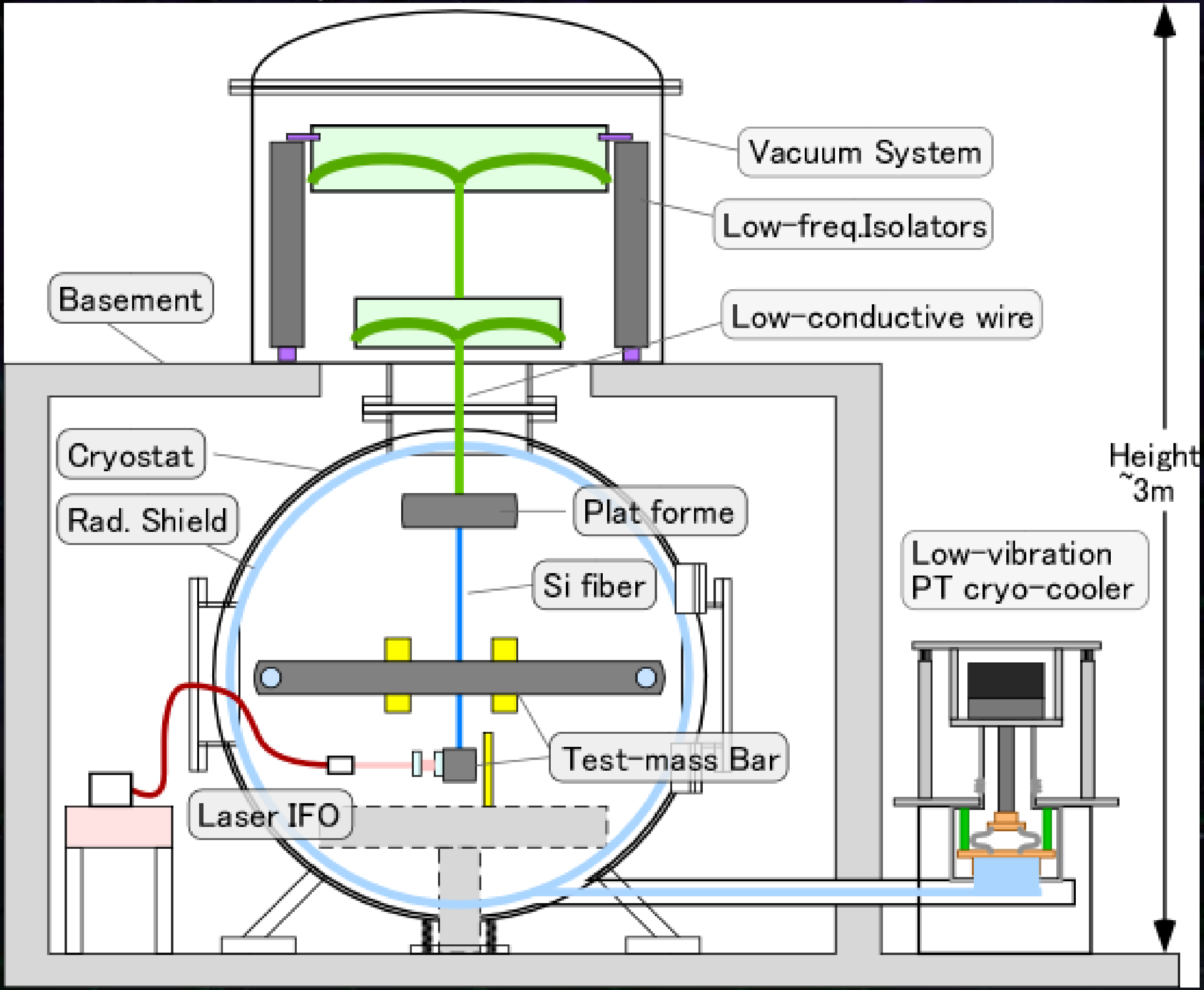
	3	0.2	219	164	6x10^{-18}	350
	1	0.15	41	3.4	3x10^{-17}	50
	[m]	[m]	[kg]	[kg・m^{2}]	[1/Hz$^{1/2}$ @0.1Hz]	[Mpc]

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

Medium-scale TOBA design

- Under discussion, but probably ... Cryo. with 1-m scale



Summary

Summary (1/2)

- Novel type GW detector : TOBA

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

  - Observable Range >10Gpc for BH inspirals.
  - Rotating TOBA for lower freq. (<1mHz) GWs.

- 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 TOBA with length ~1m.
  - Low-freq. GW detector and also a NN sensor.
  - Common techniques with KAGRA, ET, ...

- Another plan by Australian group
  - Medium-scale TOBA at room temp.
  - Please ask Bram Slagmolen!

Any suggestions are welcome!

End

Backups

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 or thin bar → α = 1
Dimension less,
Independent of matter density

Tidal force
by x-mode GW

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 → α=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.

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$^{-1/2}$

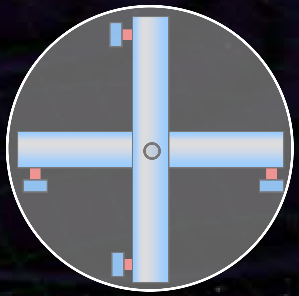
(L=10m, ϕ=0.3m)

Interferometer configuration

- Readout from reference plate

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

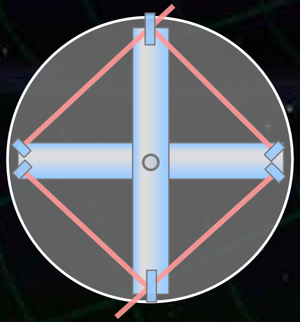
  - Independent measurement
    → Linear combination for GW signals.
  - Require a seismic-isolated reference plate.



□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



Seismic noise

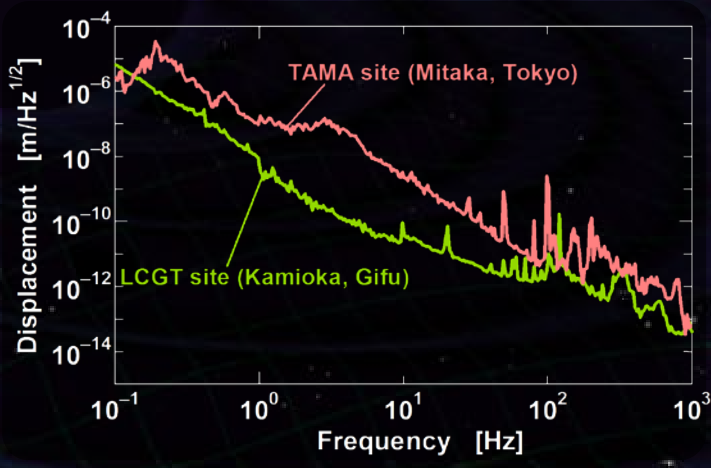
- Rotational ground motion
- Coupling from displacement DoF

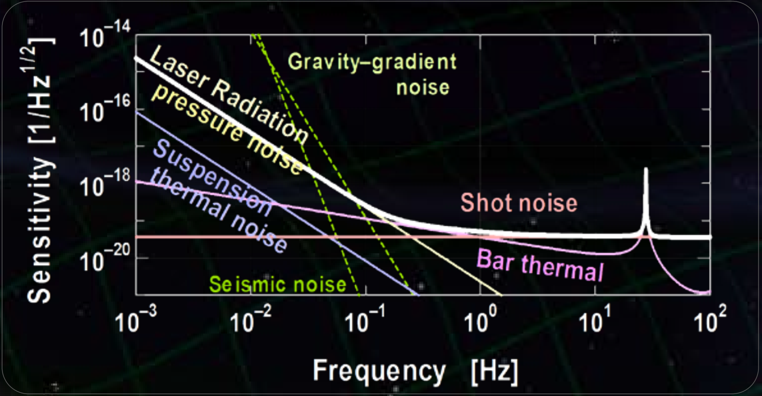
Coupling 10^{-3} or CMRR 10^{-3}

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

Horizontal : IP (10mHz) x 5 stages

Vertical : GASF ???



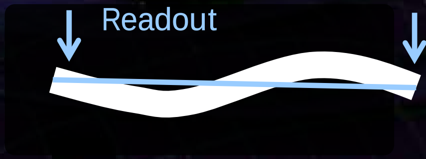


Bar thermal noise

- Thermal noise of bar mode

  Differential readout at the edges

  →Contribution of odd modes

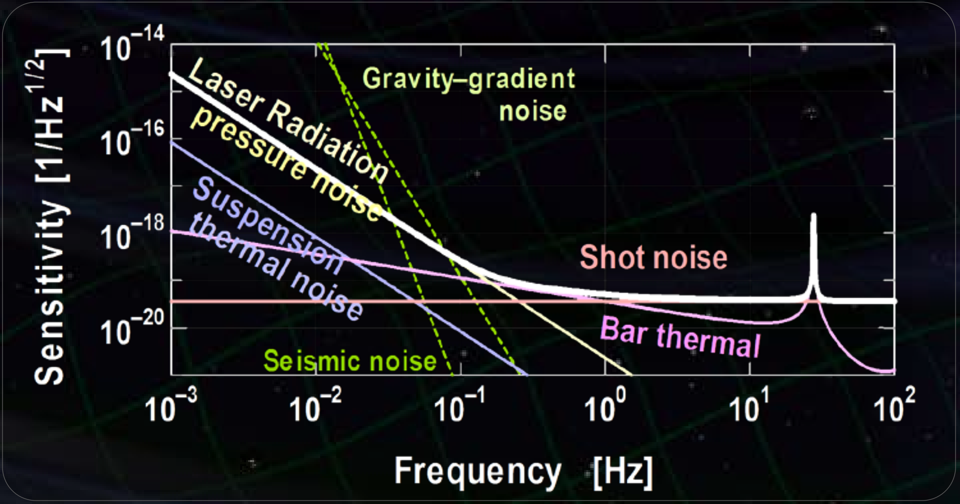


Aluminum bar (7.6 ton)

length 10 m, ϕ0.3 m

Temp. 4K, Q 10^7

⇨ 8×10^{-20} 1/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)

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

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

Detector response

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

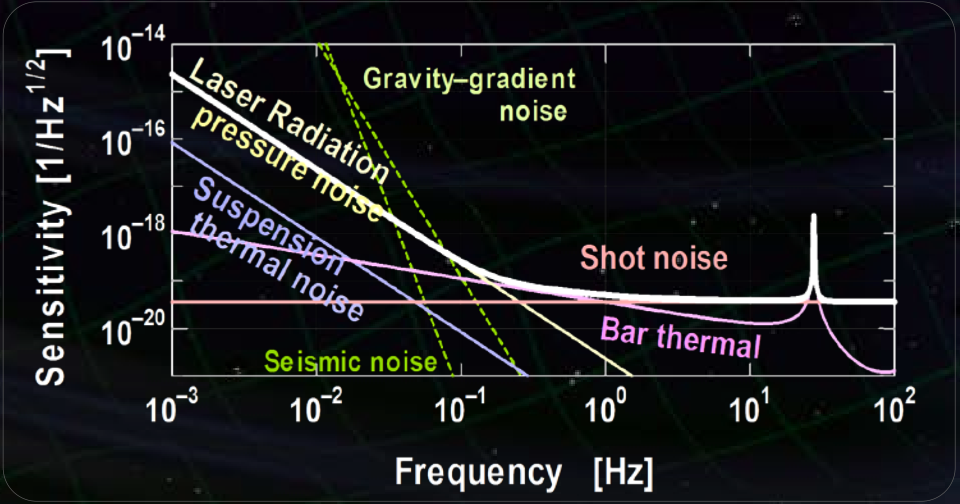
$$(\omega_0 = \sqrt{\kappa/I}, \quad Q = I\omega_0/\gamma)$$

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

- Momentum of inertia

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

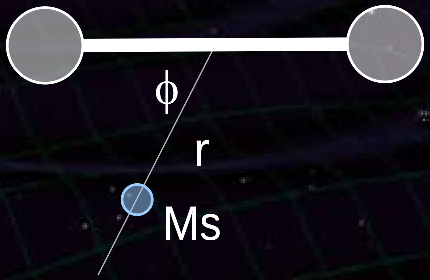
Cryogenic suspension, Temp. 4K, γ 10^{-10}



Gravity gradient noise

- Newtonian 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)

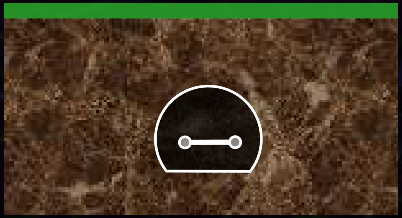
(Ex.) Human activity

Ms=100 kg, r=10m,
$\phi=\pi/2$, f=0.1Hz, a= 0.1m ⇨ δh ~ 2×10^{-12}

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.

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	1.37x10^{4}	2x10^{-17}	70
	3	0.2	219	164	2x10^{-16}	7
	1	0.15	41	3.4	1x10^{-15}	1
	[m]	[m]	[kg]	[kg·m^{2}]	[1/Hz$^{1/2}$ @1mHz]	[Gpc]

※ Acceleration noise is not included.

Discussions

New motivations for GW research field...

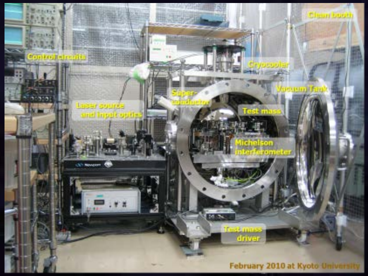
- Optical readout noise
- Low freq. seismic isolation and reduction of Newtonian noise.
- Material, bar shape, and thermal noise
- Cryogenic system

- 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

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/Hz$^{1/2}$] at 0.1Hz

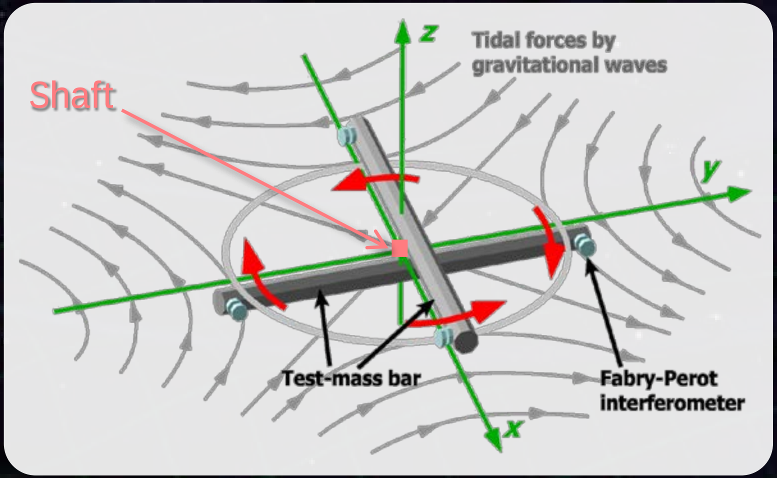
⇨
- Silicon test mass,
- Differential measurement using two orthogonal bars.
- Isolation system : LCGT type-B SUS, placed at an under ground site.

	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/Hz$^{1/2}$ @0.1Hz]	[Mpc]

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.



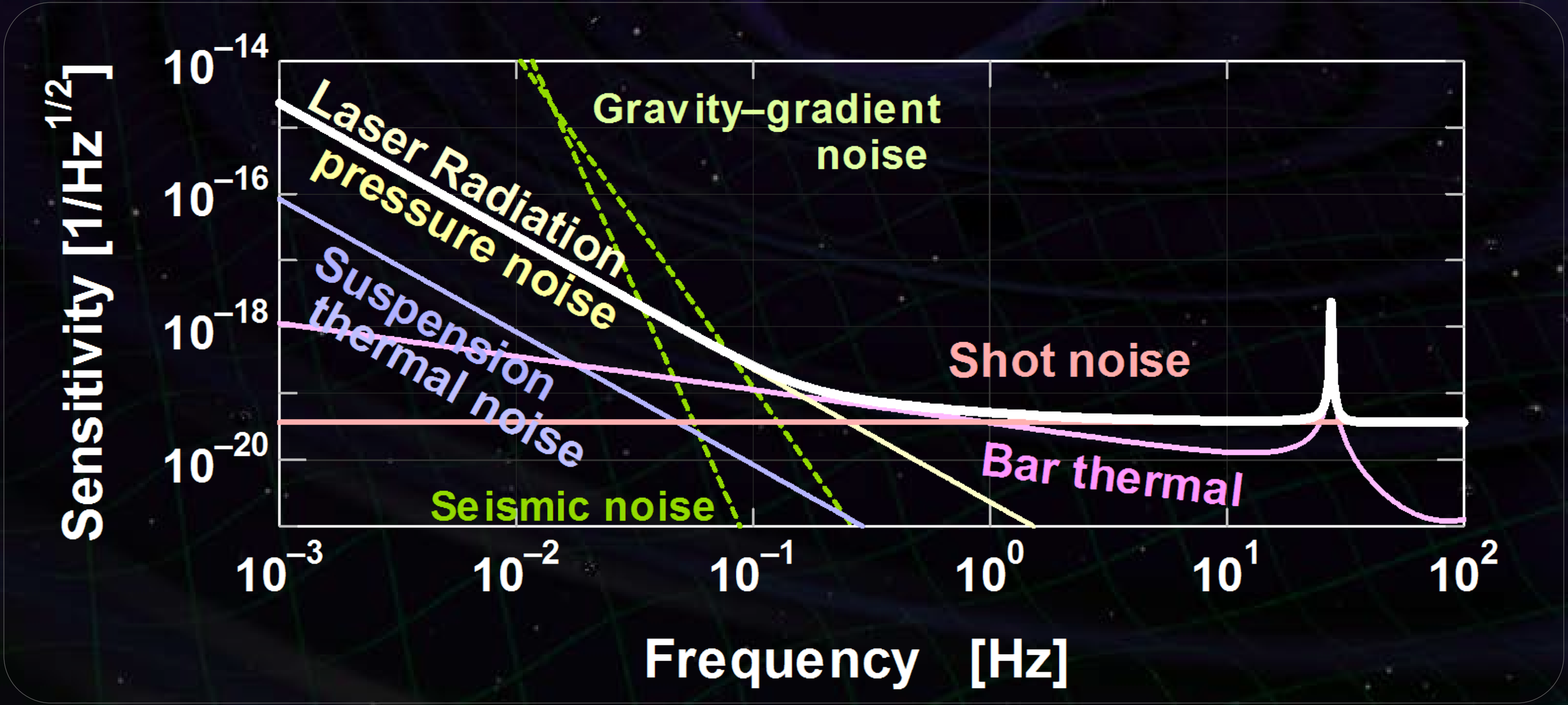
□Thermal noise level

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

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

Fundamental noise level of TOBA

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



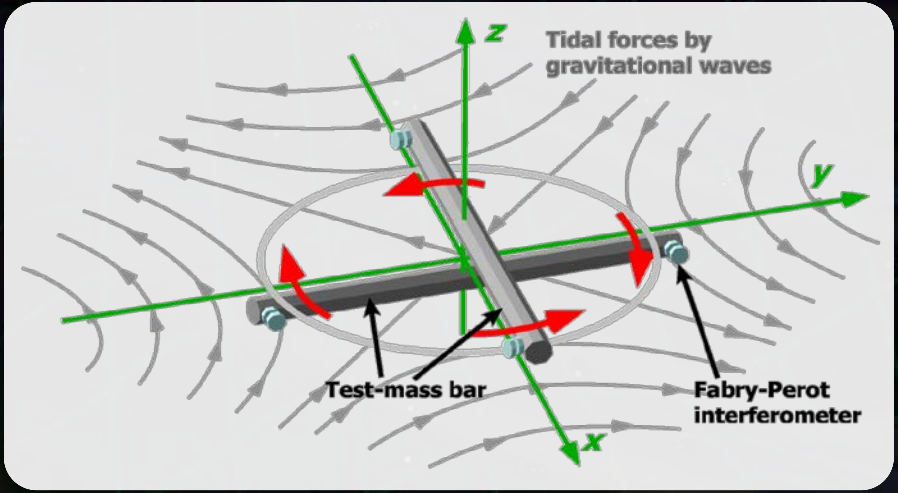
Bar length : 10m, Mass : 7600kg
Laser source : 1064nm, 10W
Cavity length : 1cm, Finesse : 100
Bar Q-value : 10^5 , Temp: 4K
Support Loss : 10^{-10}

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

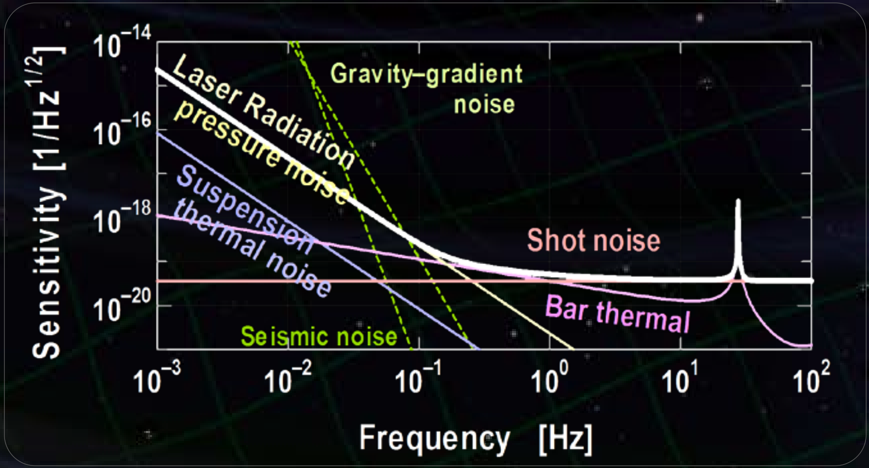
Optical readout noise

- 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

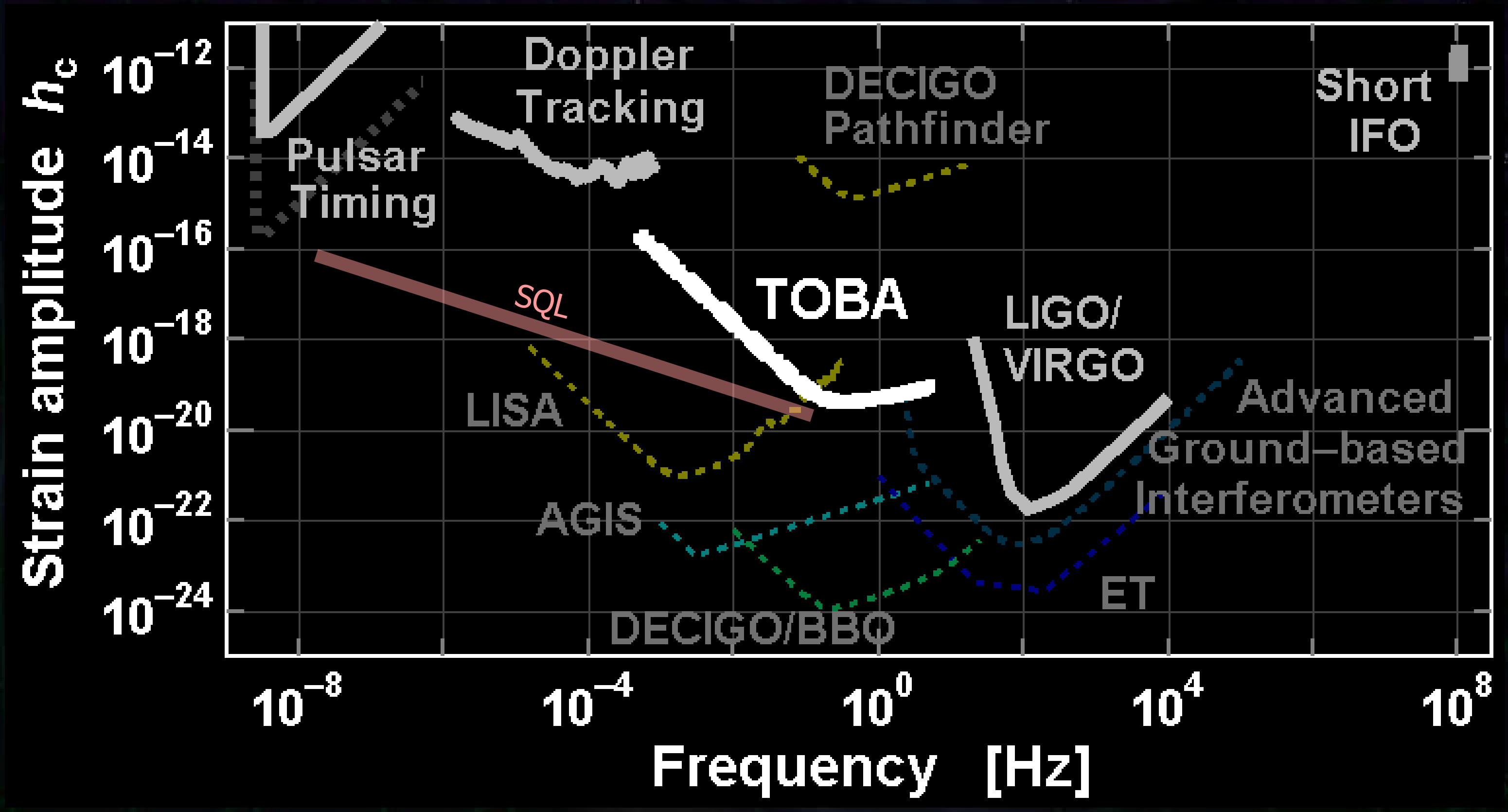


TOBA Sensitivity

Comparison with the other detectors

DECIGO/BBO band:

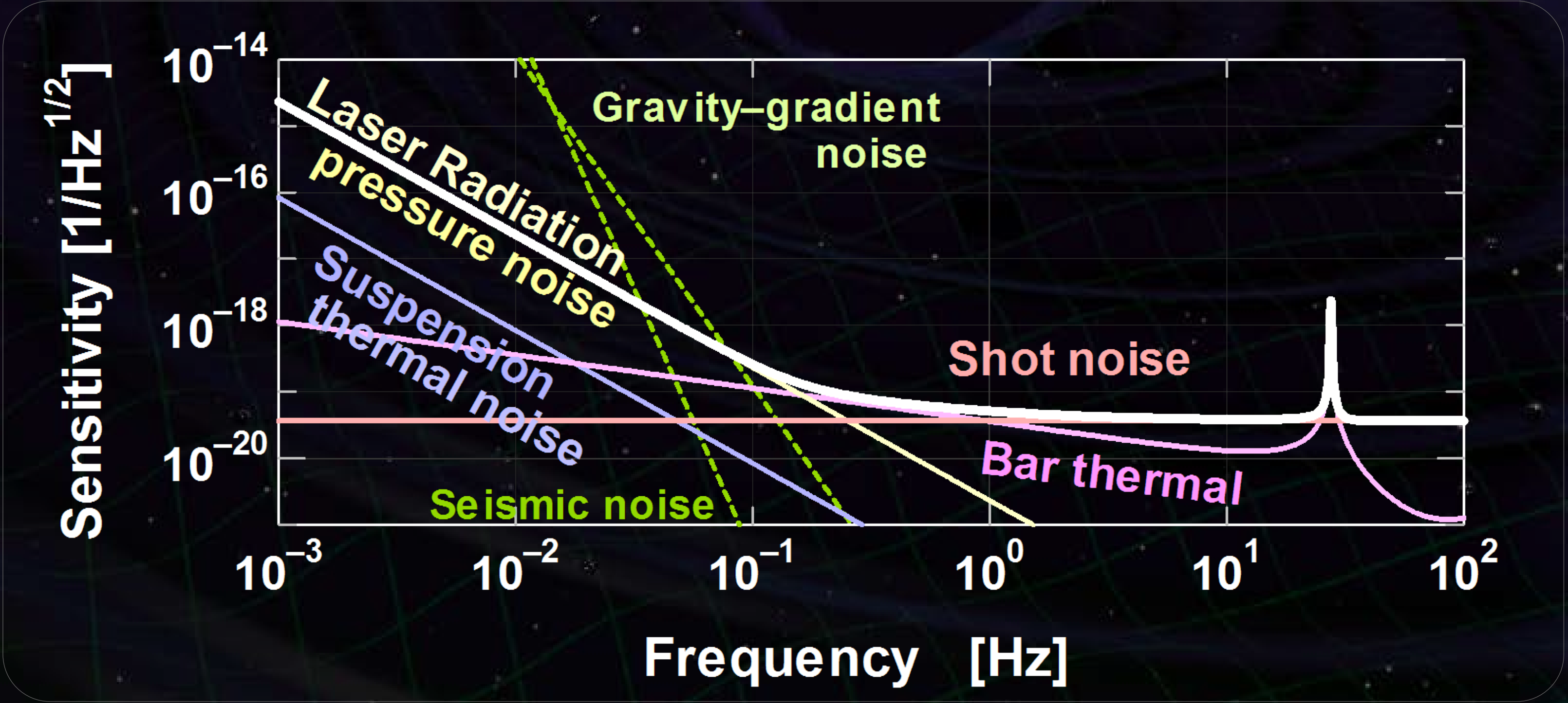
Between ground-based detectors and LISA bands



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

Fundamental noise level of TOBA

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



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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

Chirp waveform

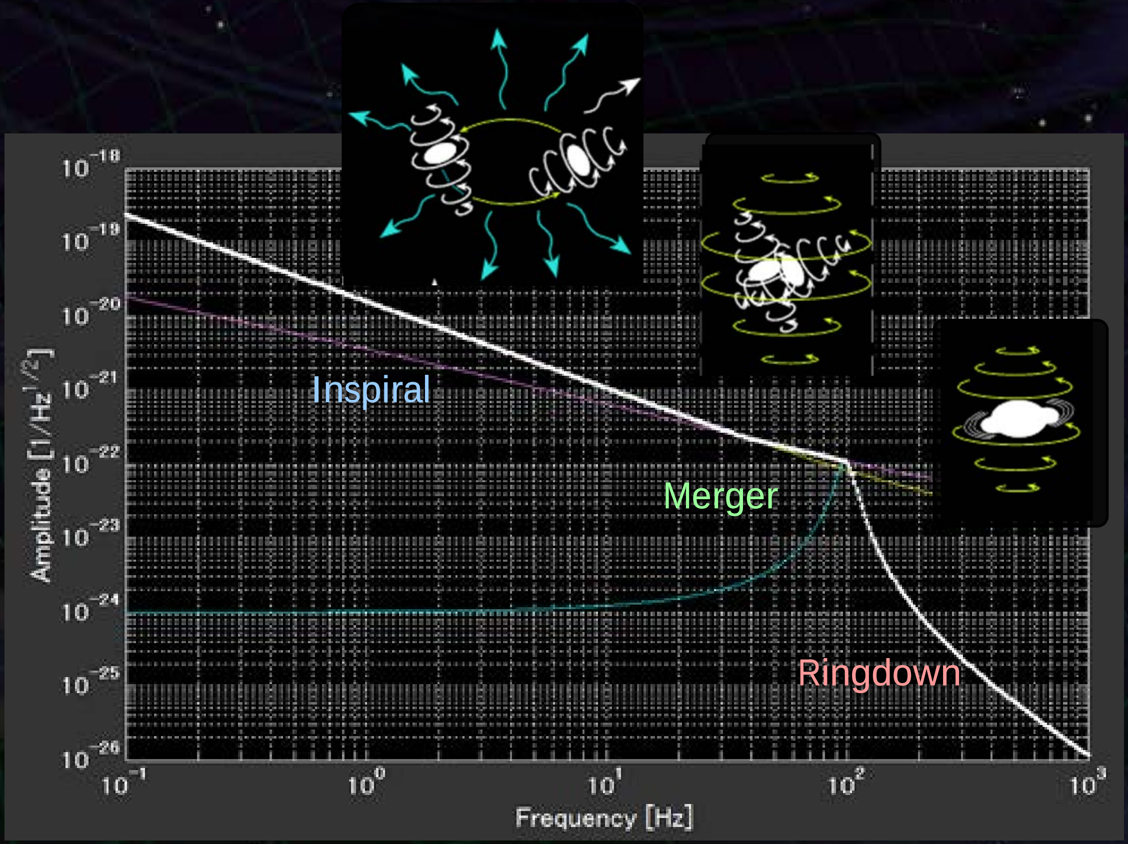
- Phenomenological waveform by numerical simulation

(Ajith+ arXiv 0909.2867)

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

GW from BH merger

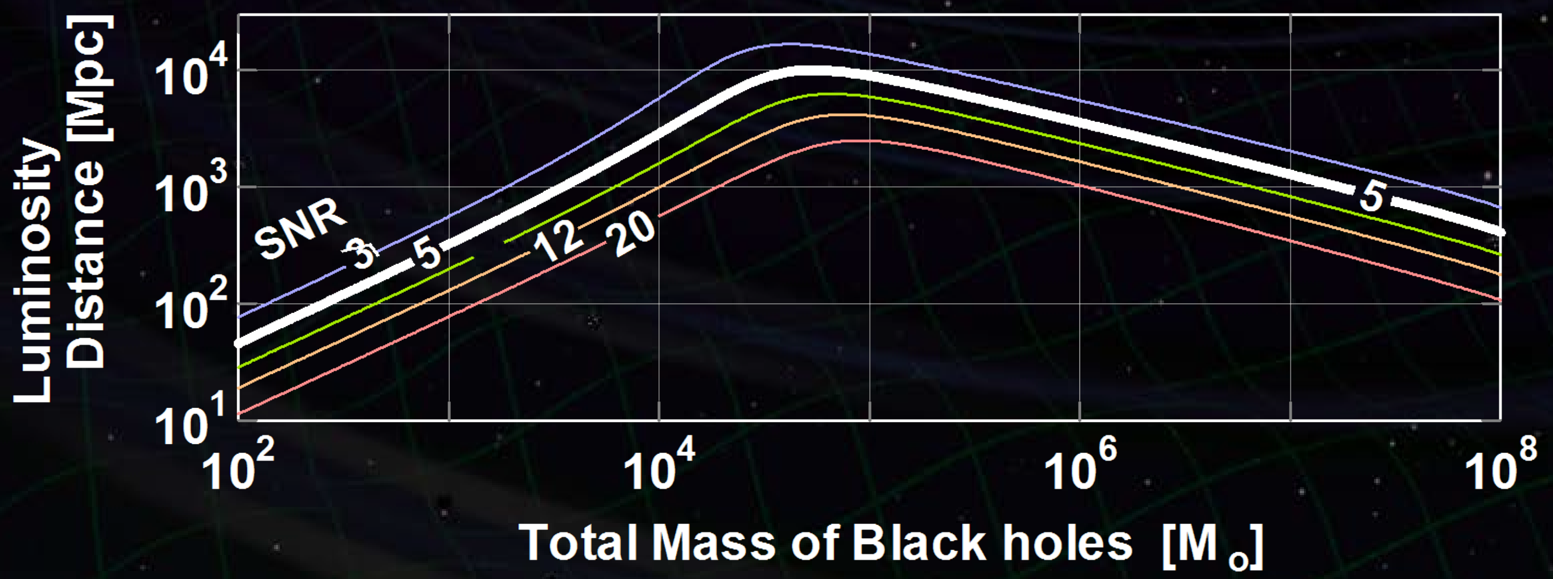
- 100 Msolar equal mass
- Spin parameter 0.5
- Distance 100 Mpc



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

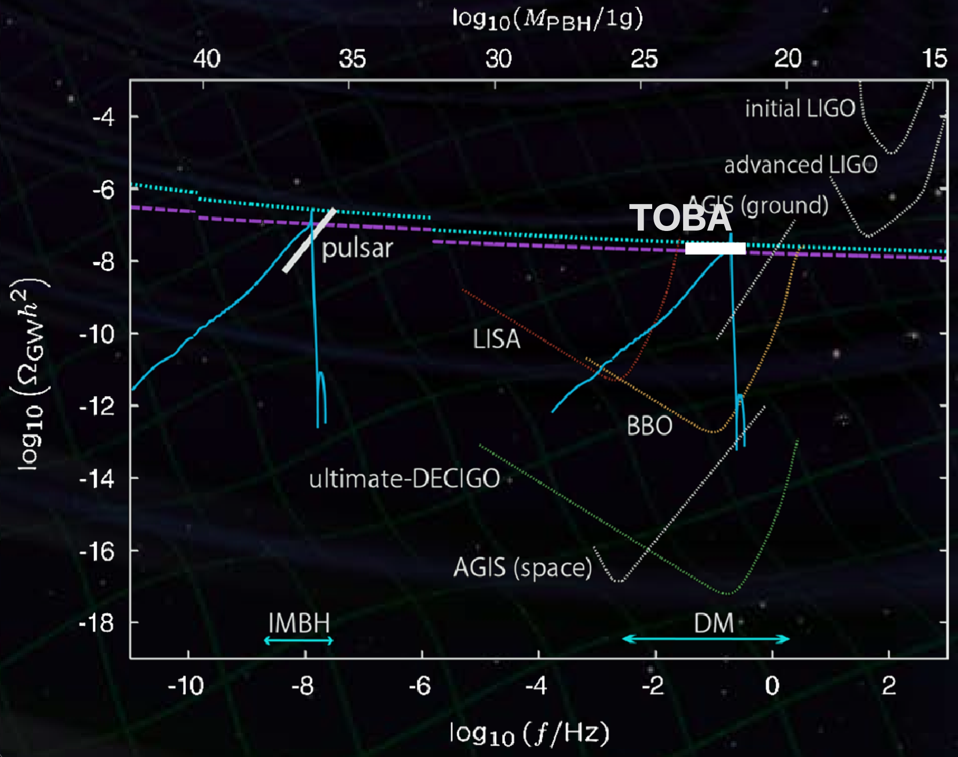
$$\Omega_{\mathrm{gw}} \sim 10^{-7}$$

(1-yr obs. by 2 TOBAs)

Beat BBN upper limit

GW by primordial tensor perturbation

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



Sensitivity by R-TOBA

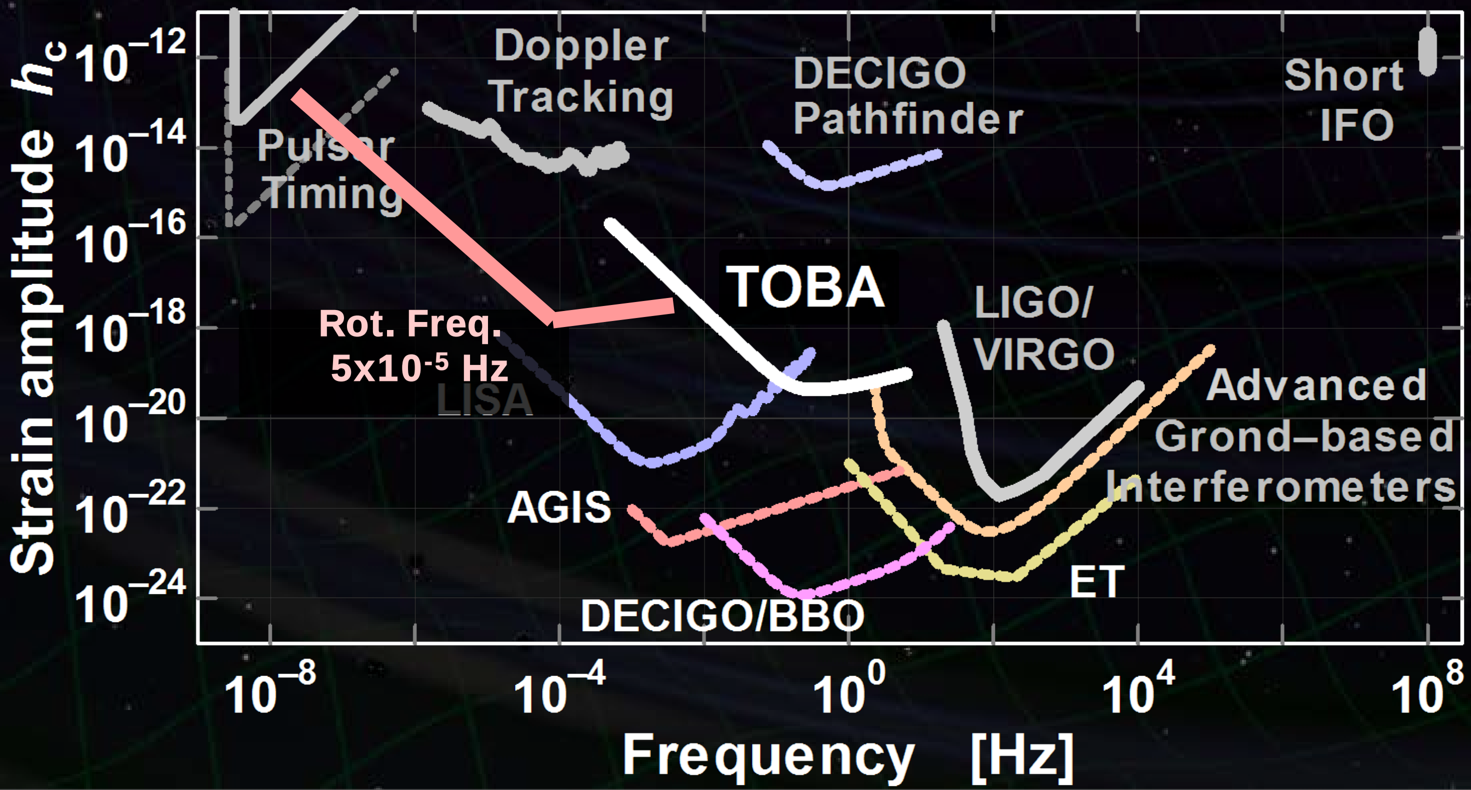
Sensitivity example

Rotation freq. 5x10^{-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}



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

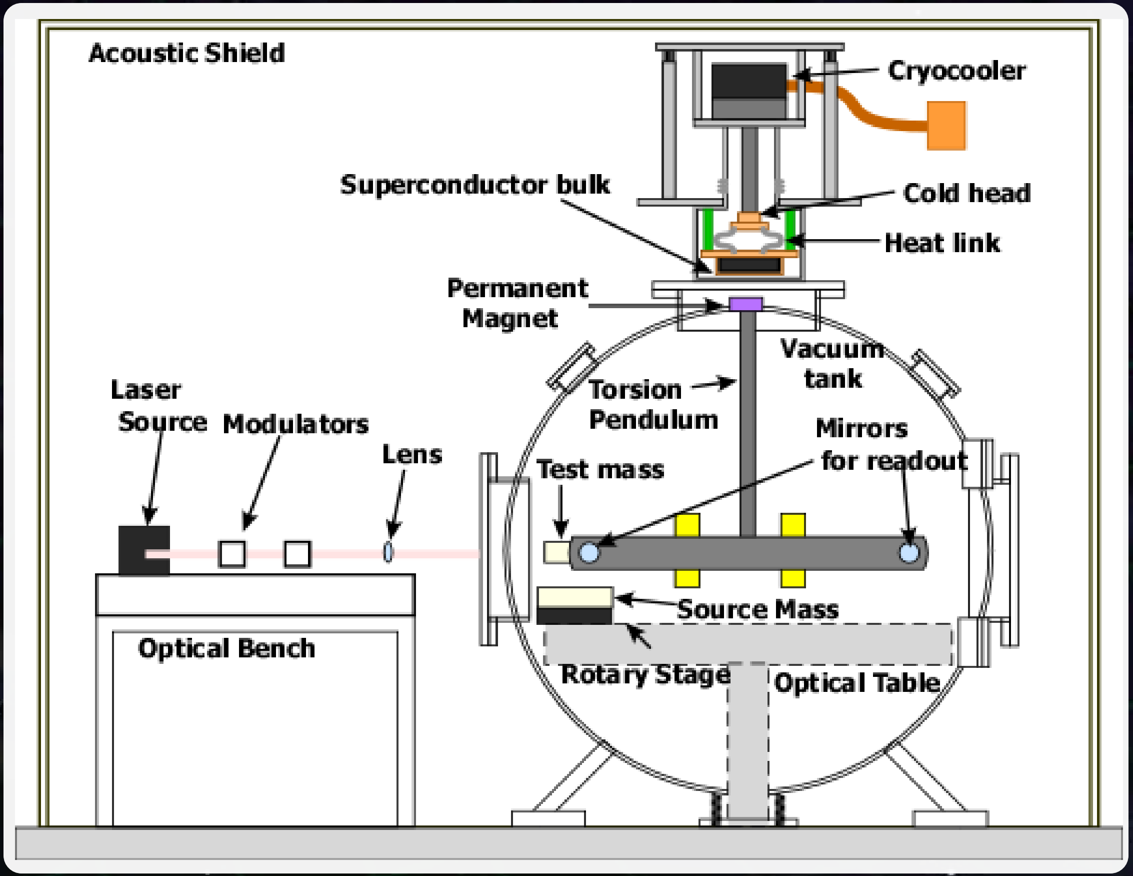
  Low-vibration cryo-cooler

  Operation temp. ~65K

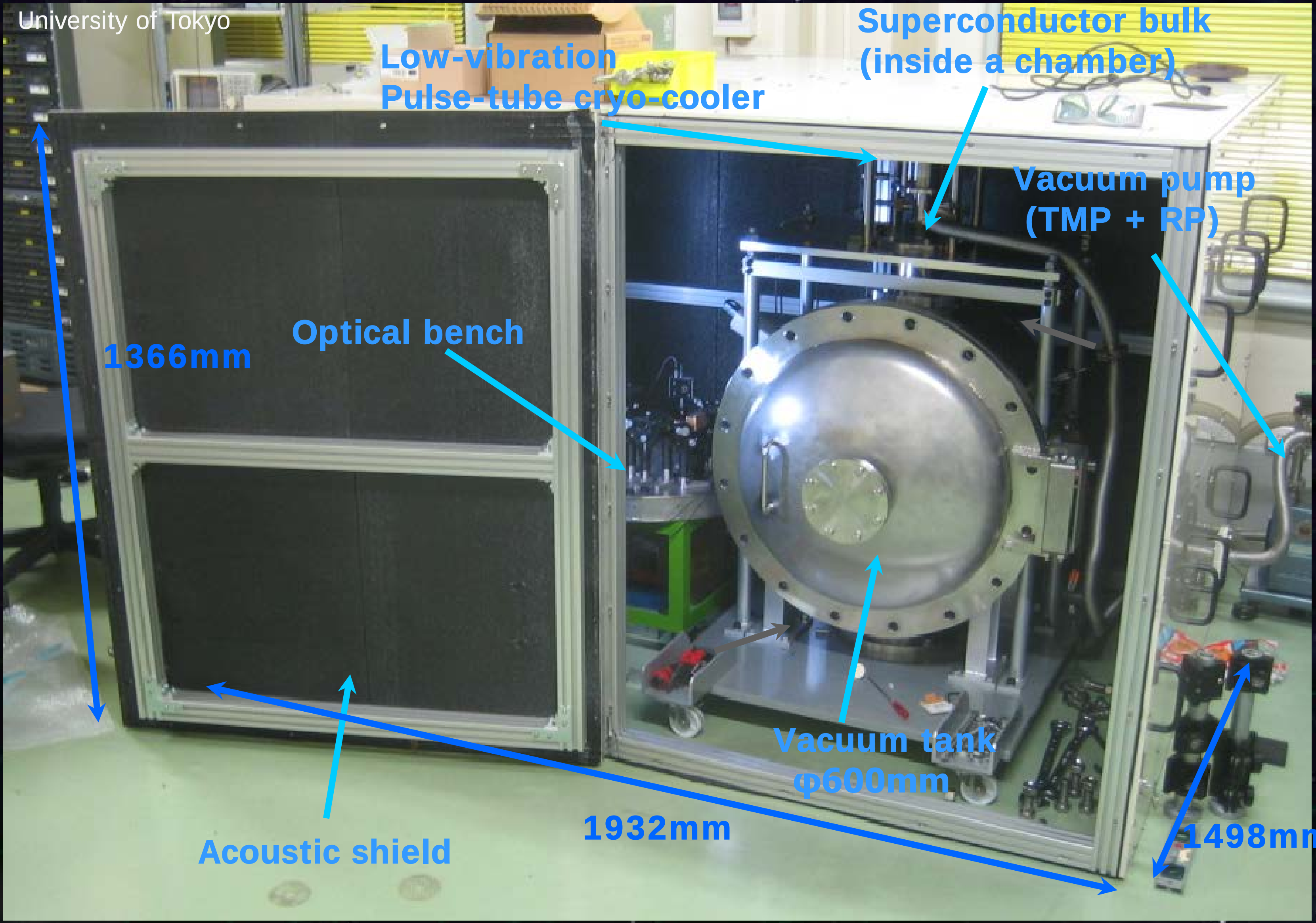
- Vacuum system

  Pressure 10^{-5} Pa by TMP+RP

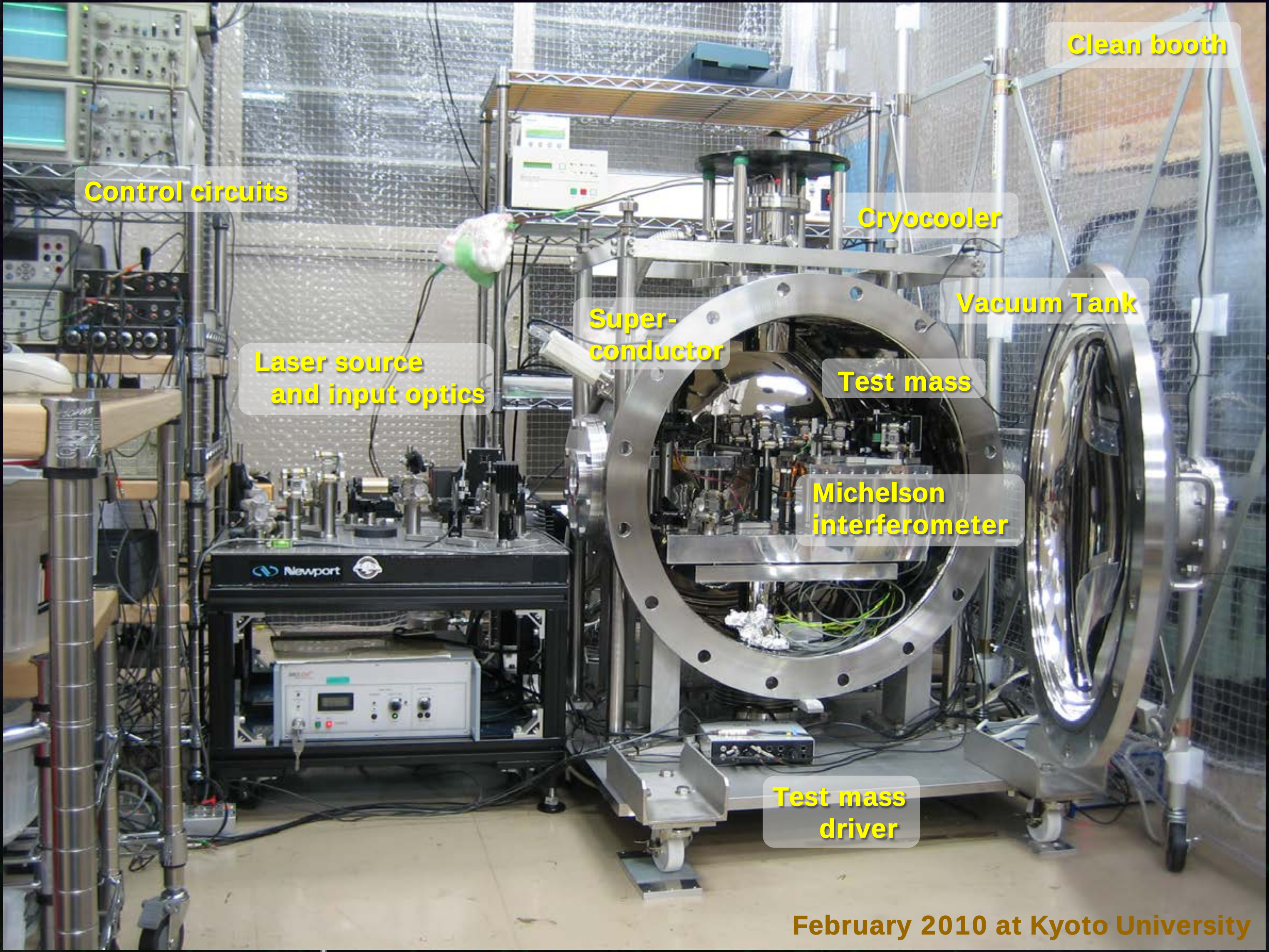
  Acoustic shield enclosure



Small-scale TOBA at Tokyo



Small-scale TOBA at Kyoto

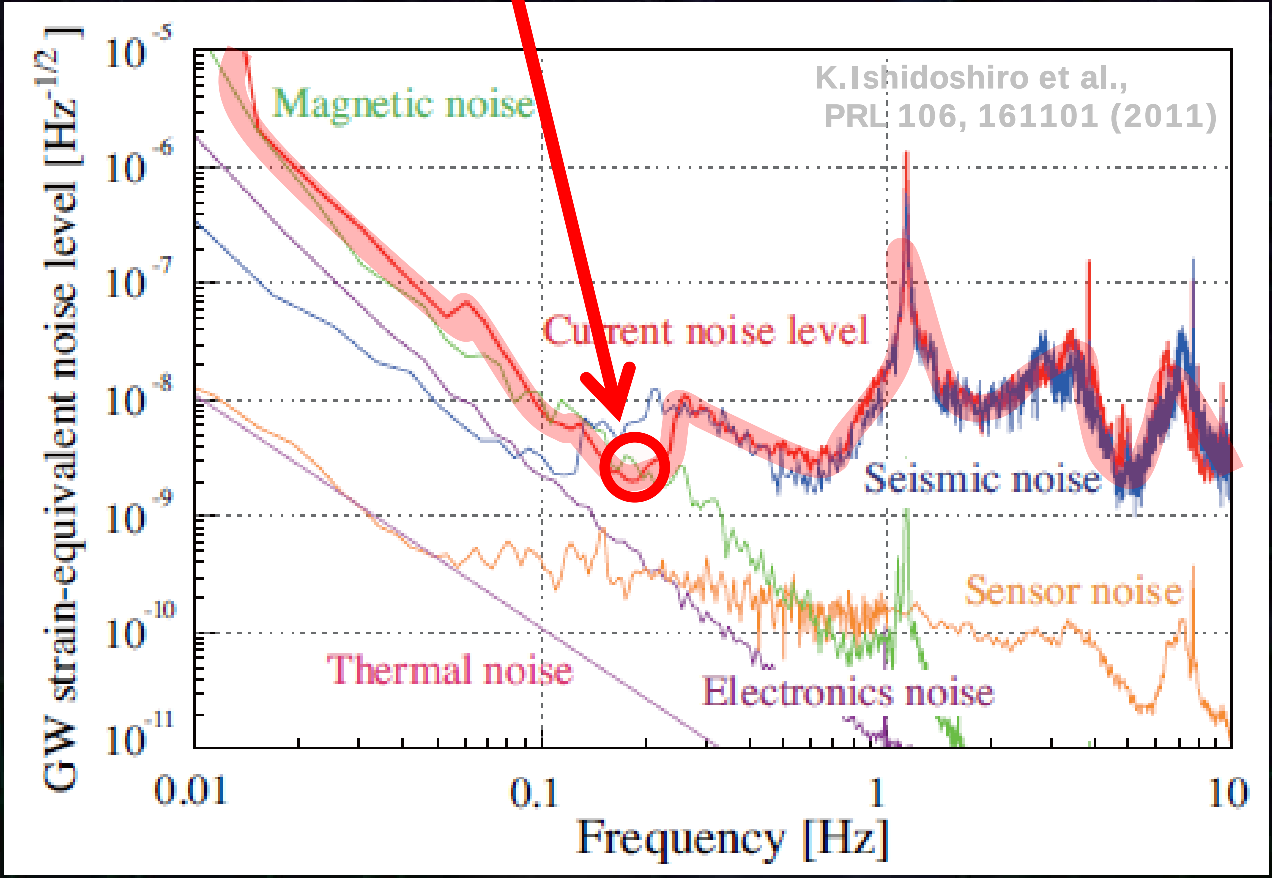


February 2010 at Kyoto University

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

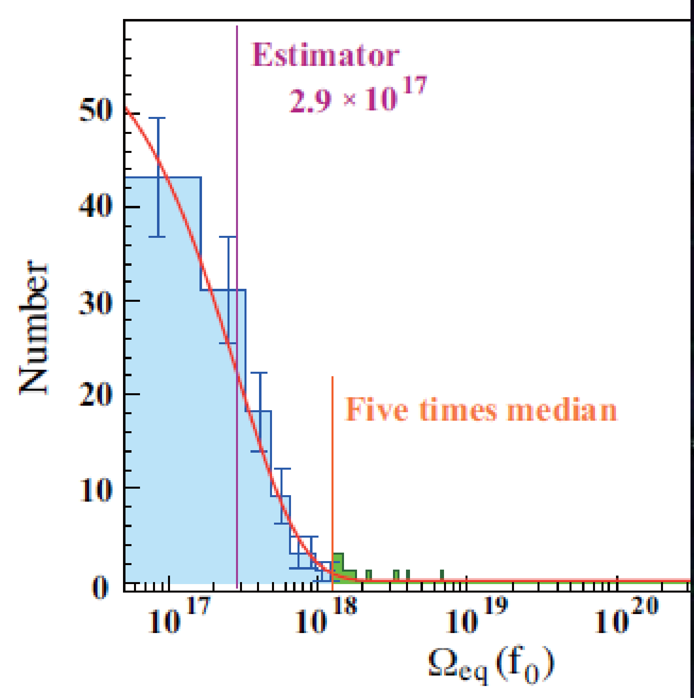
$$\Omega_{\rm eq}(f_0) = \frac{10\pi^2}{3H_0^2} f_0^3\, \tilde{h}^2(f_0)$$

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

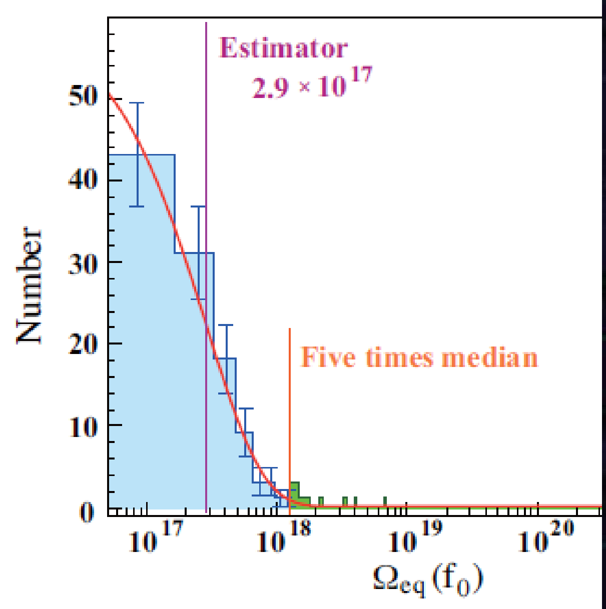
- Distribution → Averaged power at 0.2Hz

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

⇨ 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 (δh/h ~ 10%) and the other systematic errors.



Some details...

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

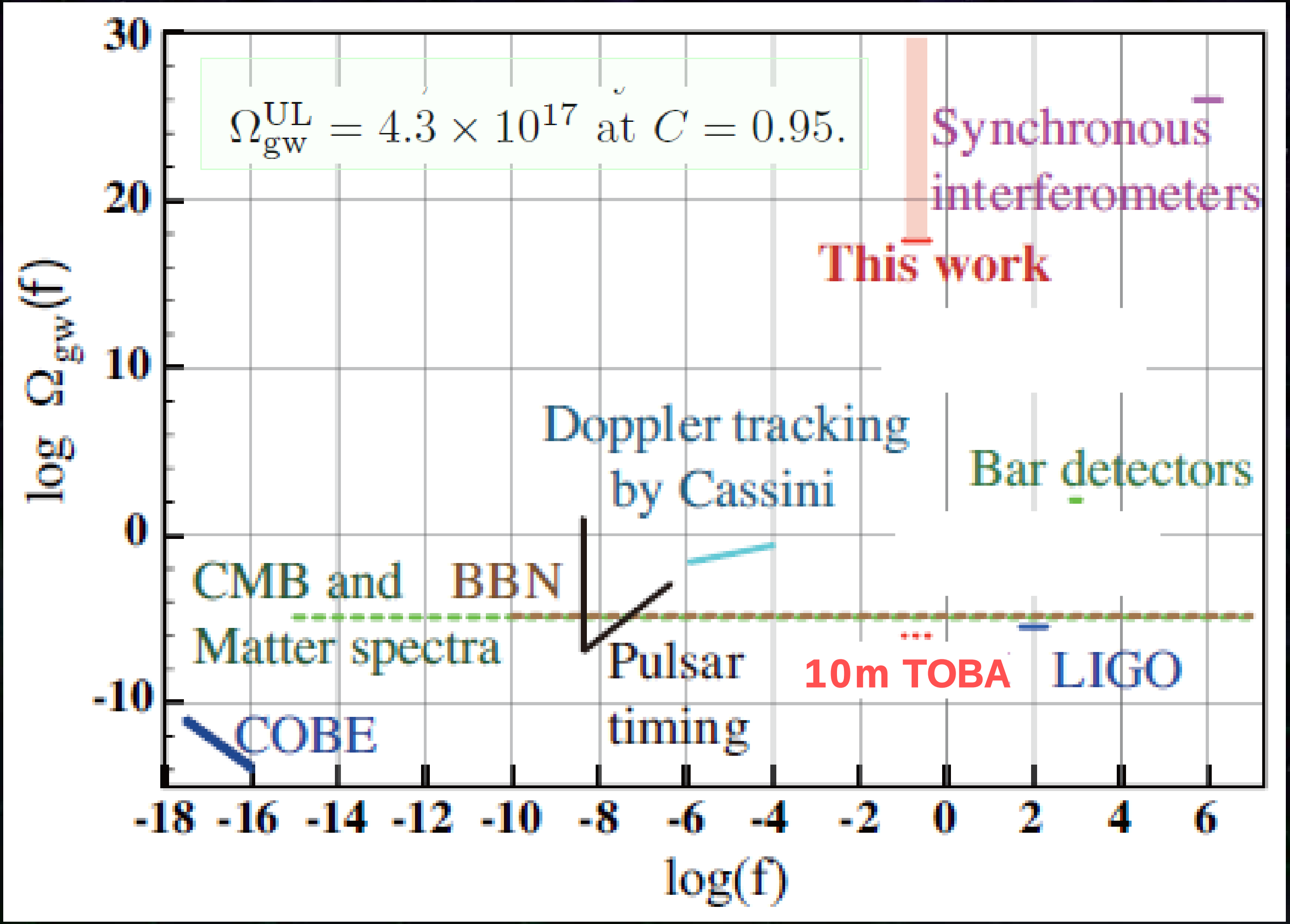
$$C = \int_{\overline{\Omega_{\mathrm{eq}}}}^{\infty} P(\Omega_{\mathrm{es}}|\Omega_{\mathrm{gw}})\, d\Omega_{\mathrm{es}}$$

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



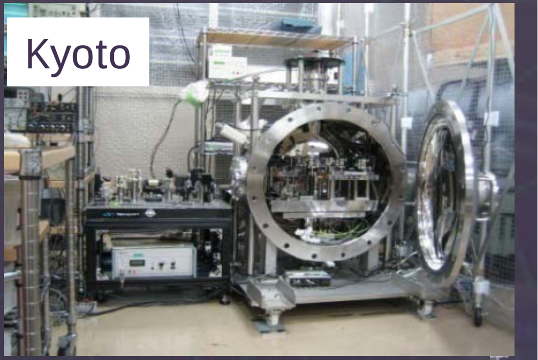
Observation with two detectors

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

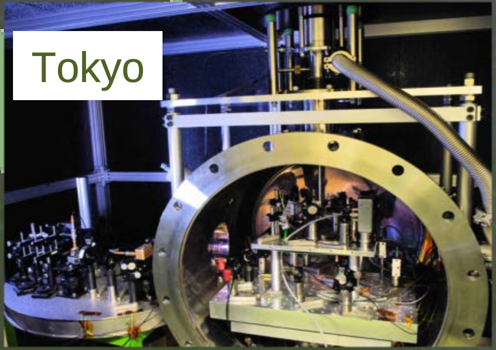
Comparable sensitivity, Separation : 370km

⇨ 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)

Observation with two detectors

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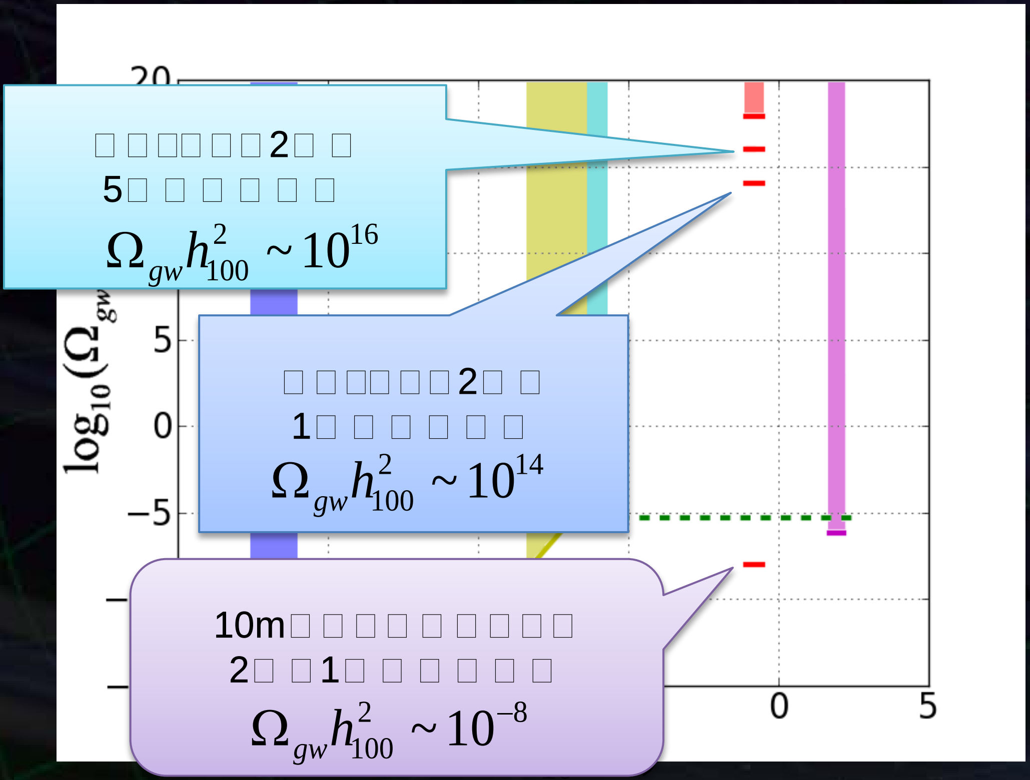
$$\sqrt{T_{\rm obs}\ \Delta f_{\rm obs}}$$

□ □ □ □ □ .

Fig. By A.Shoda



□ □ □□ □ □ 2□ □
5□ □ □ □ □ □ □
$\Omega_{gw}h_{100}^2 \sim 10^{16}$

□ □ □□ □ □ 2□ □
1□ □ □ □ □ □ □
$\Omega_{gw}h_{100}^2 \sim 10^{14}$

10m□ □ □ □ □ □ □ □ □ □
2□ □1□ □ □ □ □ □ □
$\Omega_{gw}h_{100}^2 \sim 10^{-8}$

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)

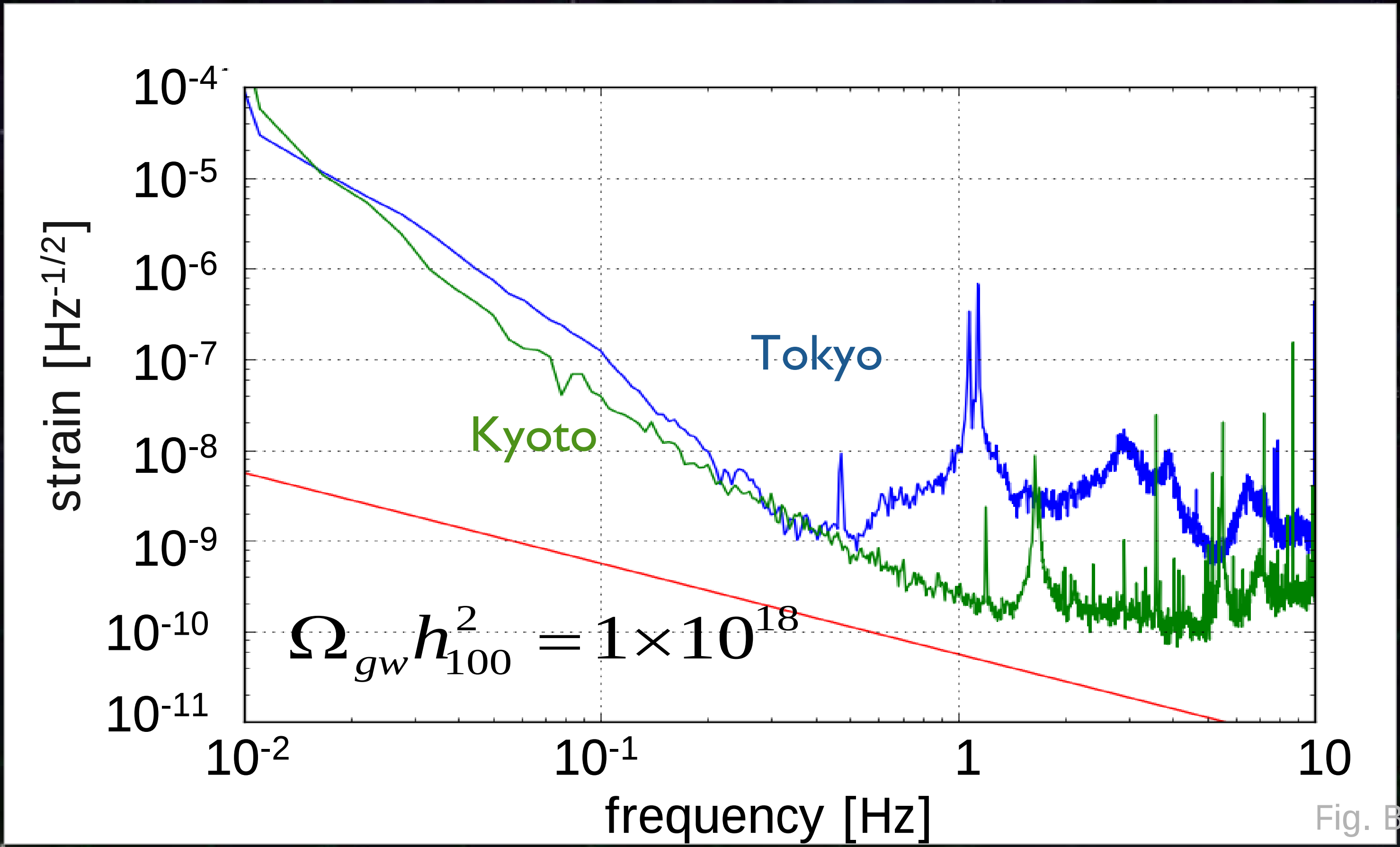


Fig. By A.Shoda

結果の見通し

□ □ □ □ □ (2010□ 7□) □ □ □ □ □ □ □ .

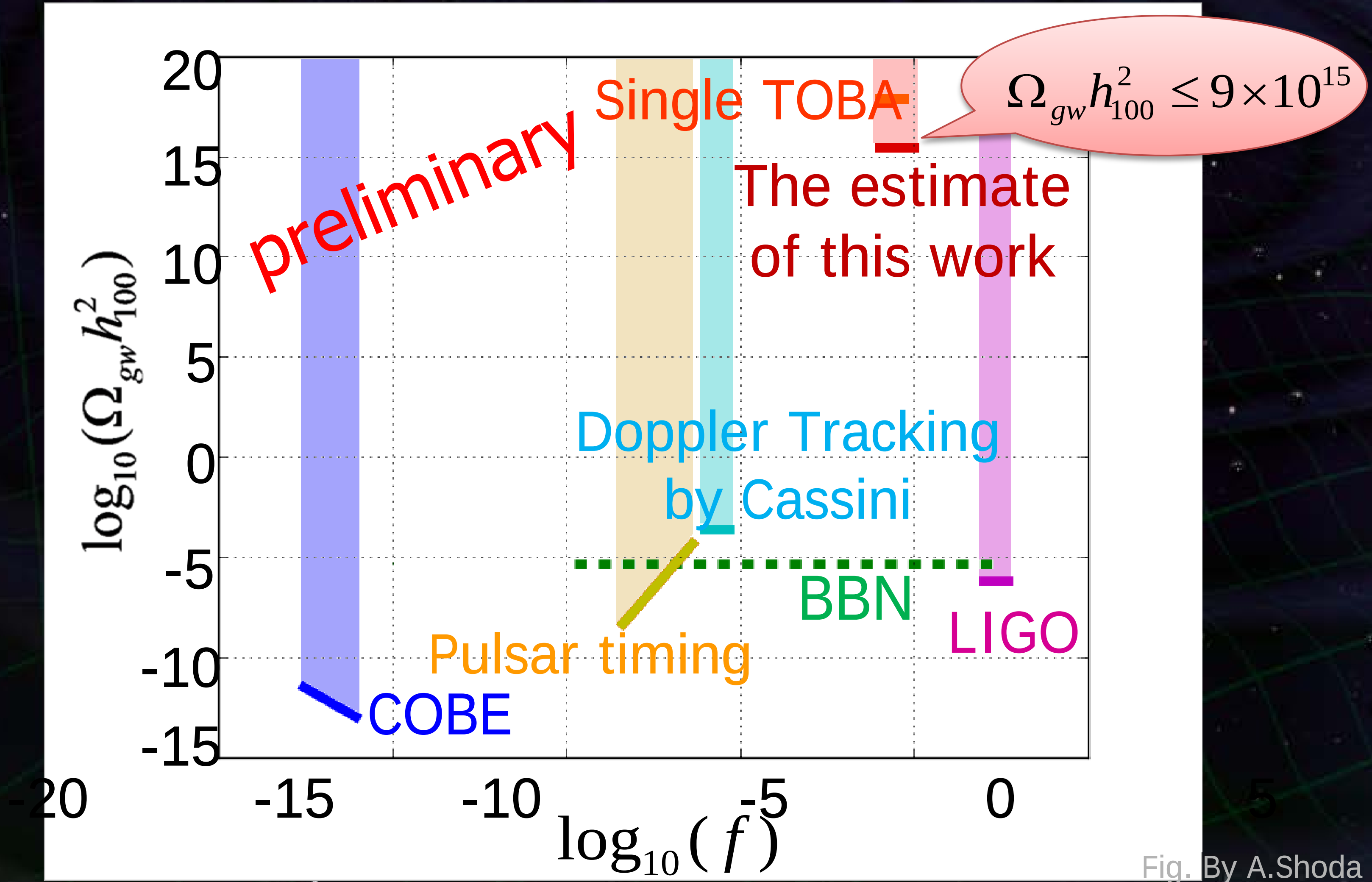
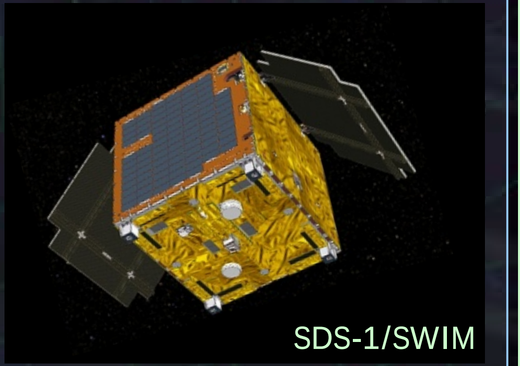
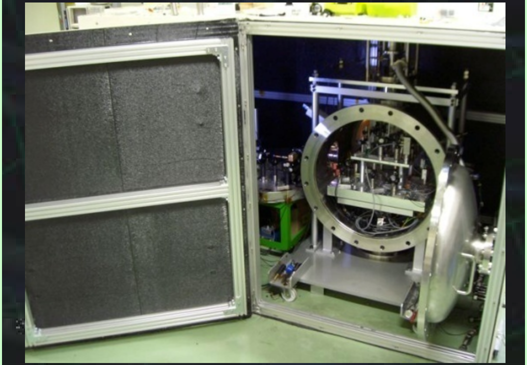
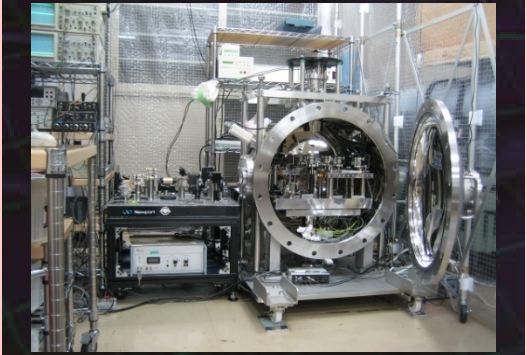


Fig. By A.Shoda

プロトタイプ

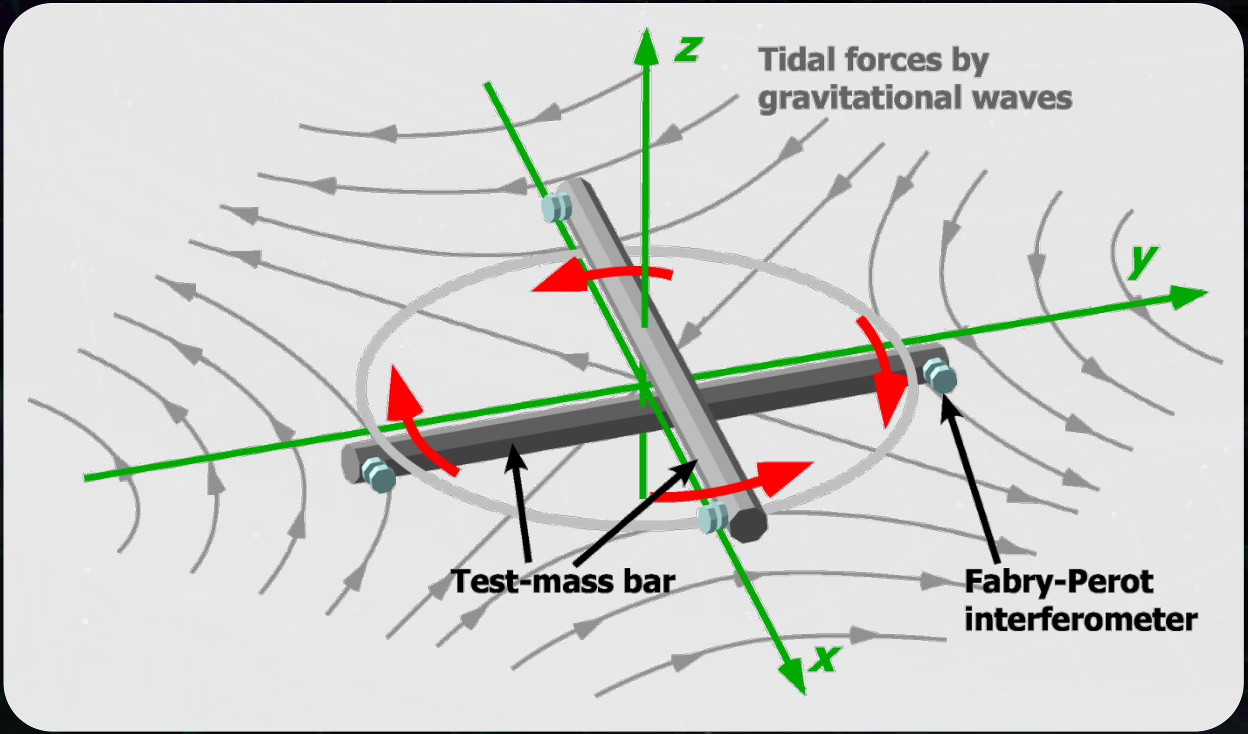
2つの地上装置, 1つの衛星搭載モジュール

	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-)
	 SDS-1/SWIM		
	質量 50g, 長さ 5cm	質量 150g, 長さ 20cm	質量 340g, 長さ 25cm
試験マス	無重力浮上 +制御	超電導磁気浮上 +制御	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

Rotating TOBA

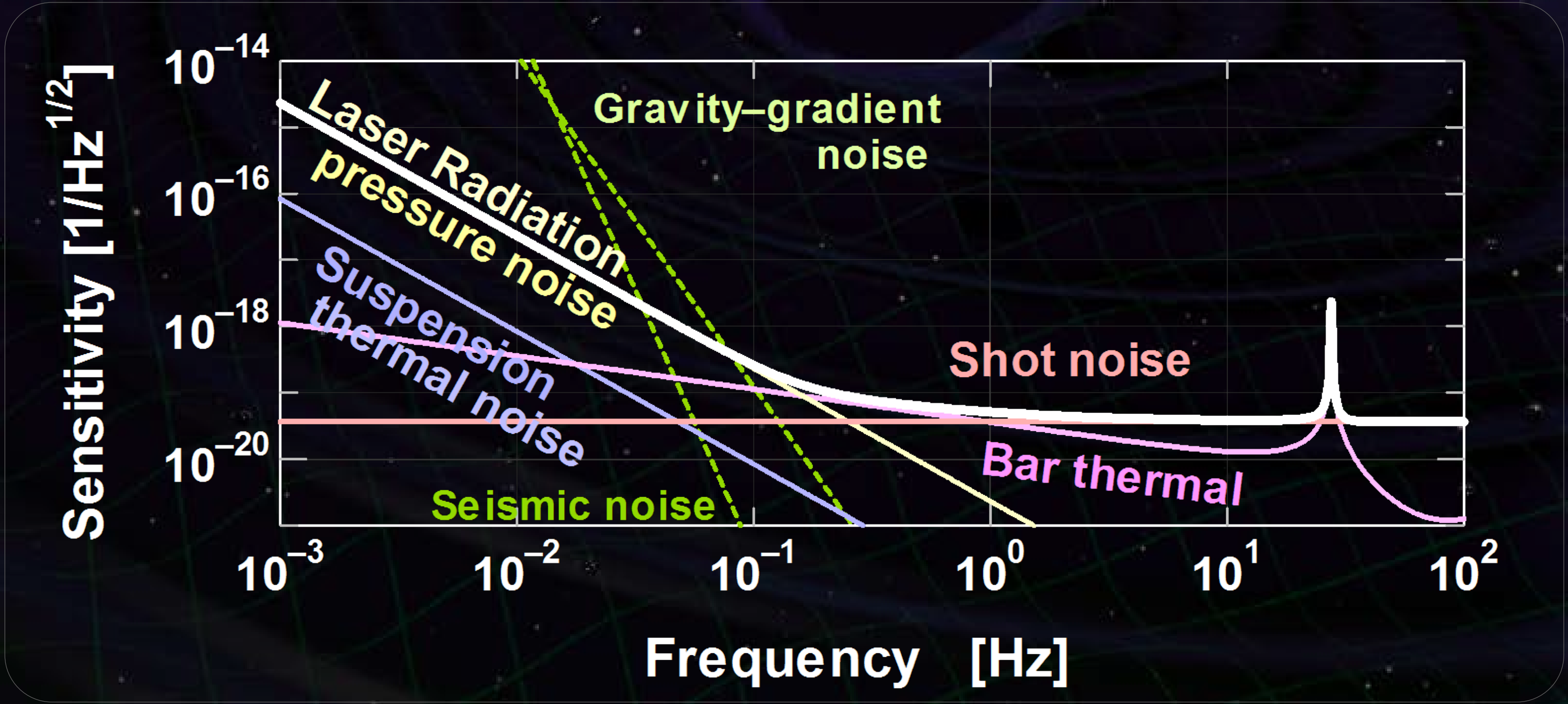
Rotate the detector along its axis

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



Fundamental noise level of TOBA

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

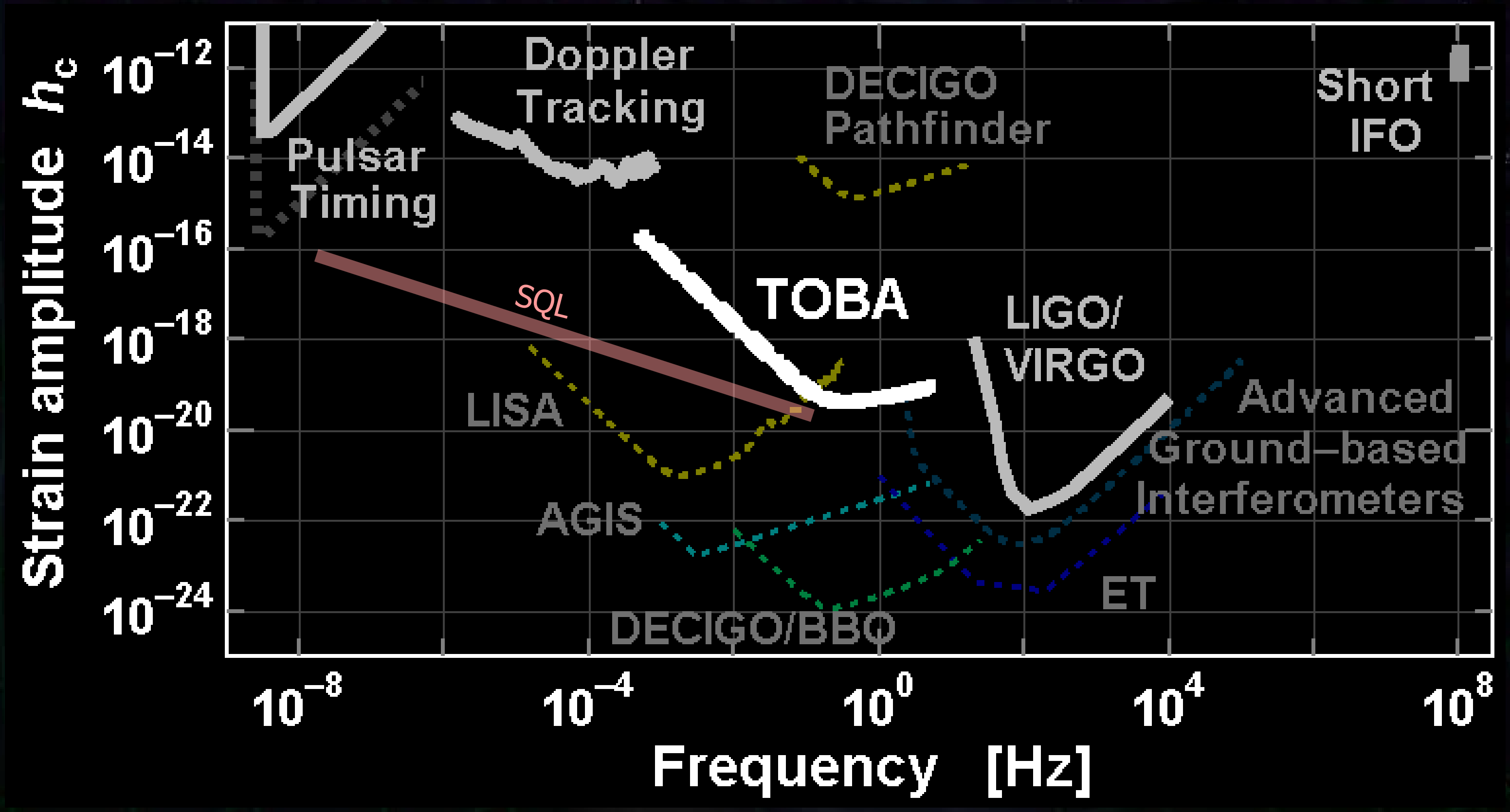
Laser Freq. noise < $10\mathrm{Hz}/\mathrm{Hz}^{1/2}$,
Freq. Noise CMRR>100
Intensity noise < $10^{-7}/\mathrm{Hz}^{1/2}$,
Bar residual RMS motion < 10^{-12} m

TOBA Sensitivity

Comparison with the other detectors

DECIGO/BBO band:

Between ground-based detectors and LISA bands

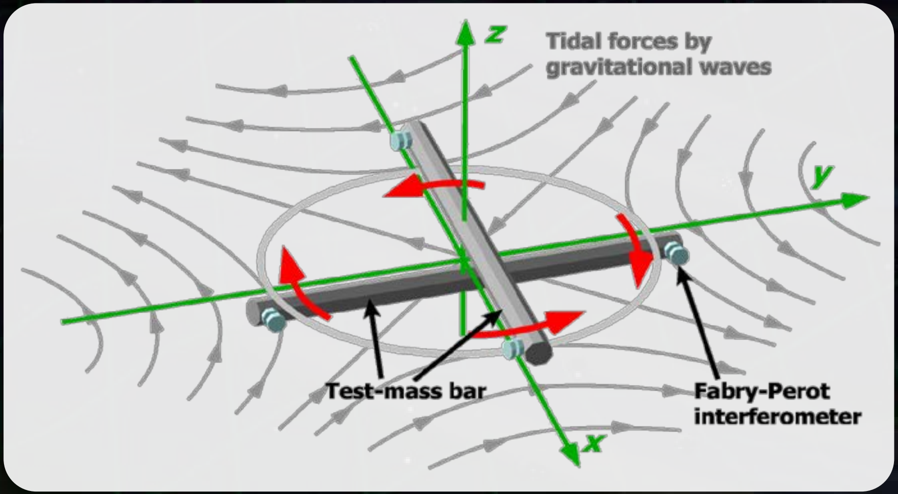


Characteristic amplitude : $h_c = \tilde{h} \times \sqrt{f_{\text{center}}}$ (Dimensionless strain)

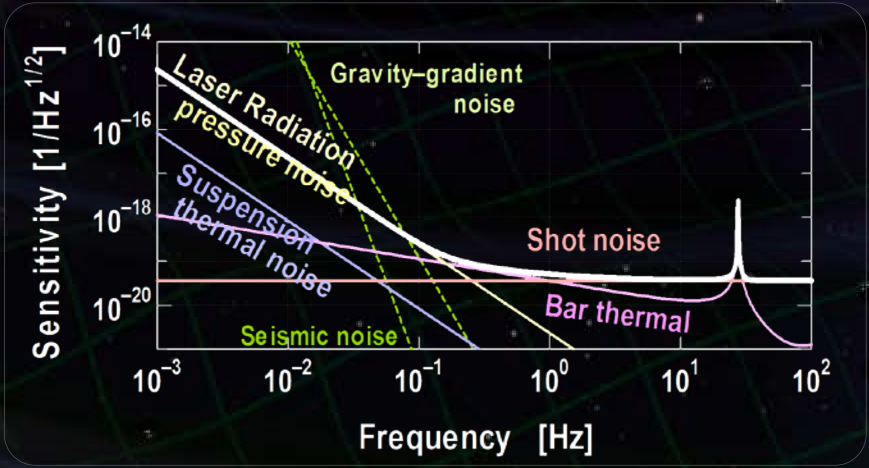
Optical readout noise

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

⇨ Shot noise + Rad. Pressure noise



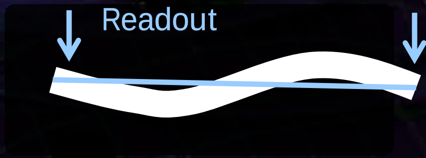
Nd:YAG 1064nm, Power 10W,
Short FP cavity, Finesse 100



Bar thermal noise

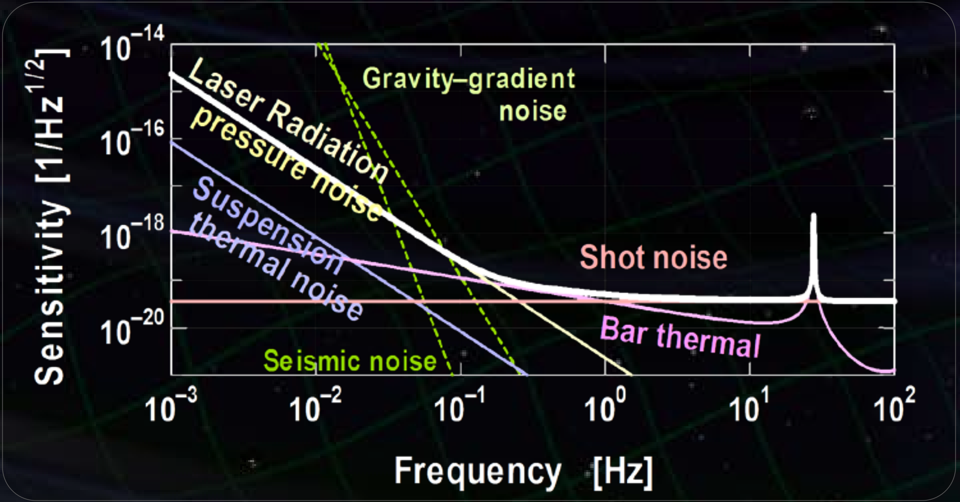
- Thermal noise of bar mode

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/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

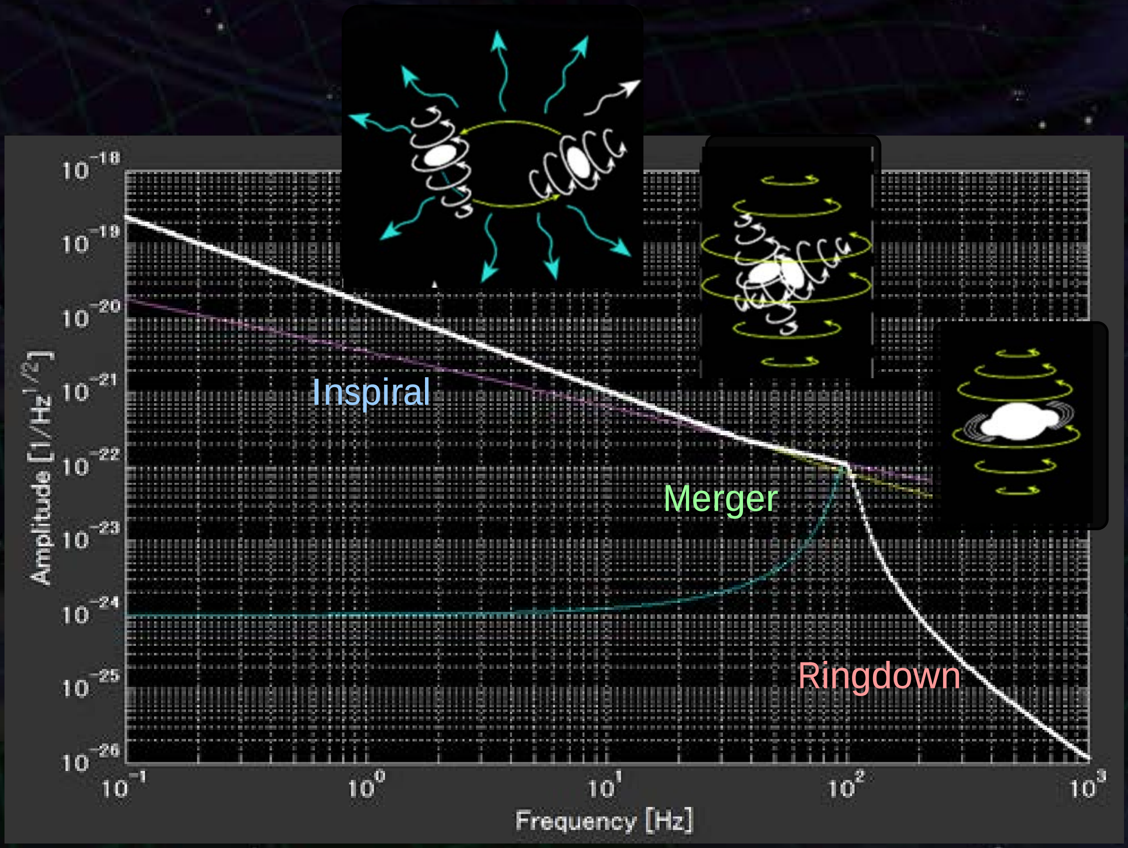
Chirp waveform

- Phenomenological waveform by numerical simulation

(Ajith+ arXiv 0909.2867)

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

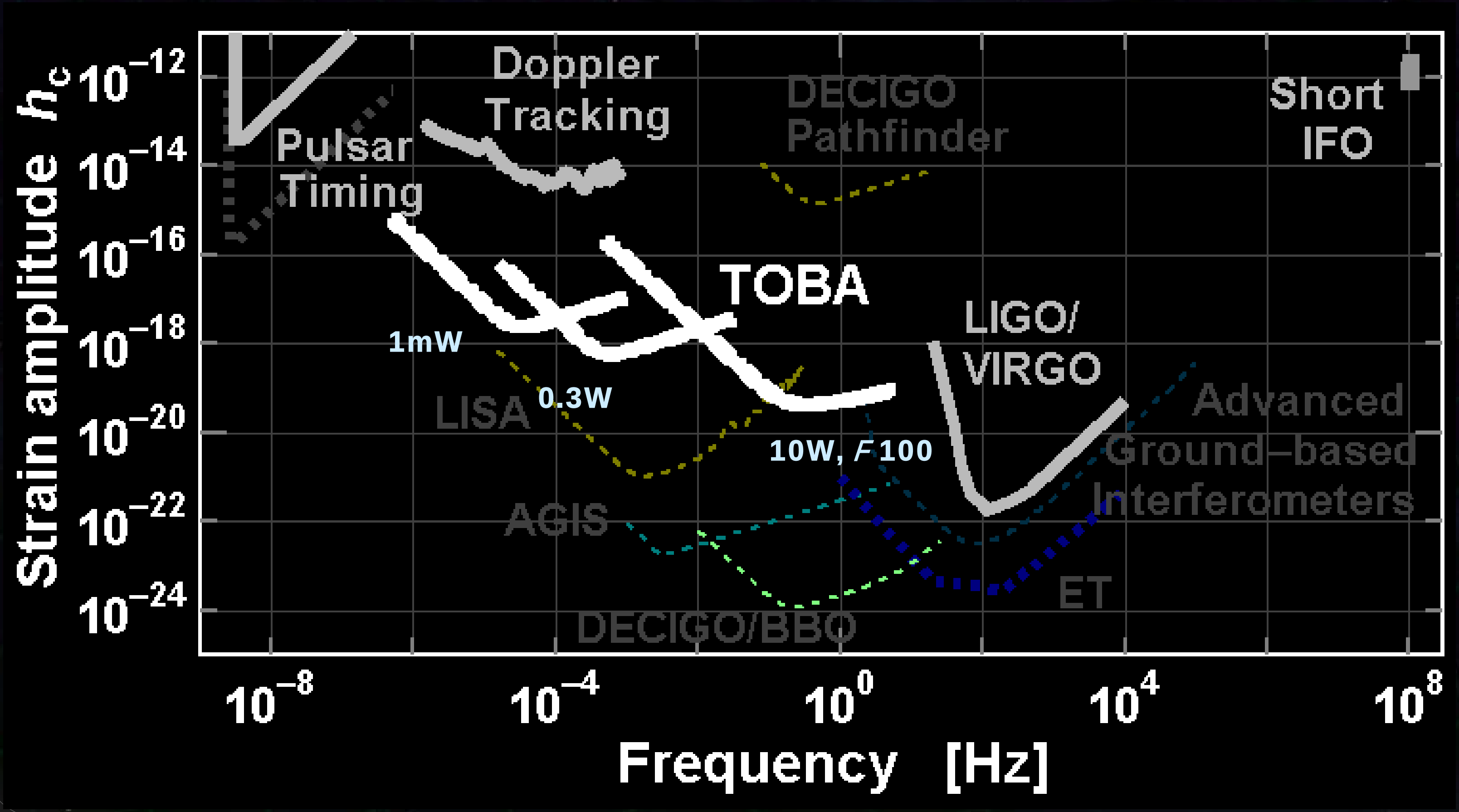
GW from BH merger
- 100 Msolar equal mass
- Spin parameter 0.5
- Distance 100 Mpc



TOBA Sensitivity

Sensitivity example

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



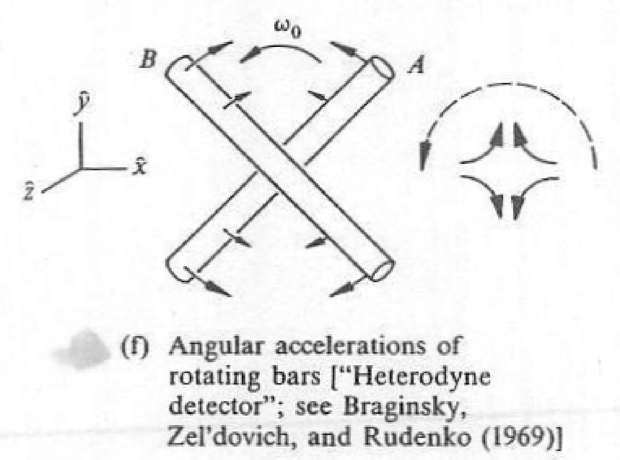
Topic

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.

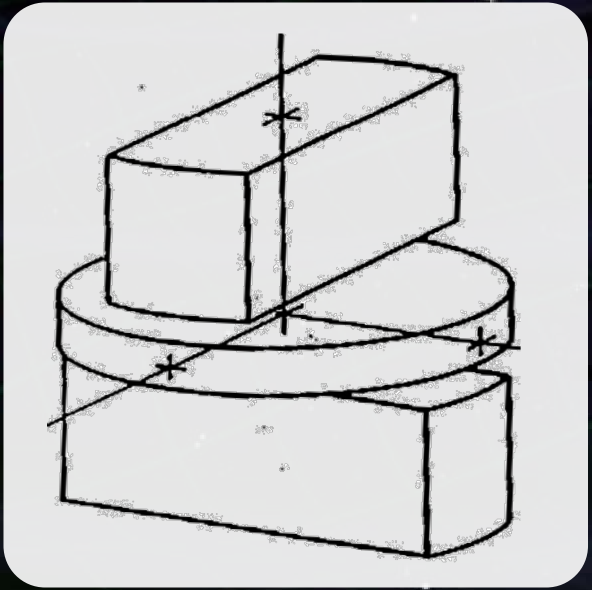


(f) Angular accelerations of rotating bars ["Heterodyne detector"; see Braginsky, Zel'dovich, and Rudenko (1969)]

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).

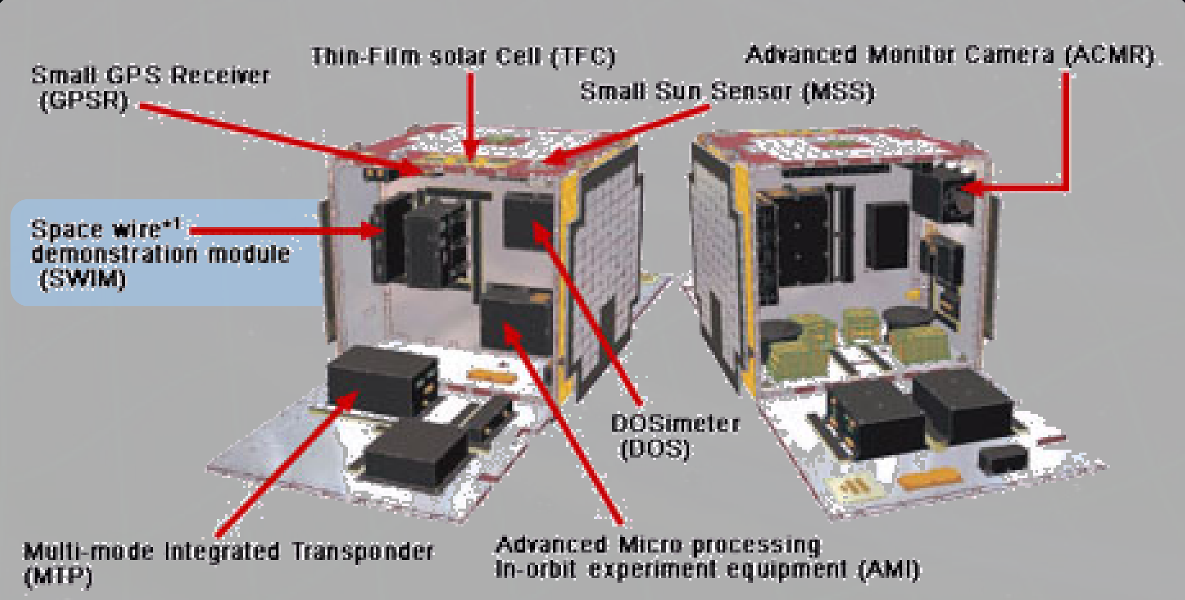


SDS-1衛星での実証

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 □ □ □□ □ □ □ .

2009□ 1□ 23□ □ □ □ .

2011□ 9□ □ □ □ □ .

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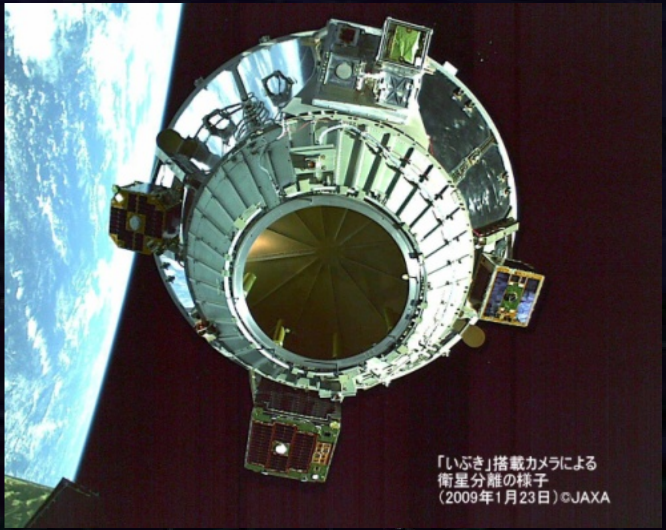
full success□ □ □□ □ .



□ □ □
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

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

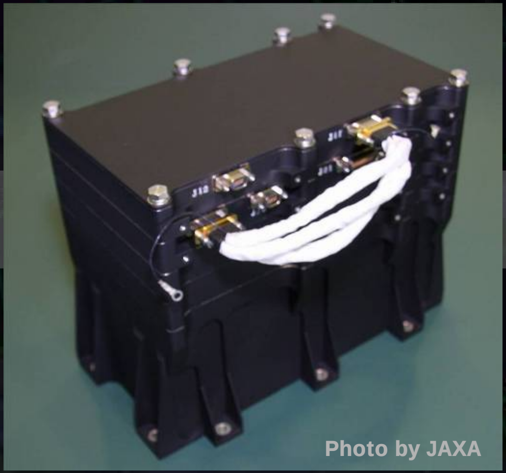


Photo by JAXA

SWIMμν GW sensor

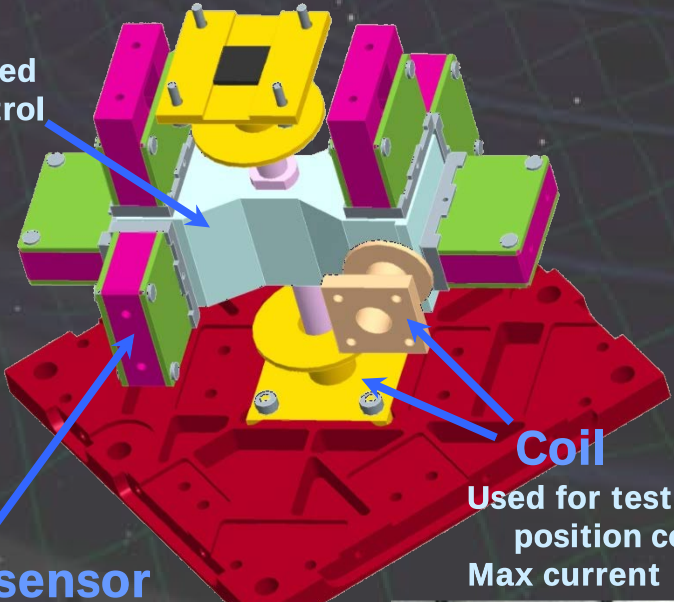
Tiny GW sensor : Test-mass length ~ 50mm

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

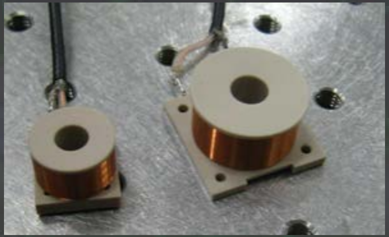
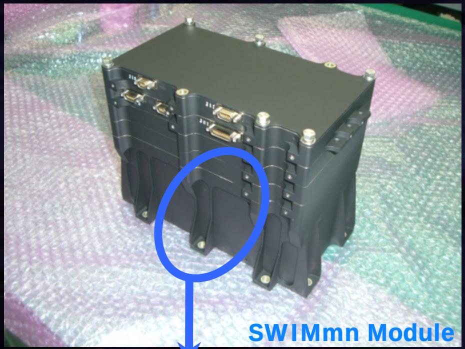
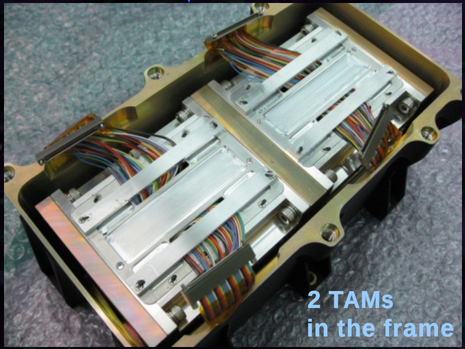
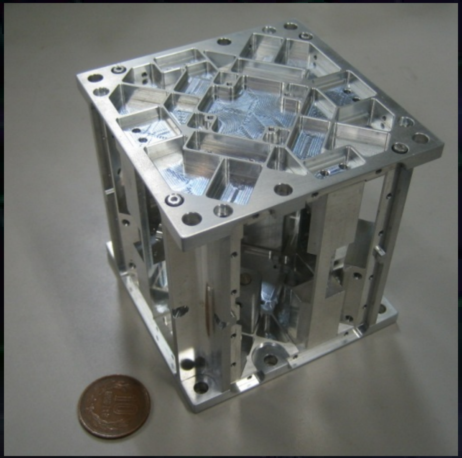


Photo sensor

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







SWIMμν 軌道上実証

SWIM

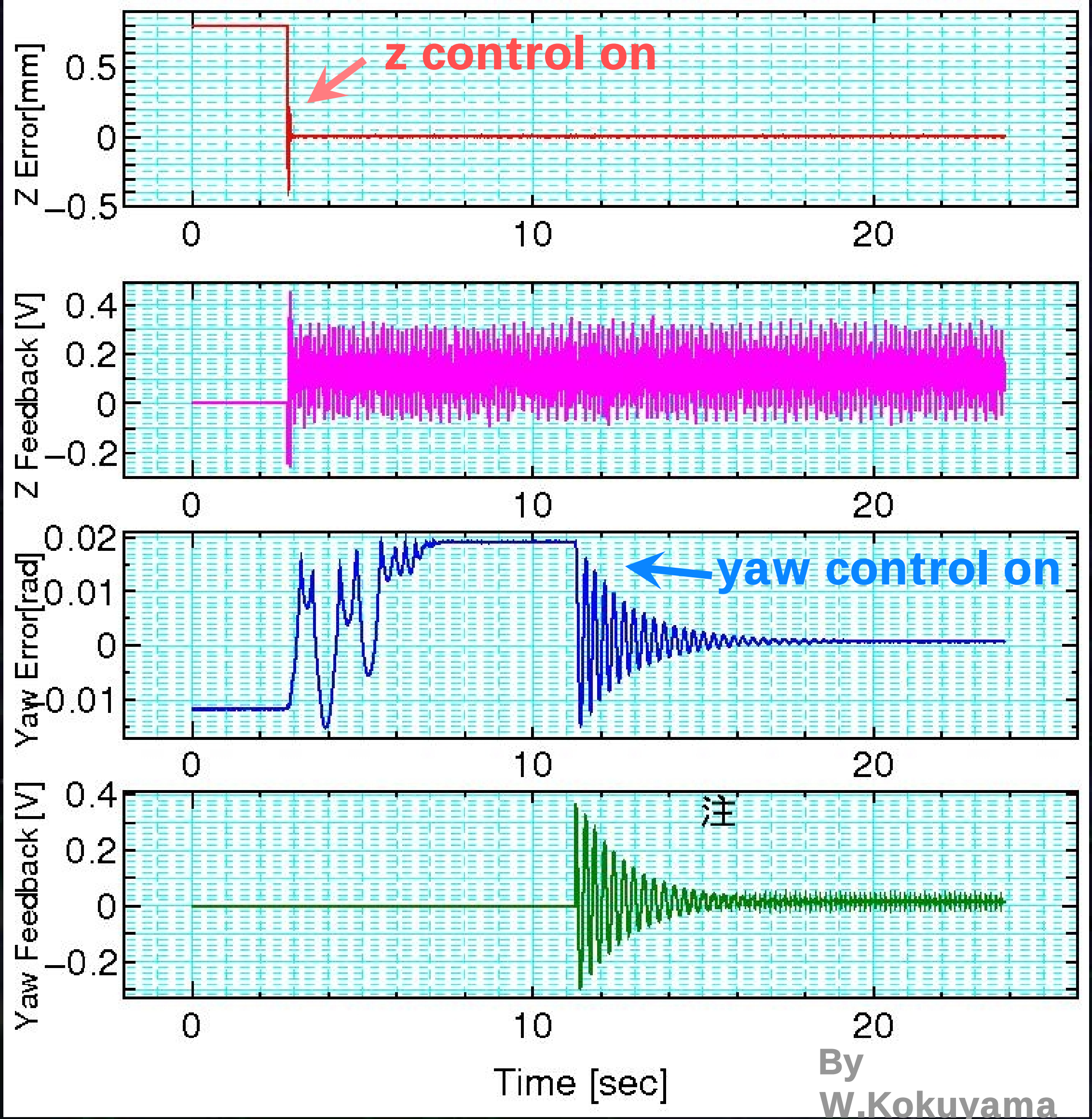
In-orbit operation

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

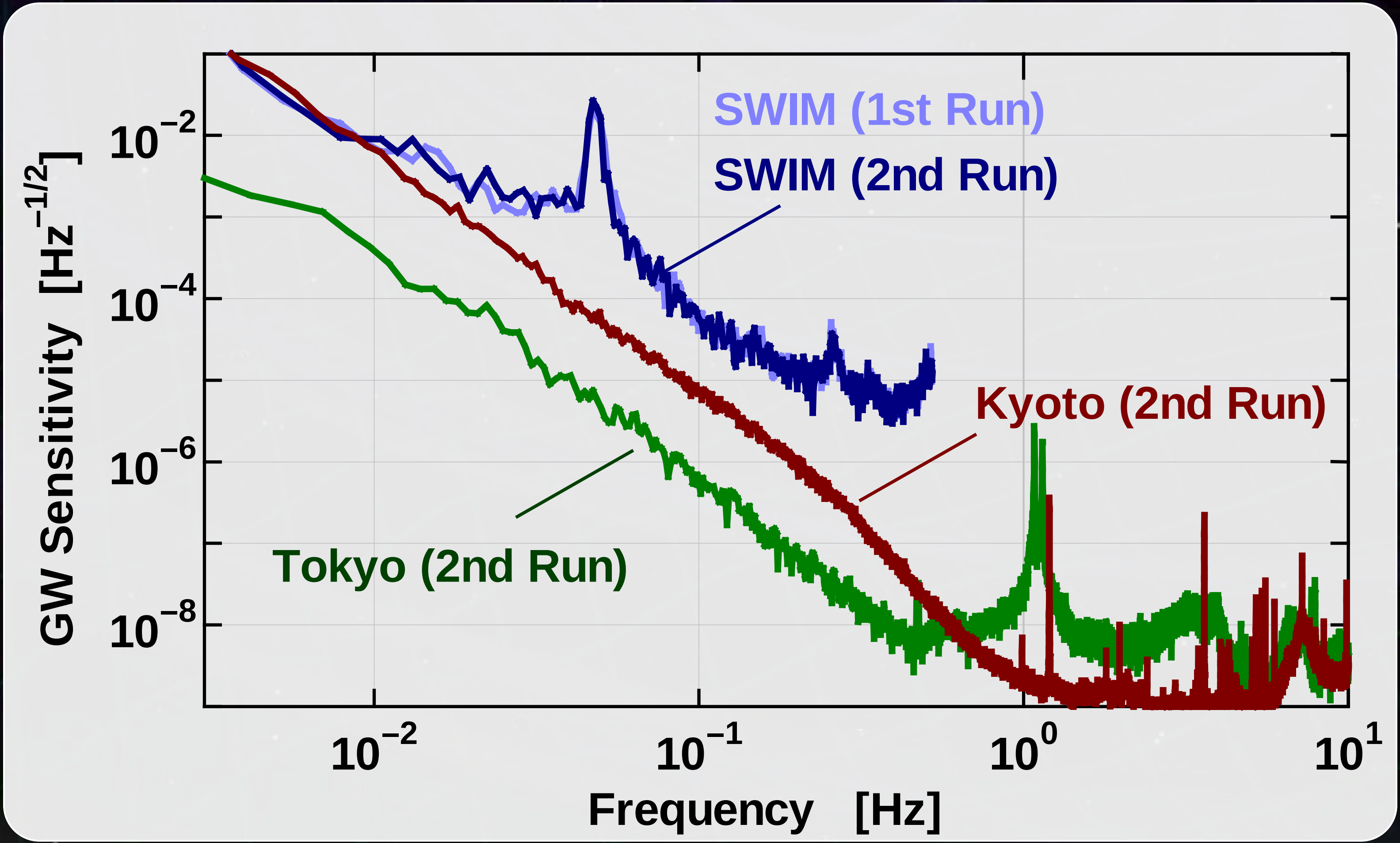
Downlink: ~ a week



By W.Kokuyama

Sensitivity

Observation by SWIM and ground-based detectors
1st run June 17 2010, 2nd run July15 2010



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... $\vec{w}(\mathbf{x}) = (-y, x, 0)$

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