An upper limit on continuous GW in low-frequency regime using a torsion-bar antenna

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(*RES*earch *C*enter for the *E*arly *U*niverse)

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Motivation

- Recently, we have developed the torsion-bar antenna (TOBA) based on PRD 90, 064039.
- We operated the TOBA for 24 hours from Dec.10 to Dec.11 in 2014.
- The sensitivity reached 10^{-10} $Hz^{-1/2}$ at around 1 Hz.

⇩

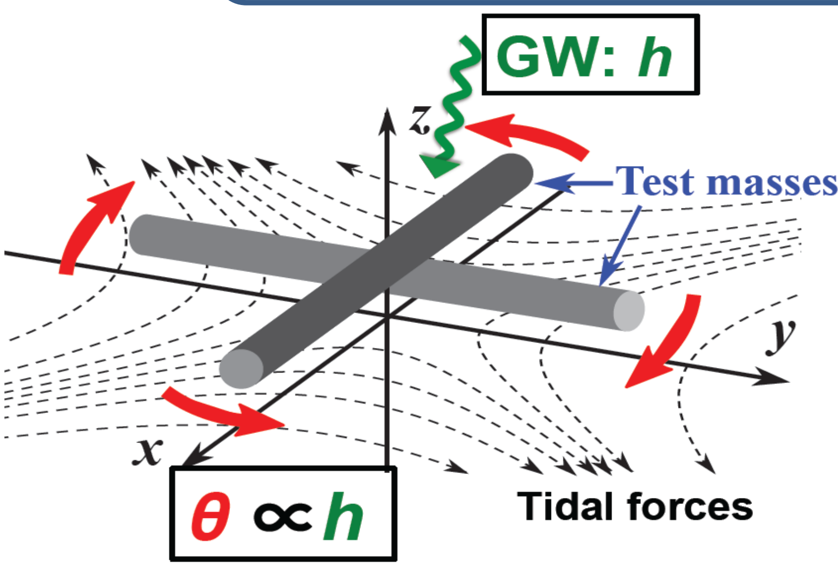
- Continuous GWs in low-frequency regime have yet to be investigated so far.
- We search for continuous GWs from an isolated neutron star.
- We put a constraint on the GW amplitude.

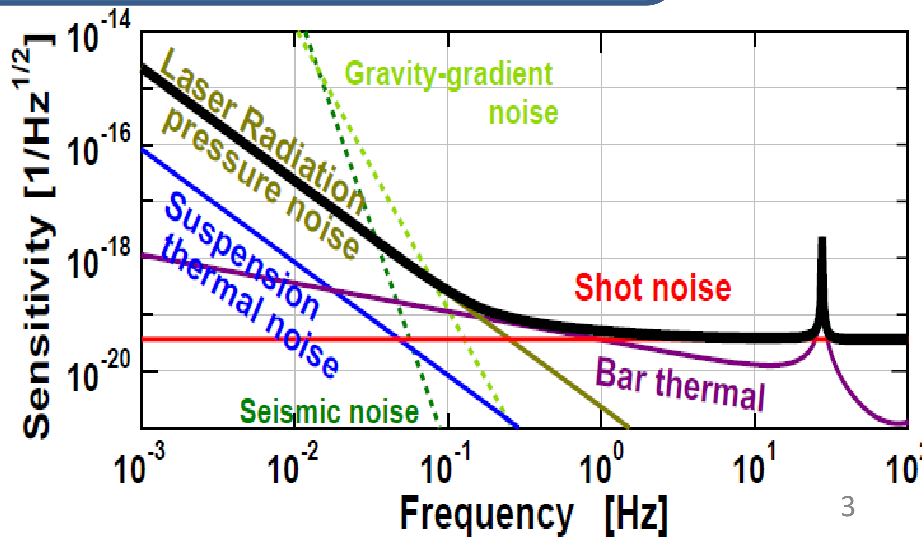
What is a TOBA ?

☐ TOrsion-bar Antenna (TOBA) (Ando et al. PRL 105, 161101 (2010))

- ✓ Low-frequency GW antenna which measures rotations of bars
- ✓ formed by two bar-shaped orthogonal test masses
- ✓ sensitive to low-frequency GWs (f=0.1-1 Hz) even on the ground thanks to its resonant frequency f_{res} < 1mHz.

Main Targets ⇨
- Compact binary coalescence
- Stochastic GW background





History

Ando et al. PRL 105, 161101 (2010)

Ishidoshiro, PhD thesis

2010 **1. Phase-I TOBA**

- ☐ Single 20-cm bar
- ☐ Single antenna

DONE!

Shoda, M thesis

2012 **2. Network of two Phase-I TOBAs**

- ☐ Single 20-cm bar
- ☐ Two-antenna network @ Tokyo and Kyoto

DONE!

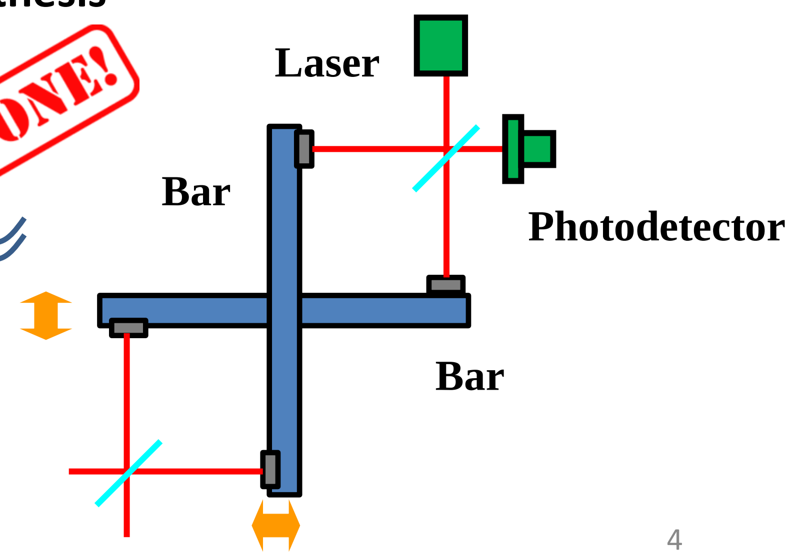
2015 **3. Phase-II TOBA** Shoda, PhD thesis

- ☐ Two 24-cm bars
- ☐ Single antenna

DONE!

20XX **4. Final TOBA**

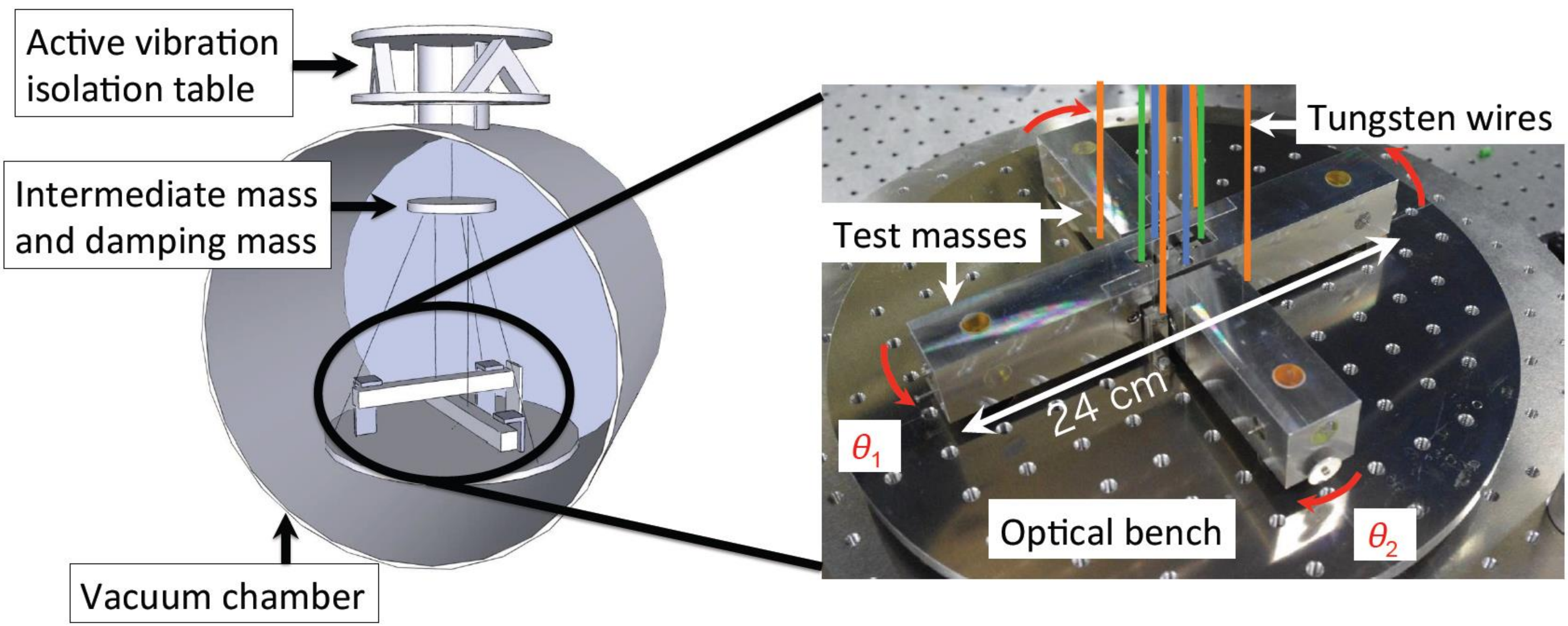
- ☐ ???



Design Overview

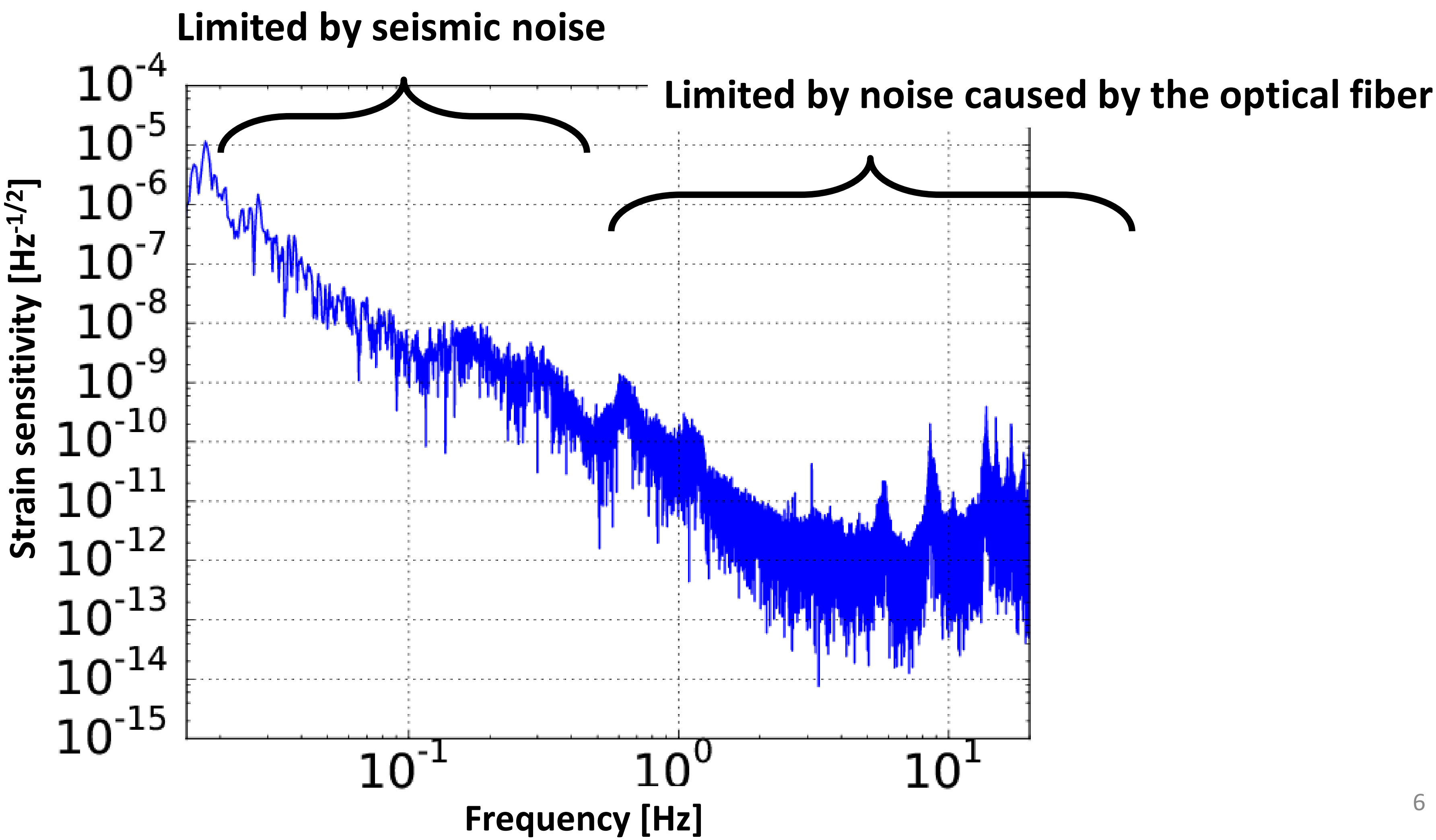
□ Basic design for the Phase-II TOBA

- ✓ Two 24-cm bars
- ✓ Mass of the bar : 0.61kg
- ✓ Location : University of Tokyo (35˚42’49.0’’ N, 139˚45’47.0’’ E)



Measured strain sensitivity

- Sensitivity curve of the Phase-II TOBA



Known isolated NS search

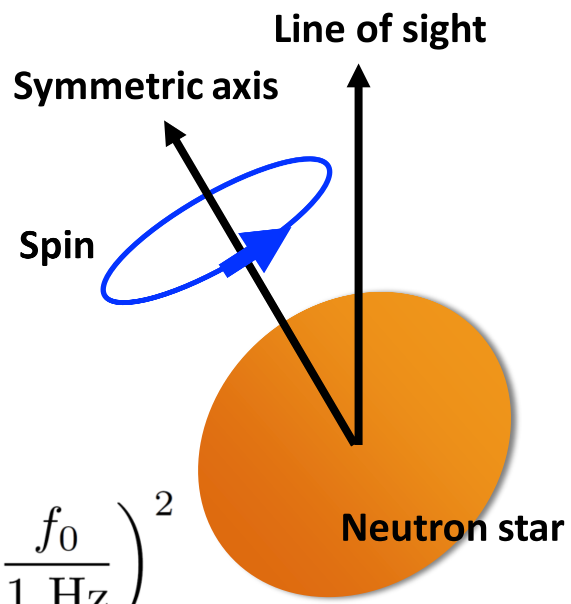
- **GW from a known rapidly rotating neutron star**
  - ✓ **GW signal in a detector**

$$h(t) = h_0 F_+(t,\psi)\frac{1+\cos^2\iota}{2}\cos\Phi(t) + h_0 F_\times(t,\psi)\cos\iota\sin\Phi(t)$$

$$\Phi(t) = \phi_0 + 2\pi f_0 t\left(1+\frac{\boldsymbol{v}(t)\cdot\boldsymbol{n}}{c}\right)$$

4 unknown parameters $\{h_0, \Psi, \iota, \Phi_0\}$

- **Amplitude**
  - ✓ **ε : Ellipticity (<10^{-6})** Horowitz & Kadau (2009)
  - ✓ **f_0 : Spin frequency**



$$h_0 = \frac{4\pi^2 G}{c^4 r}\varepsilon I f_0^2$$

$$= 1.0\times10^{-30}\left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{I}{10^{38}\ \mathrm{kgm}^2}\right)\left(\frac{1\ \mathrm{kpc}}{r}\right)\left(\frac{f_0}{1\ \mathrm{Hz}}\right)^2$$

Detection statistic

□ *F*-statistic

- ✓ ***F*-statistic is based on the method of maximum likelihood.**
- ✓ **If 2*F* > 2$F_{threshold}$, we regard that the signal is detected.**
- ✓ **We use *F*-statistic to discriminate whether or not GW signals exist in the antenna.**

$$\ln\Lambda\left(\boldsymbol{s};\boldsymbol{h}\right)=\ln\frac{P\left(\boldsymbol{s}|\boldsymbol{h}\right)}{P\left(\boldsymbol{s}|\boldsymbol{h}=\boldsymbol{0}\right)}=\left(\boldsymbol{s}|\boldsymbol{h}\right)-\frac{1}{2}\left(\boldsymbol{h}|\boldsymbol{h}\right)$$

$$2\mathcal{F}\equiv\max_{h_0,\phi_0,\iota,\psi}\left[2\ln\Lambda\left(\boldsymbol{s};\lambda\right)\right]$$

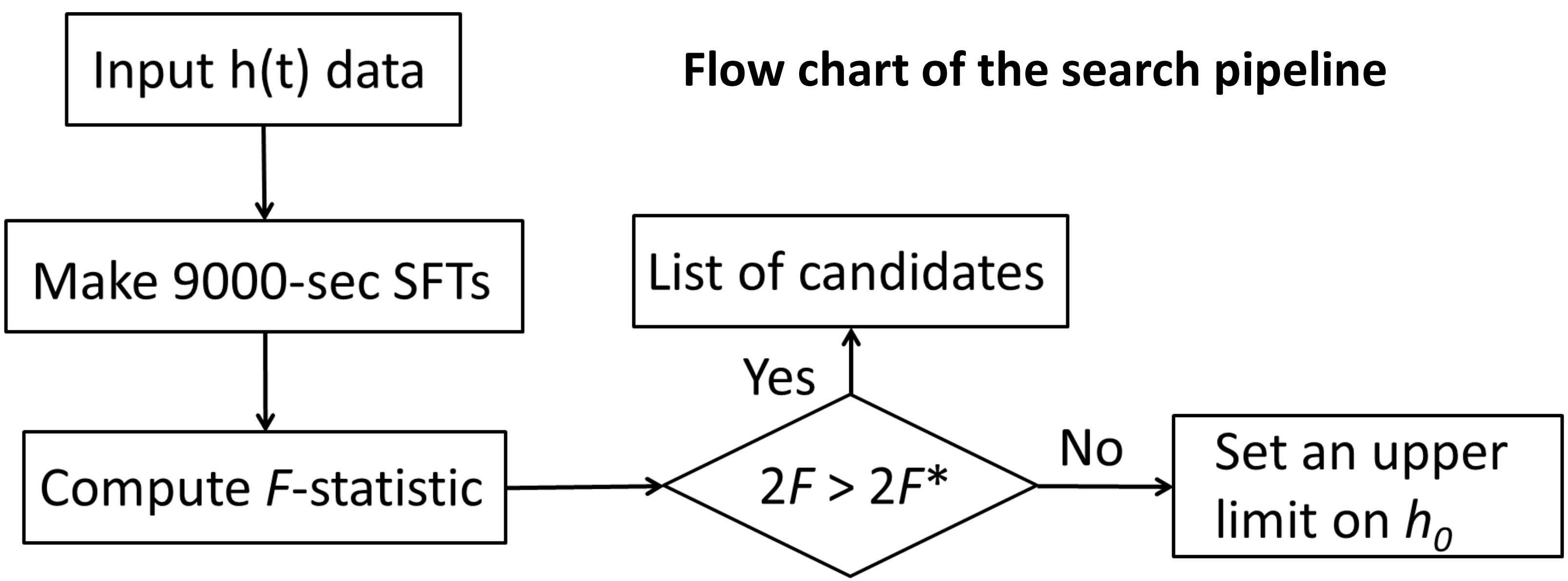
$$\mathrm{E}\left[2\mathcal{F}\right]=4+\left(\mathrm{S/N}\right)^2$$

Setting an upper limit

- **How to set an upper limit on h_0**
  - ✓ **If $2F < 2F_{th}$, we place an upper limit $h_0(C)$ with confidence C.**
  - ✓ **The upper limit with confidence level C can be found by solving the below integration using Monte Carlo simulations.**

$$C\left(h_0\right) = \int_{2\mathcal{F}_{\rm obs}}^{\infty} p\left(2\mathcal{F} | h_0; \psi, \cos\iota\right) \mathrm{d}\left(2\mathcal{F}\right)$$

Flow chart of the search pipeline



Search for GWs from PSR B 1944+17

☐ Results

- ✓ Our target is a known isolated pulsar, PSR B 1944+17.
- ✓ We calculated 2*F*.
- ✓ The measured value of 2*F* is not significant.
- ✓ Then, we proceeded to set an upper limit on the targeted signal using Monte Carlo simulations.

Distance r	Right ascension α	Declination δ	Spin frequency f_0	Spin down $\dot{f}$
0.30 kpc	19:46:53.0	+18:05:41.24	2.2695 Hz	-1.24×10^{-16} [Hz/s]

$$2\mathcal{F}_{\rm obs} = 4.5$$

$$h_0^{95\%} = 8.7 \times 10^{-13}$$

Summary

- The Phase-II TOBA was constructed based on PRD 90, 064039.
- We operated the Phase-II TOBA during Dec.10 to Dec.11.
- The sensitivity reached 10^{-10} $\mathrm{Hz}^{-1/2}$ at around 1 Hz.

⇩

- We searched for the GW from PSR B 1944+17.
- We set an upper limit on h^0 as 8.7×10^{-13} with 95% confidence level using the 24-hour TOBA data.