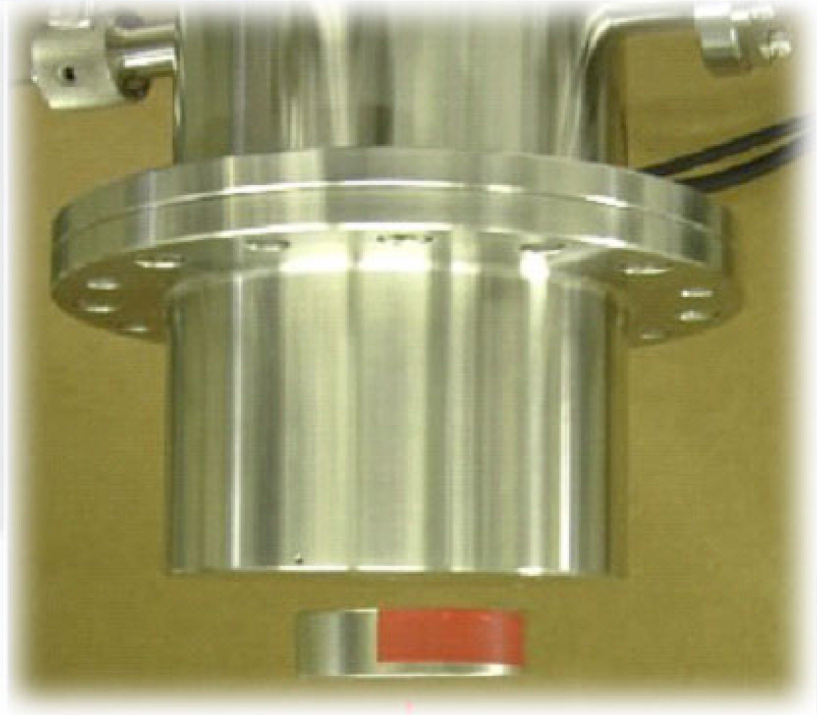
Development of a Low-Frequency Gravitational-Wave Detector Using Superconductor Magnets



Masaki ANDO, Koji Ishidoshiro, Wataru Kokuyama,
Akiteru Takamori, Akito Araya, Kimio Tsubono
Department of Physics, The University of Tokyo
Earthquake Research Institute, The University of Tokyo

7th Edoardo Amaldi Conference on Gravitational Waves (July 8-14, 2007, Sydney, Australia)

Outline

Ground-based Low-frequency GW detector by
Torsion antenna supported by a superconductor magnet

Bar-shaped test mass, which rotates freely
→ Fundamental sensitivity for low-freq. GWs

- Introduction
- Principle and Concept
- Sensitivity and Science
- Prototype test
- Summary

Introduction

- **Low-frequency GW observation**

Current (and proposed) GW detectors

Ground-based Interferometer
Support a mirror (test mass)
as a suspension pendulum
⇨ Almost no fundamental sensitivity for lower frequency GWs (~1Hz)

Resonant-mass detector
Take advantage of
mass resonance
⇨ Observation band is limited around its resonant frequency

Space interferometer
Almost ideal free mass
Long baseline length
⇨ Require huge resources (efforts, time, costs …)

⇩

Ground-based low-frequency GW detector

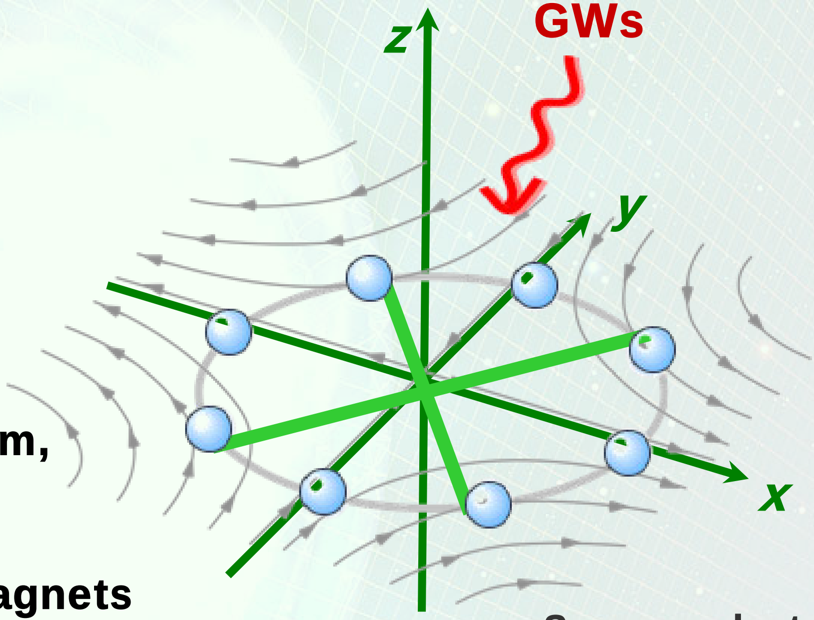
Requires less resources
Longer lifetime → longer signal integration time
Continuous upgrades, easier maintenance

Concept

- **Torsion Antenna with Levitated Bars**

Torsion antenna

Two orthogonal bars
→ GWs (or tidal force)
cause differential rotation
Angular motion is
measured by interferometers

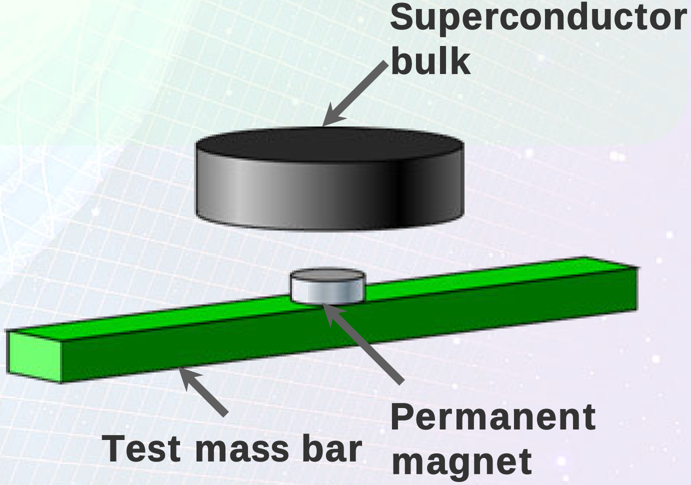


Levitated bar

Bar is supported as a torsion pendulum,
by pinning effect of
a superconductor magnet (SCM)
Axisymmetric SCM and permanent magnets

In ideal situation…
Bar is levitated without control
No restoring nor frictional force
in its rotational degree of freedom

Fundamental sensitivity
for low-frequency gravitational waves



Free mass vs. Free Bar

- **Comparison with IFOs**

Compared with ground-based IFO detectors...

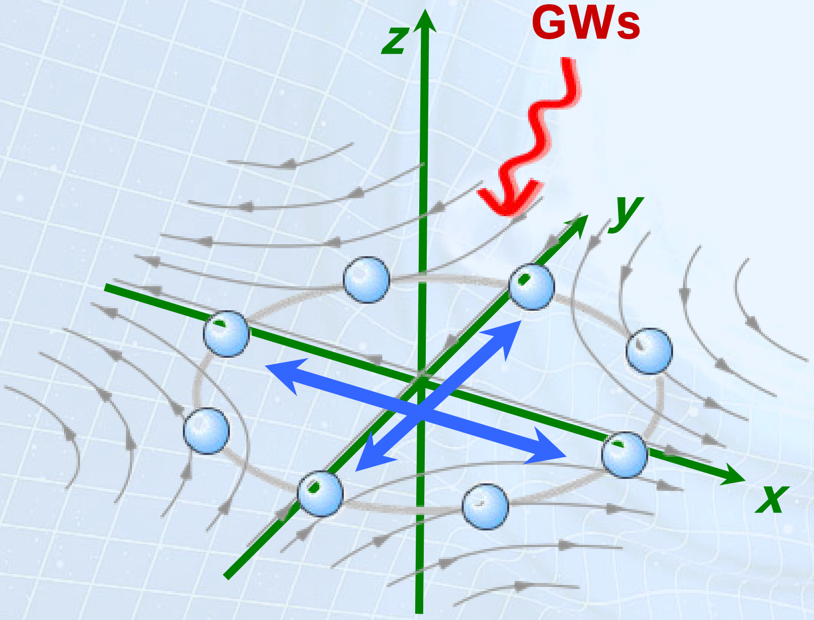
No resonant frequency of the mass suspension

Smaller scale, limited by the bar length

⇨

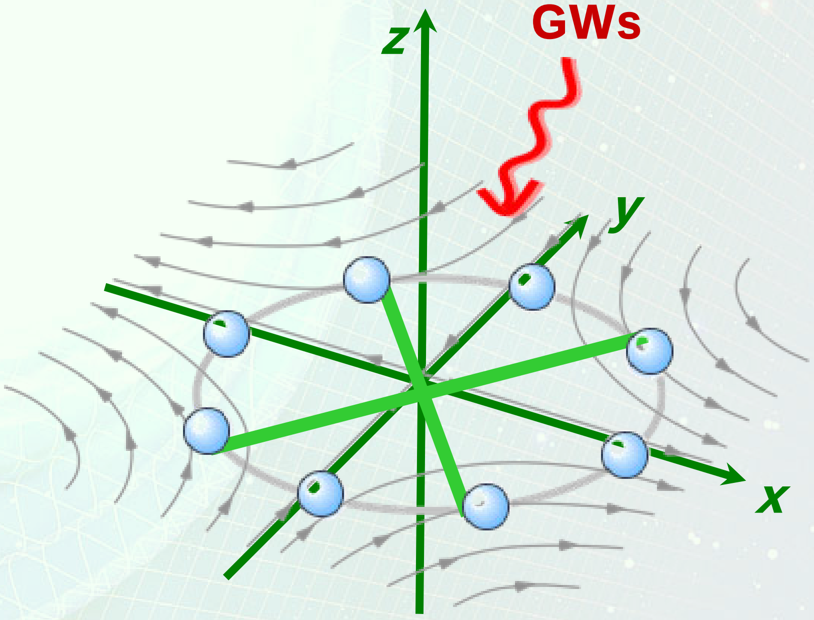
Fundamental sensitivity to low-frequency GWs

Limited sensitivity



Traditional IFO detector

Detect differential length change



Torsion Detector

Detect differential rotation

Sensitivity to GWs

Response to GWs

GWs cause tidal force
→ Detect GWs by measuring rotation of proof masses

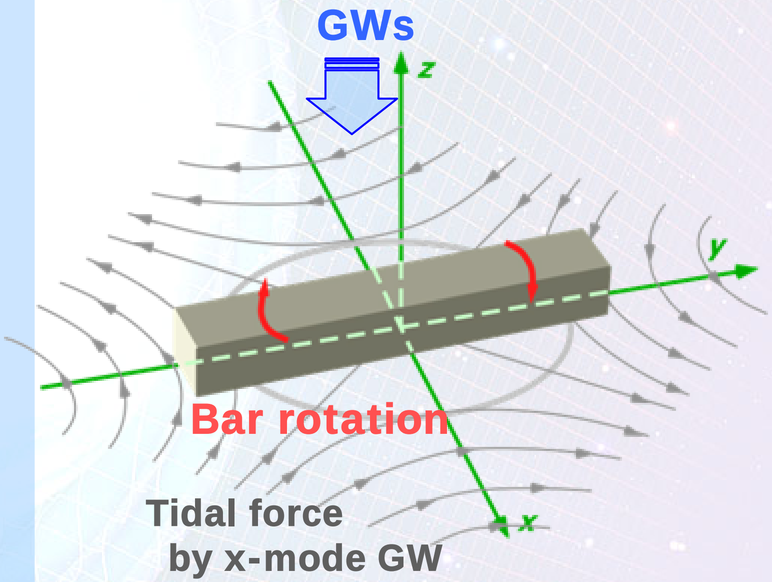
Equation of motion for bar rotation

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

I : Moment of Inertia
q^{ij} : Dynamic quadrupole moment

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

α : shape factor, between 0 to 1
Dumbbell → α = 1
Thin bar → α = ½
Dimension less,
Independent of matter density



Differential rotation of two orthogonal bars
→ Doubles GW signals
Cancels the common rotation (seismic disturbances etc.)

Conceptual design

- **Torsion antenna with levitated bars**

Two levitated bars in orthogonal direction

→ **Measure differential rotation by laser interferometers**

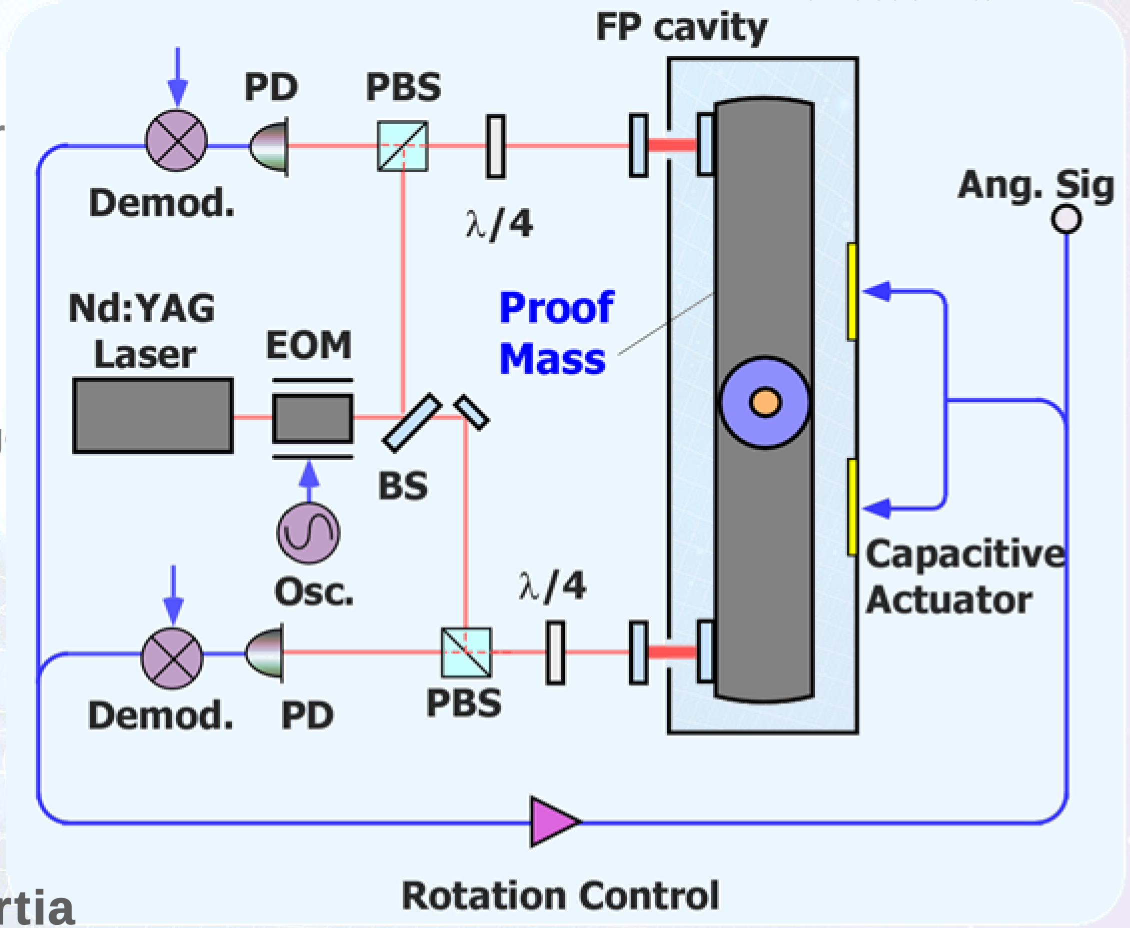
Bar (proof mass)

Permanent magnet at its center
Levitated by pinning effect of a superconductor magnet
Rotate freely in the horizontal plane

Interferometer

Measure the bar-angular chang
by differential displacement at the bar edge
Short (~1cm) FP cavity to avoid the effect of laser-frequency noise

Housed in a vacuum tank



For better sensitivity…

Longer bar
Larger momentum of Inertia

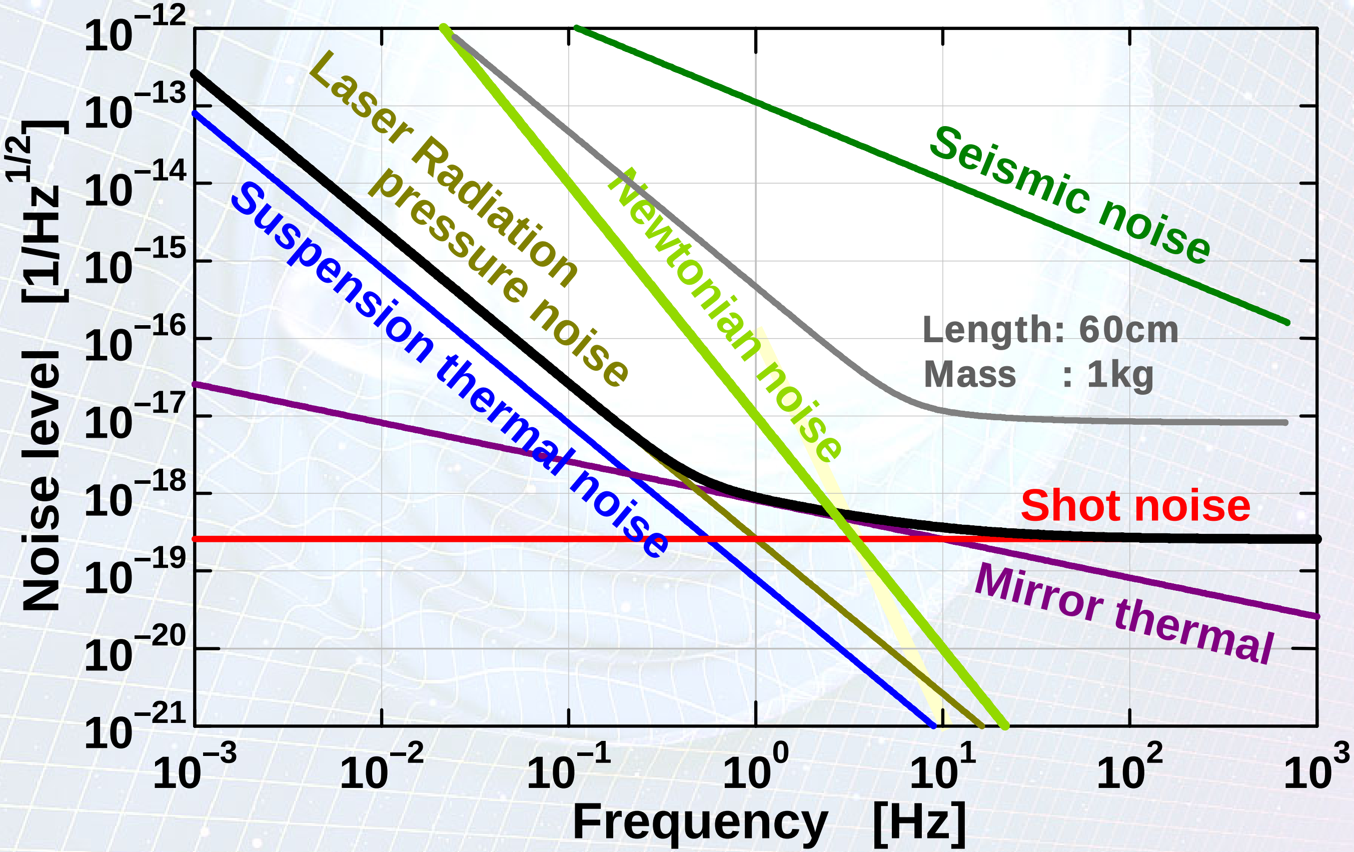
Sensitivity

- **Sensitivity**

Bar length : 20m, Mass : 10kg
Laser source : 1064nm, 100mW
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

Seismic noise (CMRR ~100, upper limit)
Newtonian noise (rough estimation)



Science

- **Expected GW source**

BH quasi-normal mode

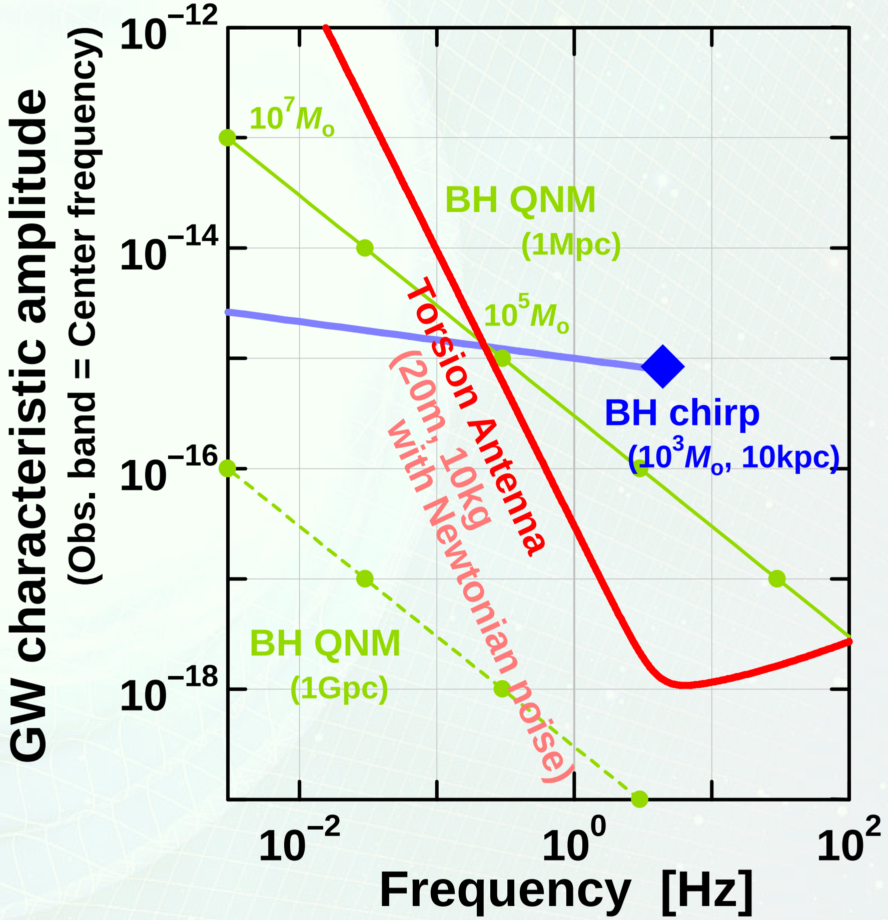
$$h \sim 10^{-15} \left(\frac{m}{10^5 M_\odot}\right) \left(\frac{1\mathrm{Mpc}}{r}\right)$$

$$f \sim 3 \times 10^{-1} \left(\frac{10^5 M_\odot}{m}\right) \quad [\mathrm{Hz}]$$

Mid.-scale BH inspiral

$$h \sim 10^{-15} \left(\frac{m_c}{10^3 M_\odot}\right)^{5/6} \left(\frac{1\mathrm{Hz}}{f}\right)^{1/6} \left(\frac{10\mathrm{kpc}}{r}\right)$$

$$f \sim 4 \times \left(\frac{10^3 M_\odot}{m_t}\right) \quad [\mathrm{Hz}]$$



Possibility to detect such events at the Galactic center

Prototype detector

Levitated bar setup for prototype test

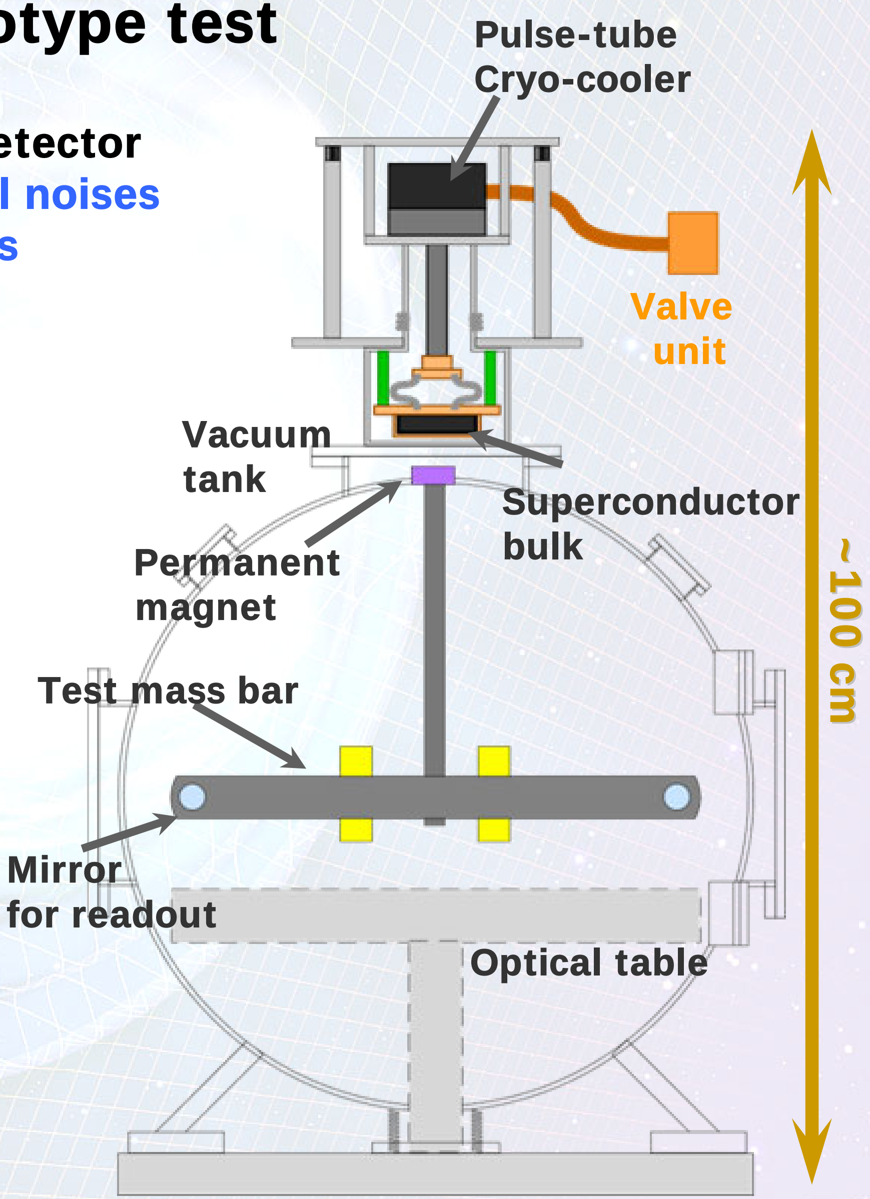
Purpose

Obtain knowledge for a larger-scale detector

- * Check basic ideas and fundamental noises
- * See contributions and cancellations of practical noises

Features (some parameters are not fixed)

- Placed at The University of Tokyo
- Test mass
  - Length ~ 50cm
  - Mass ~ 300g
- Superconductor bulk
  - Gd-Ba-Cu-O
  - Φ60 mm, t 20 mm
  - Critical temperature: 92K (sufficient pinning at 70K)
- Cryo-cooler
  - Low-vibration pulse-tube
  - Temp. : 60K
- Readout
  - Simple Michelson interferometer
- Vacuum chamber
  - Pressure < 10^{-6} Pa

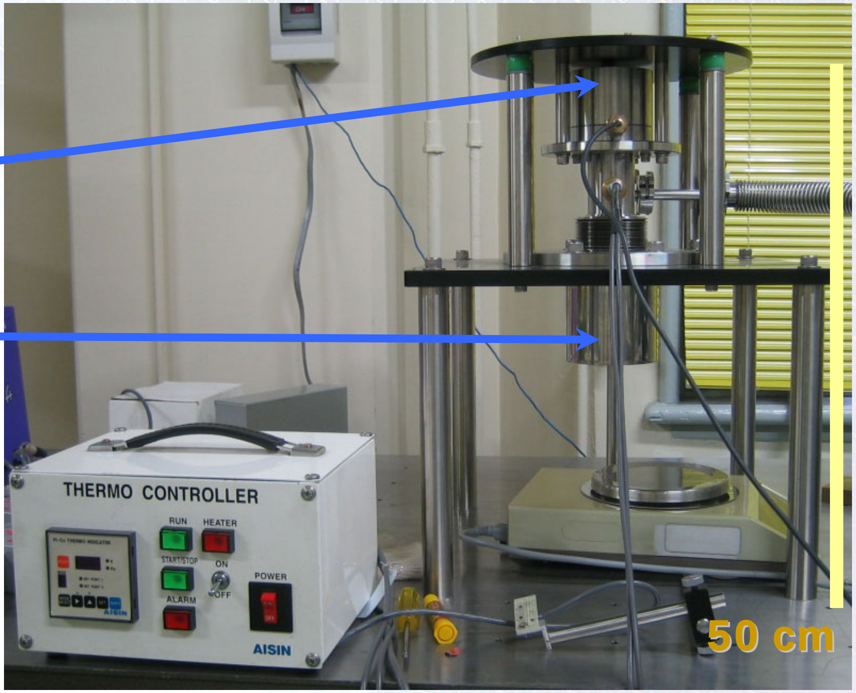


Photos

- **Superconductor module**

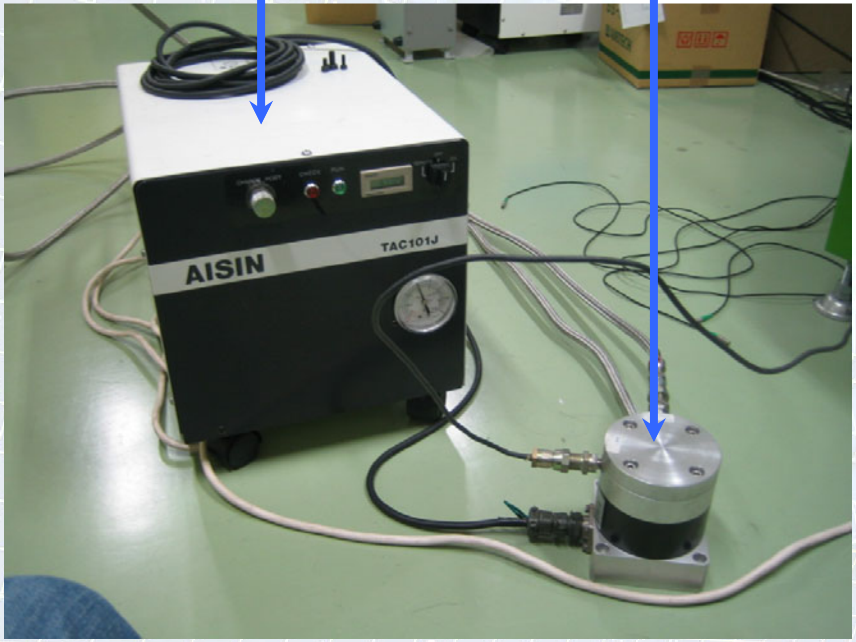
Pulse-tube Cryo-cooler

Super-conductor bulk



Compressor

Valve unit



Heat link
Ag-coated
Cu wires

Preliminary Measurements (1)

- **Super-conductor module**

Low-vibration cryo-cooler

Superconductor bulk :

stiffly connected to the ground

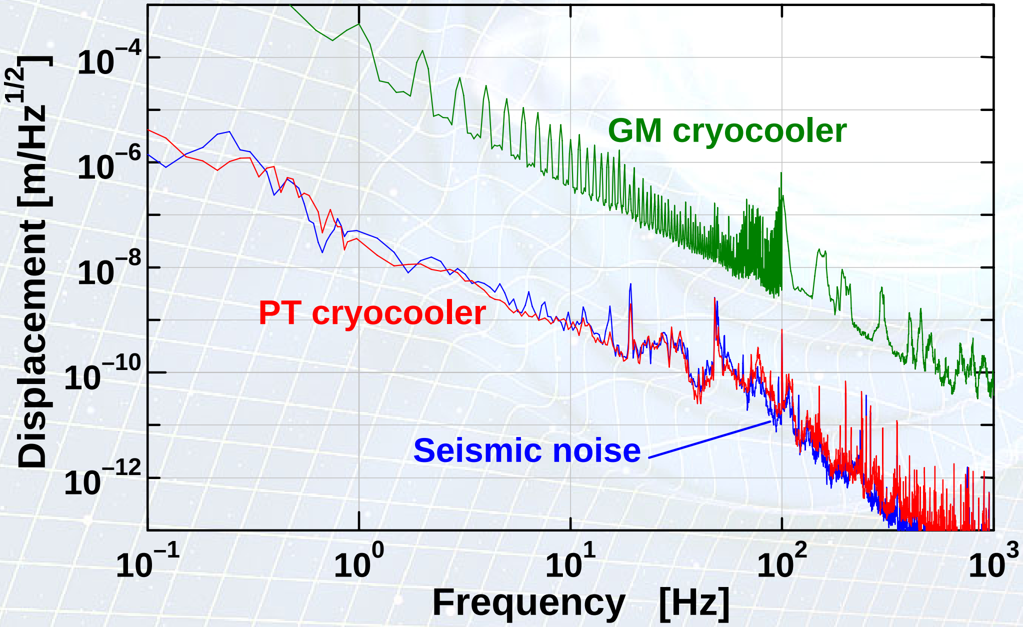
softly connected to the cold head

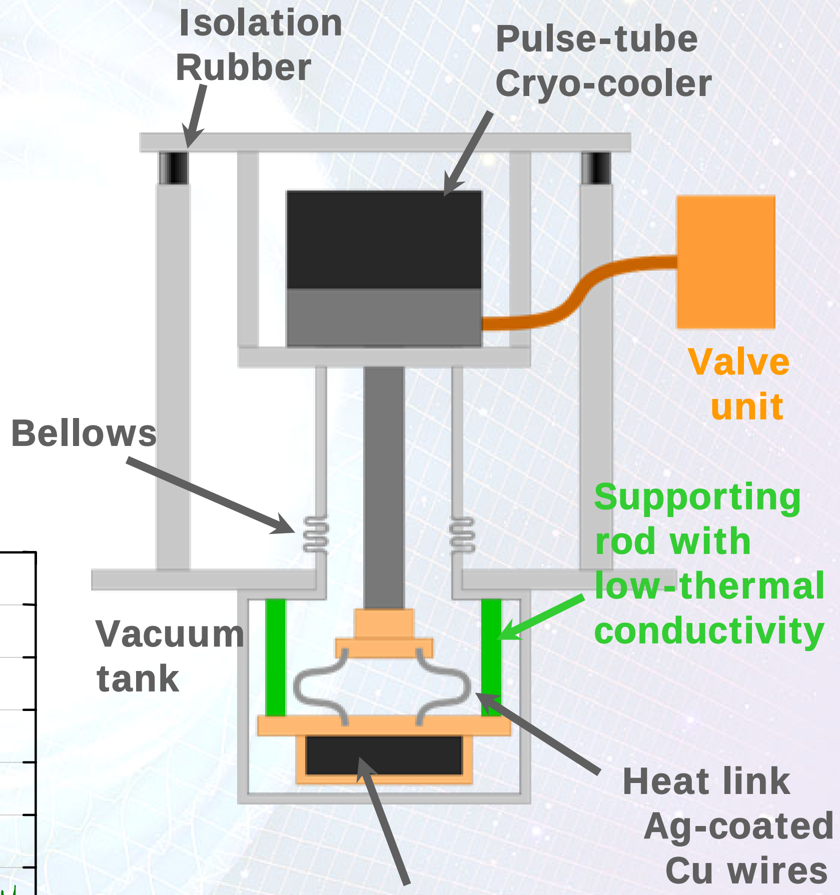
Vibration measurement

GM-type, PT-type cryo-coolers

Measured on the surface of the vacuum tank

→ PT vibration < seismic level





Super-conductor bulk

Gd-Ba-Cu-O

Φ60 mm, t 20 mm

Critical temperature: 92K

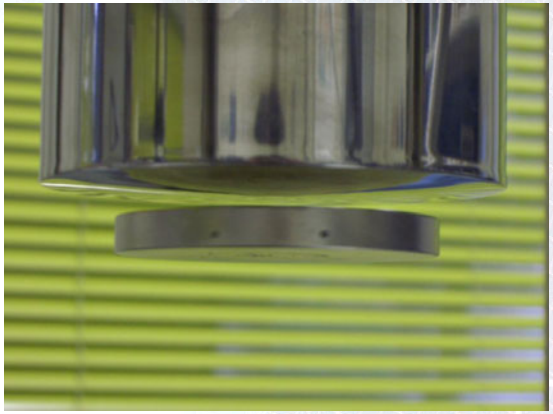
(sufficient pinning at 70K)

Preliminary Measurements (2)

- **Force by the super-conductor bulk**

Steps to 'pin' a magnet

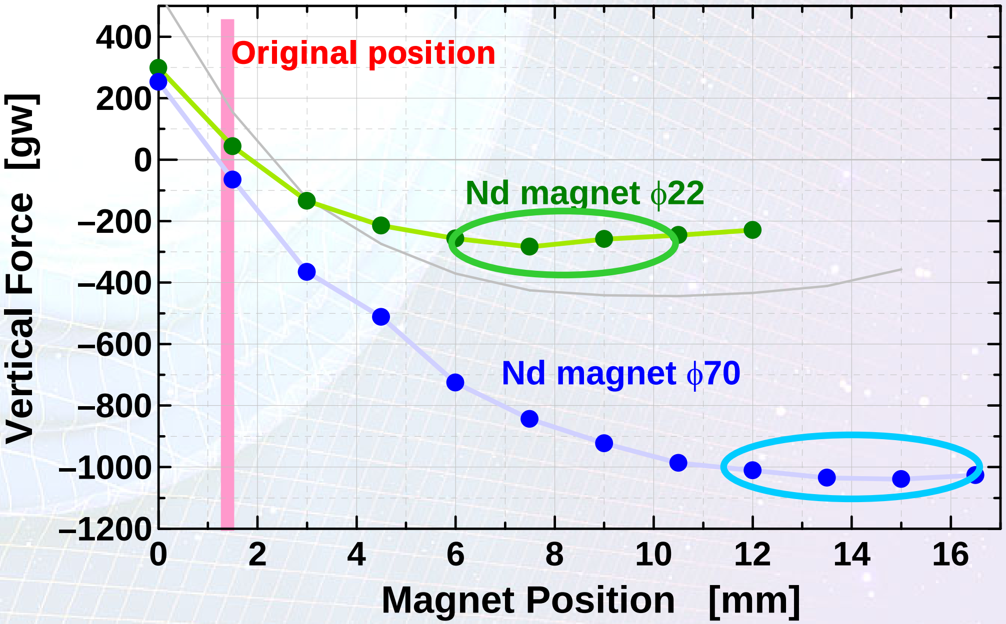
1. Place a permanent magnet just below the SCM.
2. Cool down the SCM below its critical temperature.
3. Magnetic field inside the SCM is trapped.
4. SCM tries to keep the magnet at its original position.



Measured vertical force

Magnets: Nd magnet (~1T)
Φ22 mm, t 18 mm
Φ70 mm, t 18 mm

Maximum force >1 kgw



Flat position dependence around maximum (small spring constant)
→ small coupling for vertical direction

Preliminary Measurements (3)

- **Damping factor**

Superconductor suspension
has no restoring force nor frictional force,
but will have magnetic damping from inhomogeneity
→ thermal noise may be a problem

Measurement of damping factor

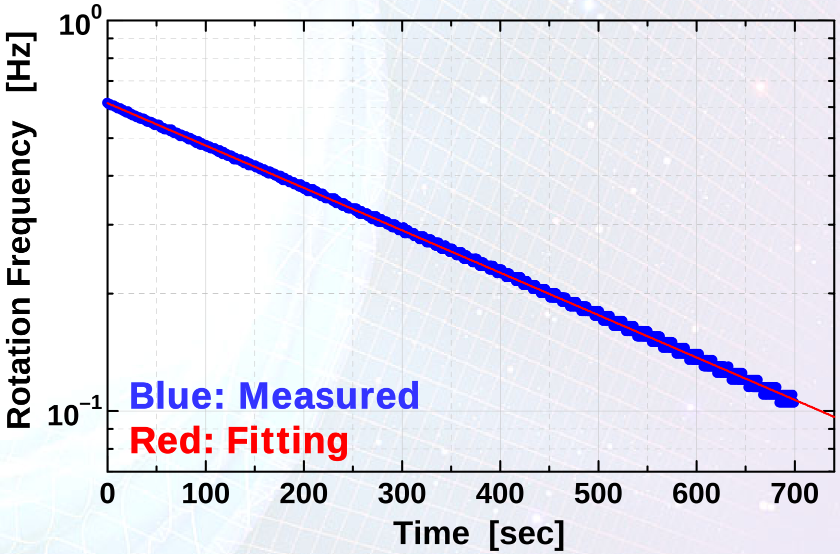
Rotate the levitated magnet
Nd magnet (Φ22 mm, t 18 mm)
Monitor the rotational frequency
by a reflective photo sensor

$$I\ddot{\theta} + \gamma\dot{\theta} = 0$$
$$\rightarrow \theta \propto e^{-\frac{\gamma}{I}t}$$

Exponential decay
→ Estimate damping factor

⇨ $\gamma = 1.5\mathrm{x}10^{-9}$ [N•m•s/rad]
(Measurement in the air)

Torsion pendulum for LISA GRS test
$\gamma = 1.5\mathrm{x}10^{-10}$ [N•m•s/rad]



LISA GRS test facility
L.Carbone et al, CQG 22 (2005) S509
Au-coated Ti mass
Tungsten fiber
length 1m, diameter 25 μm
Q~3000, f_0 ~2mHz

Summary and Current status

Ground-based Low-frequency GW detector will be possible by

Torsion antenna supported by a superconductor magnet

Fundamental sensitivity for low-freq. GWs

Without a wire → No restoring force, No frictional force

Levitated → small coupling with external vibration

Ex) Assume a bar with 20m length, 10kg mass

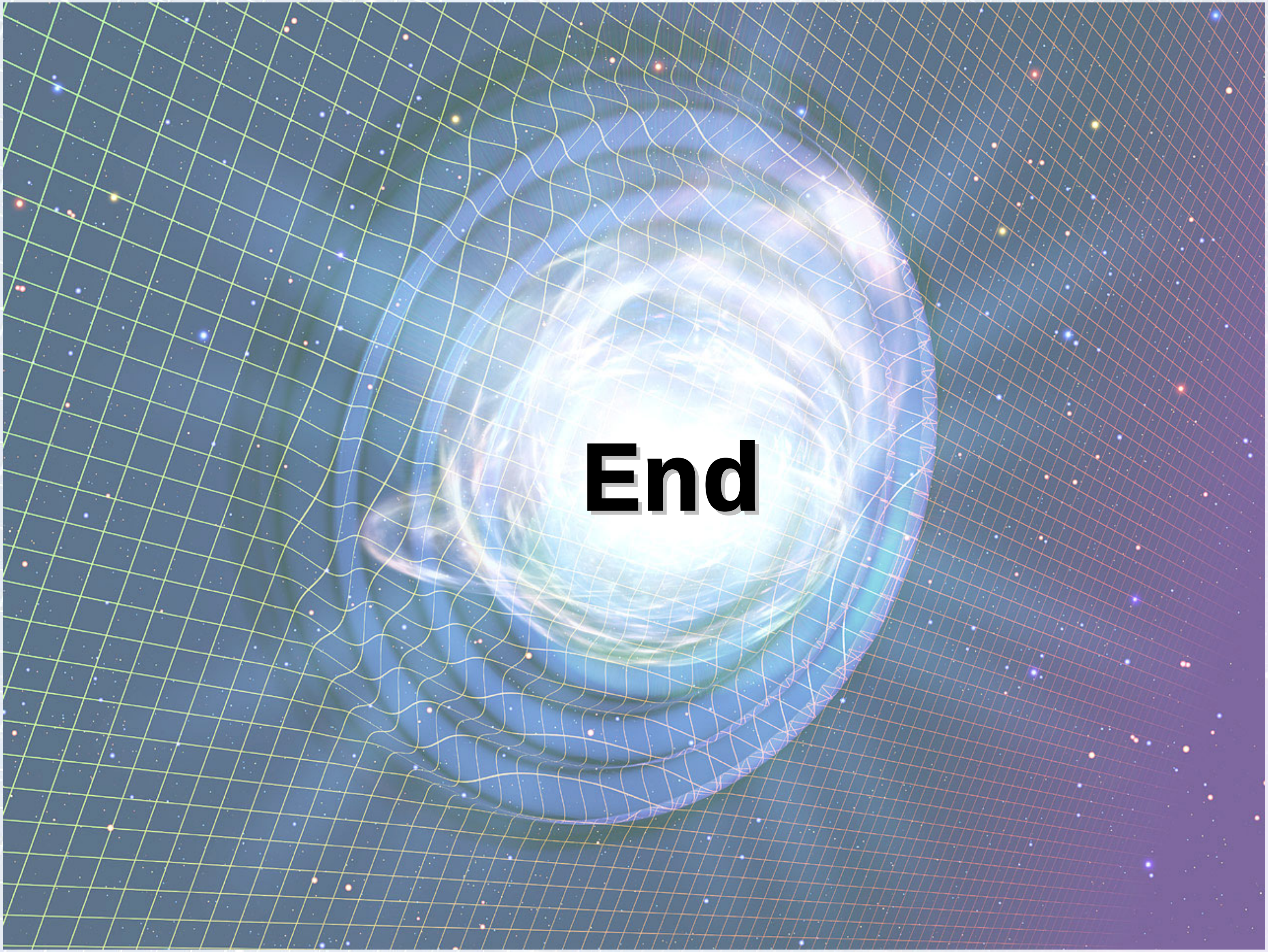
→ **Sensitivity limit : $h_c \sim 10^{-18}$**

Targets : GWs from QNM of MBH, Binary inspiral of MBH

Uncertainty in Newtonian and seismic noises

Prototype test

- Testing the characteristics of a super-conductor module
  - Vibration of cryo-cooler : lower than seismic vibration
  - Maximum force > 1kgw
  - Damping factor : $\gamma = 1.5\times10^{-9}$ [N•m•s/rad] (in the air)
- Designing the test-mass module to be levitated
- Vacuum system is under construction → to be delivered in Sept.
- Readout optics are under development



End

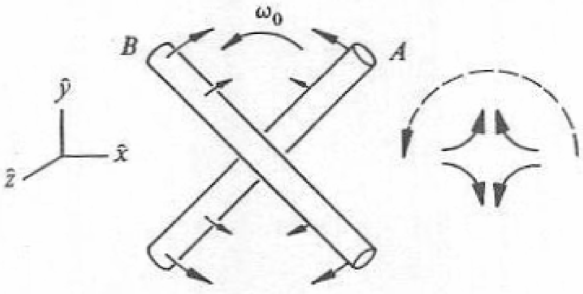
Topic

- **Heterodyne detection**

Rotate the bar at an angular frequency of ω
→ up convert the GW signal to $\omega_{GW}+2\omega$
→ avoid many practical noises at low frequency

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.



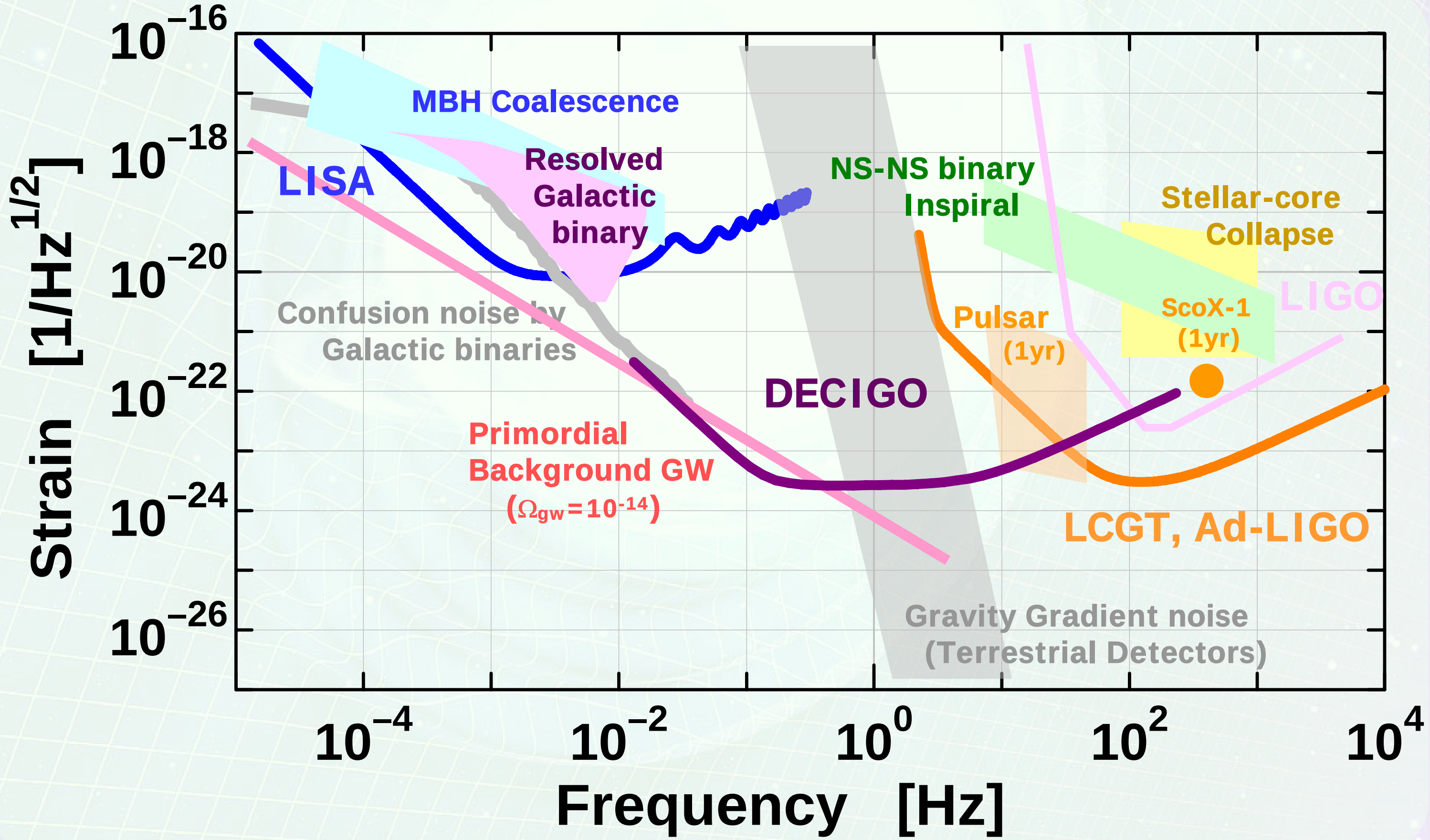
(f) Angular accelerations of rotating bars ["Heterodyne detector"; see Braginsky, Zel'dovich, and Rudenko (1969)]

Introduction

- **DECIGO**

Deci-hertz **I**nterferometer **G**ravitational Wave **O**bservatory

⇨ bridges the gap between LISA and terrestrial detectors



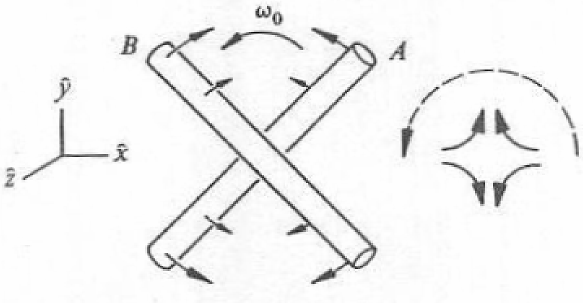
Topic

- **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).