Current Status of TOBA experiment at Univ. of Tokyo

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6 Oct. 2016 E-GRAAL 2nd meeting

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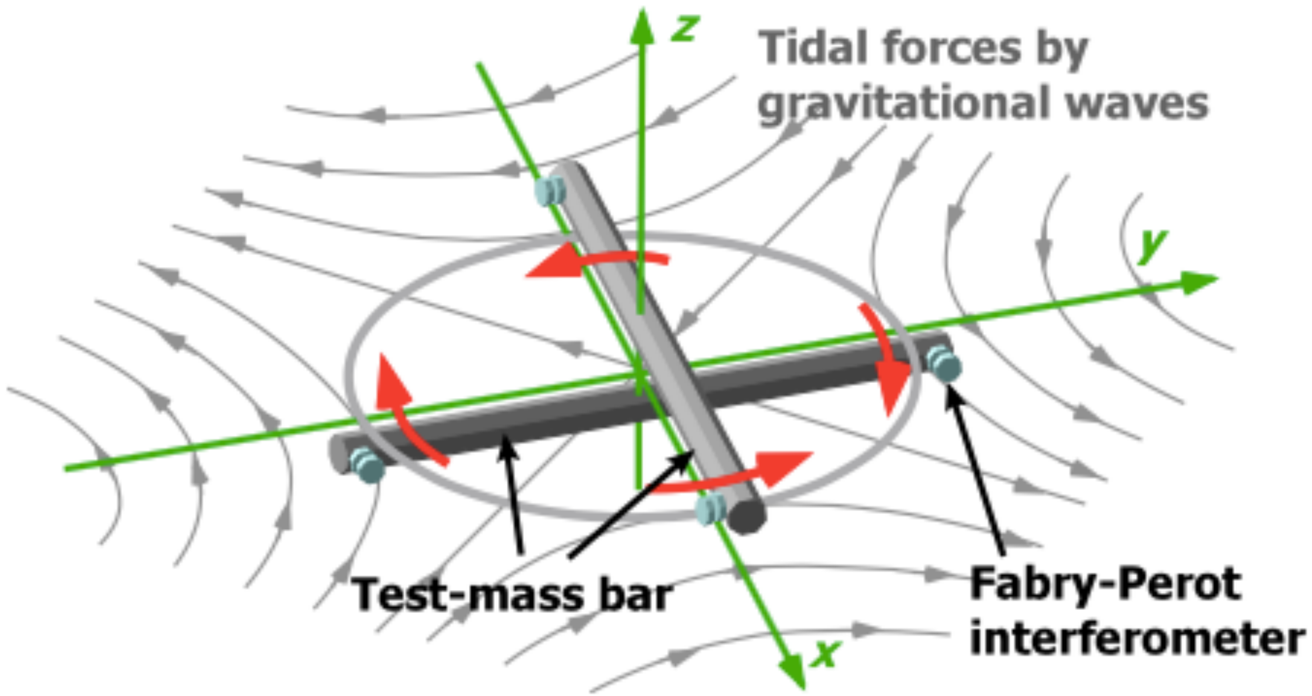
- summary and future plan

Introduction

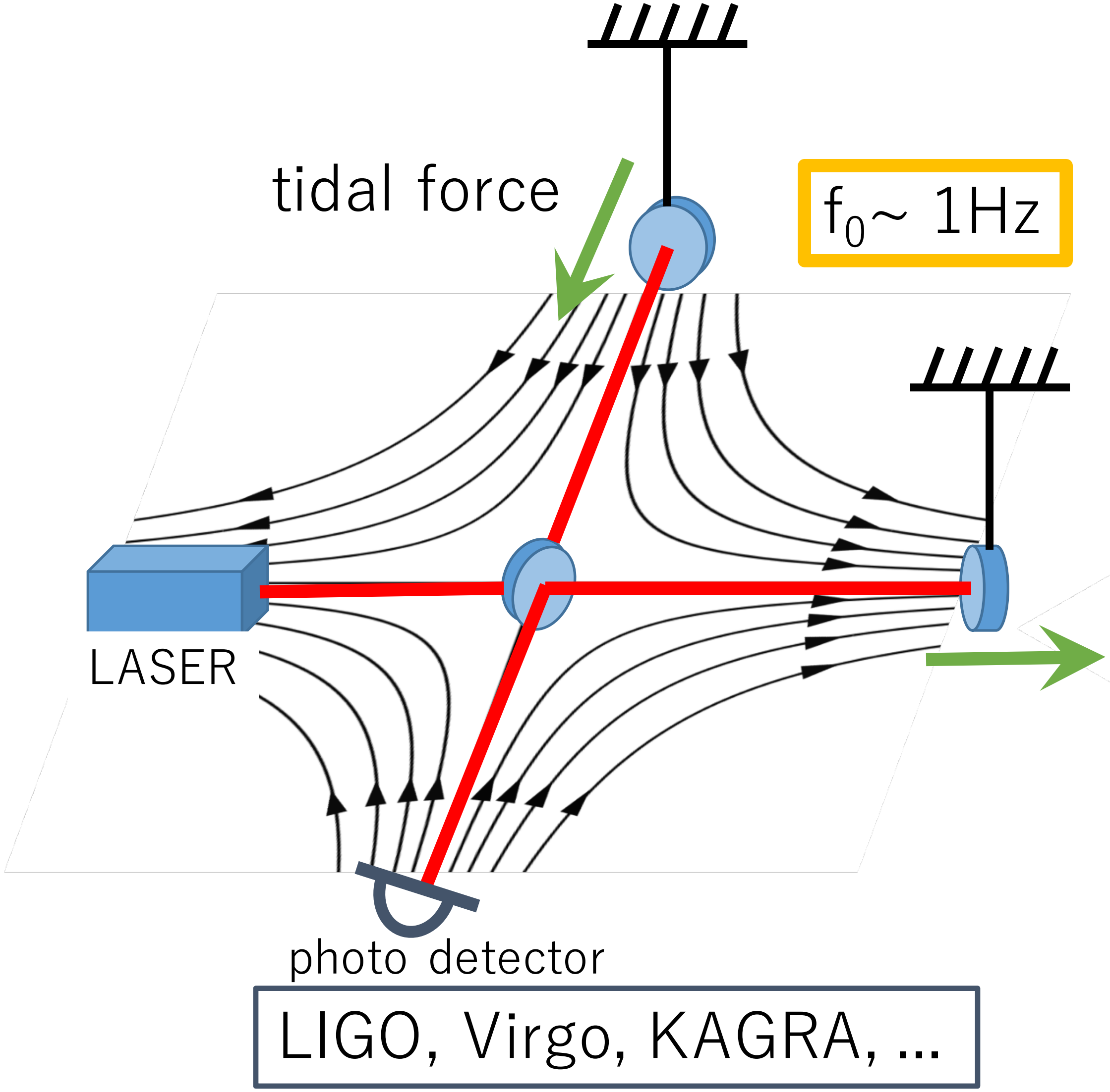
TOrsion-Bar Antenna

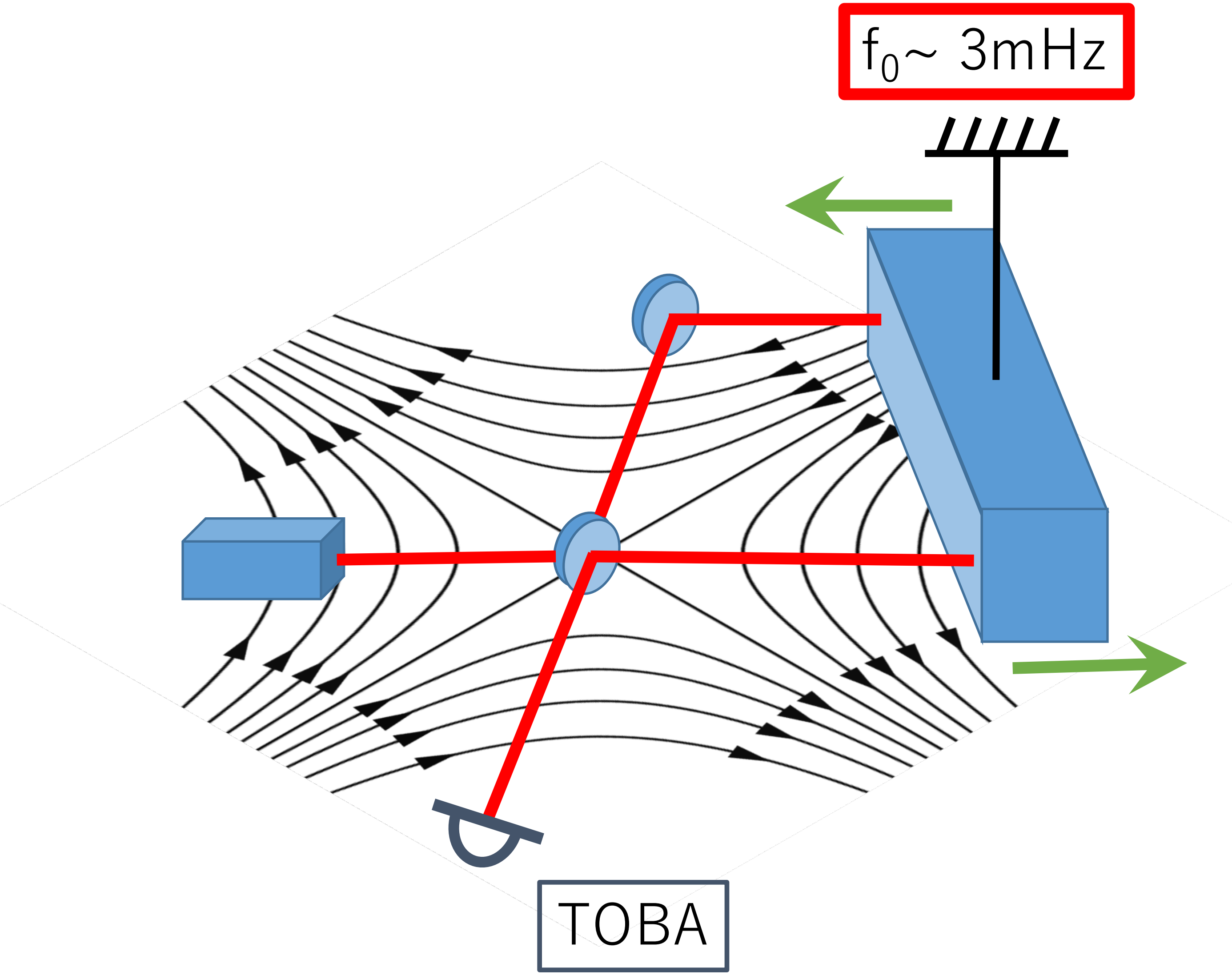
- TOBA = a gravitational wave detector using a torsion pendulum
- sensitive to lower-frequency GWs because of low resonant frequency(~3mHz) of Yaw rotation



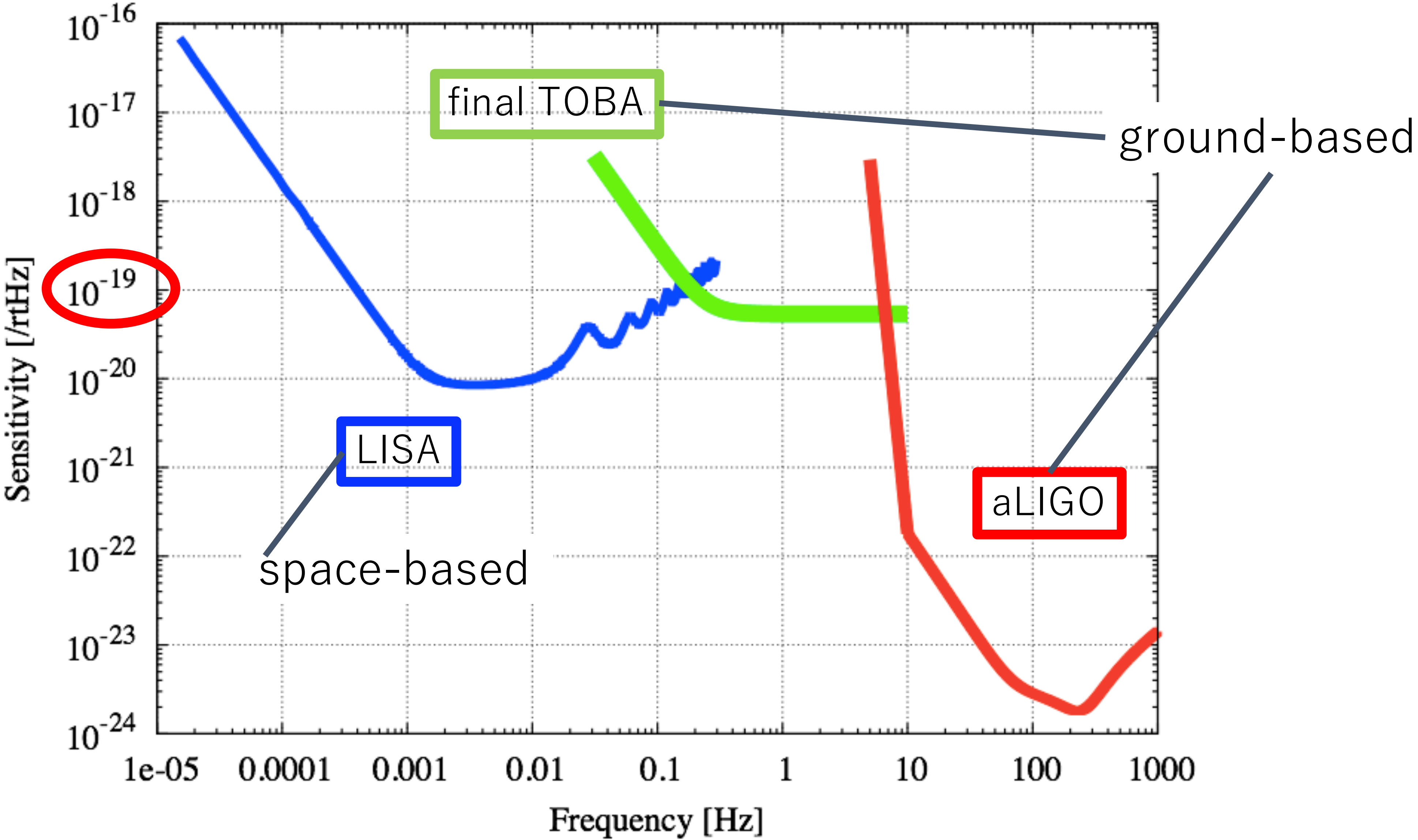
Principle

- Gravitational waves act as tidal force on test masses





Gravitational Wave Detectors



final TOBA

ground-based

LISA

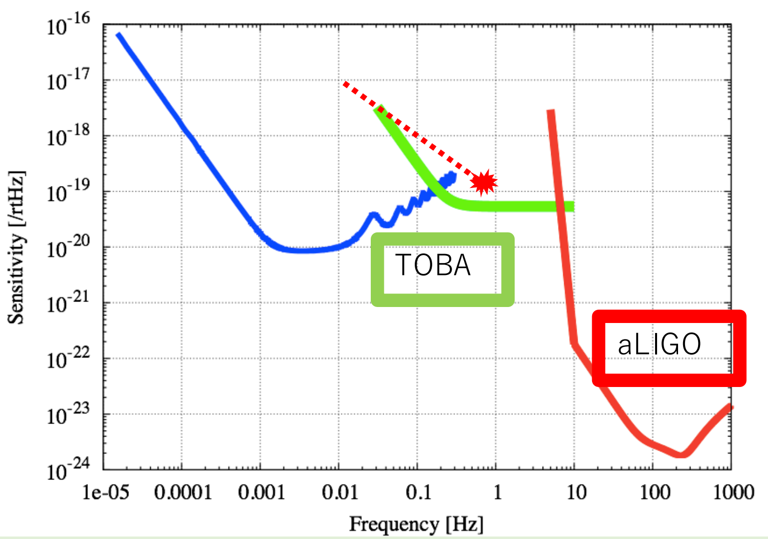
aLIGO

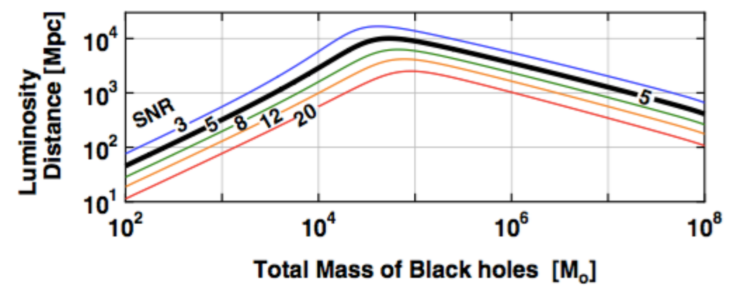
space-based

Target of TOBA : gravitational wave

Gravitational Wave observation

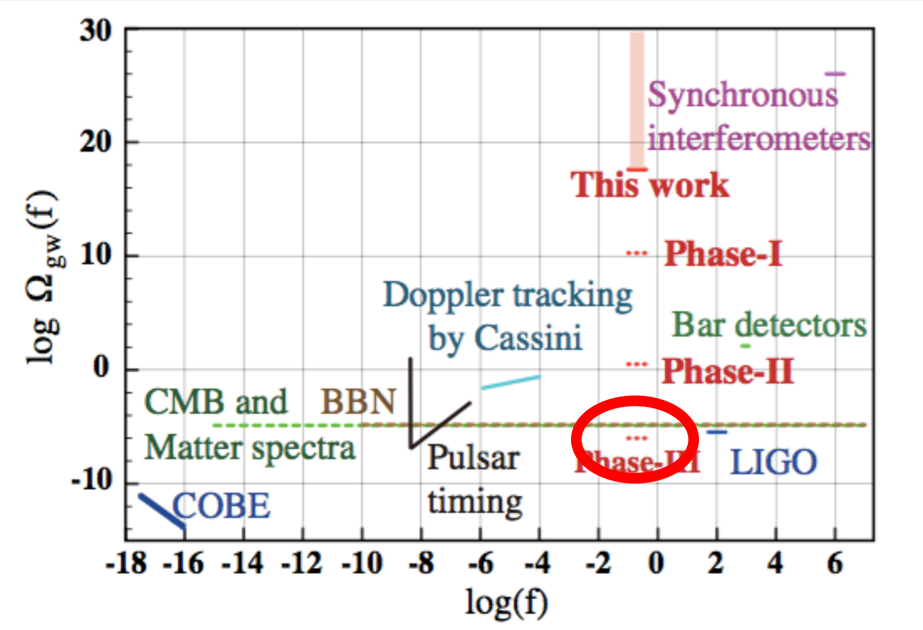
- Intermediate Massive Black Hole binaries
  (within 1~10Gpc for $M=10^{3\text{-}5} M_{sun}$)





PhysRevLett. 105.161101

- stochastic GW background
  (upper limit on $\Omega_{GW} < 10^{-7}$)



Phys. Rev. Lett. 106.161101

Target of TOBA : other measurements

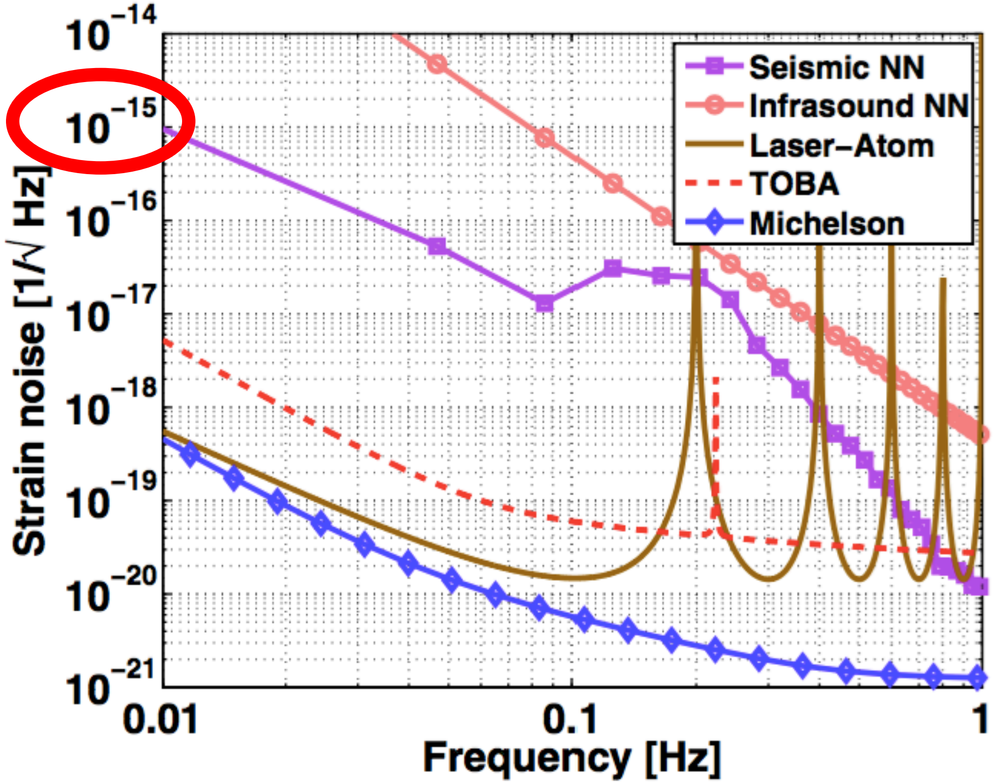
Apply to other experiments

- as a gravity-gradiometer :
  - Newtonian Noise measurement
  - Earthquake early alert by detecting gravitational field fluctuation

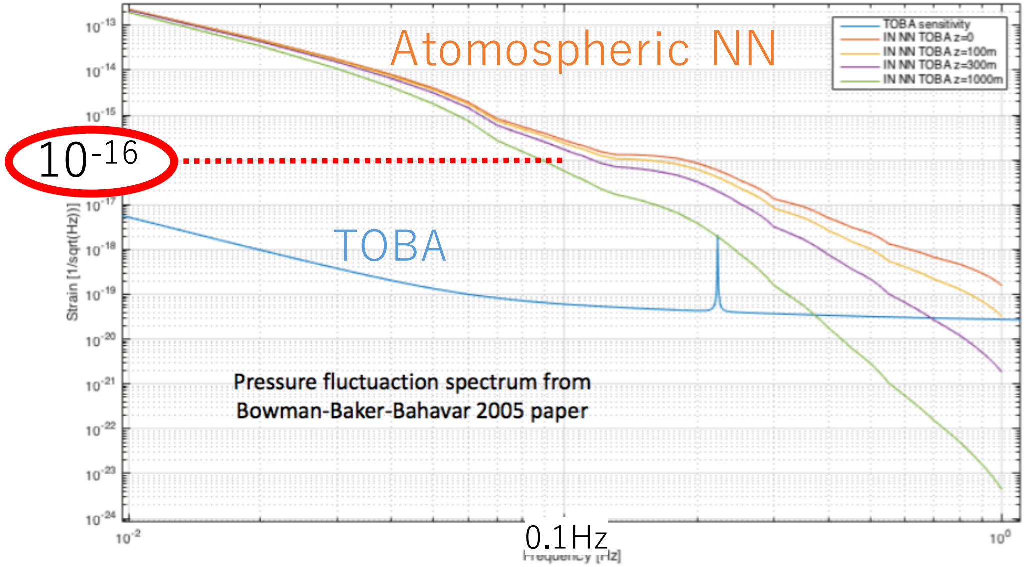
- other tiny force measurements :
  - gravity inverse-square law
  - test for space missions
  - quantum noise measurement

Newtonian Noise

- Newtonian gravity fluctuation from fluctuation of seismic field & atomosphere
- Noise amplitude (GW strain equivalent) = $\underline{10^{-15} \sim 10^{-16}\ /\mathrm{Hz}^{1/2}\ @0.1\mathrm{Hz}}$



(J.Harms et al., 2013)



Pressure fluctuaction spectrum from Bowman-Baker-Bahavar 2005 paper

(by Donatella Fiorucci)

Earthquake early alert

- density perturbation by earthquake generate gravitational field perturbation

  ⇒ detectable with gravitational wave detectors

- GW strain equivalent signal level :

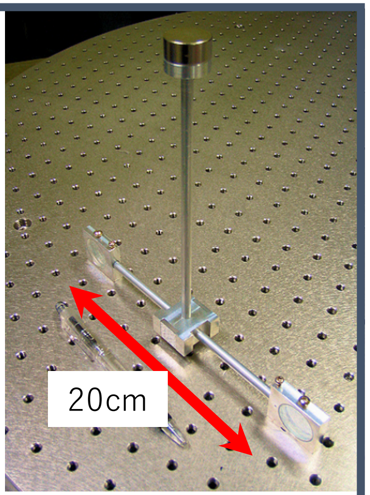
$$h(t) = \frac{6\sqrt{14/5}\,G}{{r_0}^5}\, I_4[M_0](t)$$

⋯ M6.0 , r_0=70km ⇒ $\underline{h\sim10^{-15}/\mathrm{Hz}^{1/2}}$

Development history

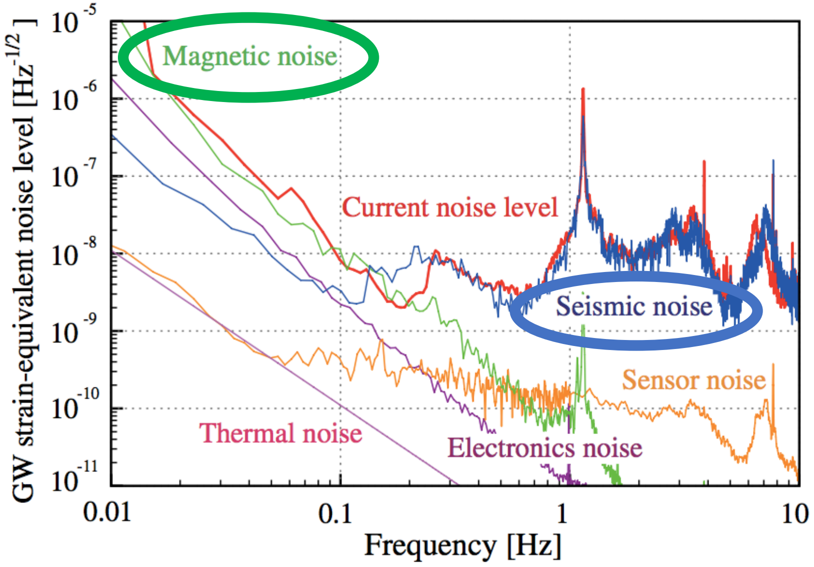
Phase-I

(magnetic levitation)
→ h ~ 10^{-8} /Hz$^{1/2}$
@0.1Hz



limited by …

- magnetic noise
- seismic noise



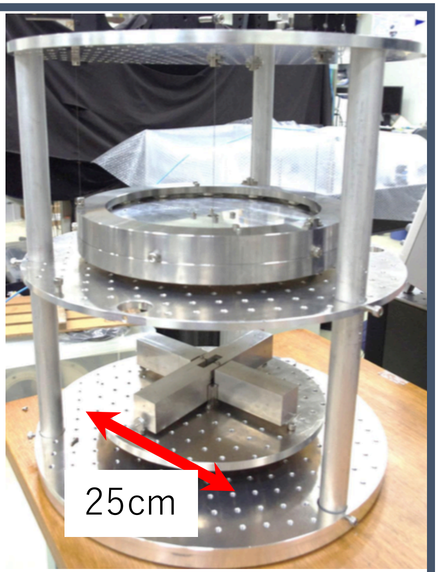
(Ishidoshiro et. al., 2011)

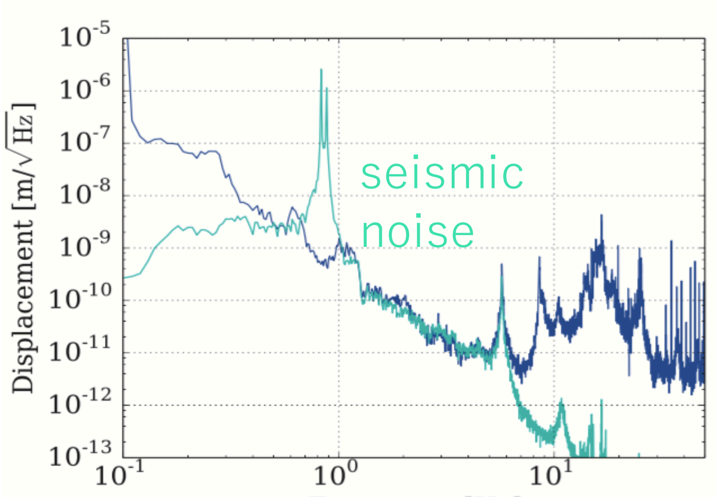
Phase-II

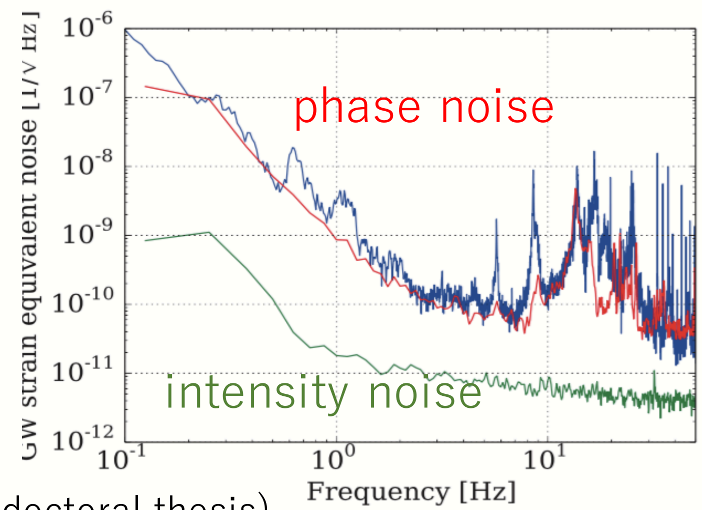
(wire suspension)
→ h ~ 10^{-10} /Hz$^{1/2}$ @5Hz

limited by …

- sensor noise(fiber optics)
- seismic noise







(A. Shoda doctoral thesis)

Phase-III TOBA

Next step : Phase-III TOBA

✓Proof of principle

✓understanding of noise sources

completed

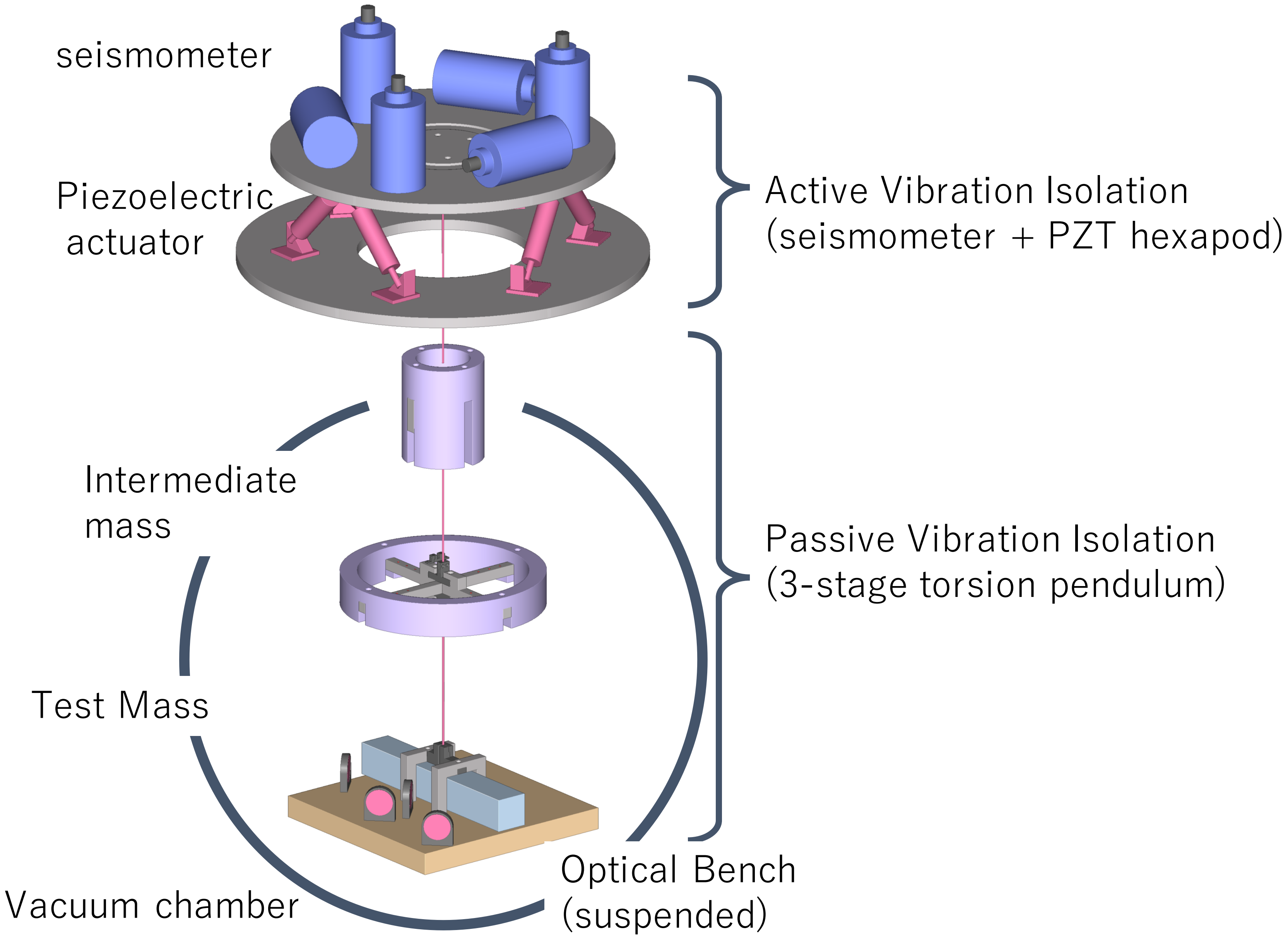
✓Next : noise reduction & scientific observation

- direct detection of Newtonian noise
- early alert for big earthquakes
- nearby IMBH search (d<100kpc)

Target Sensitivity

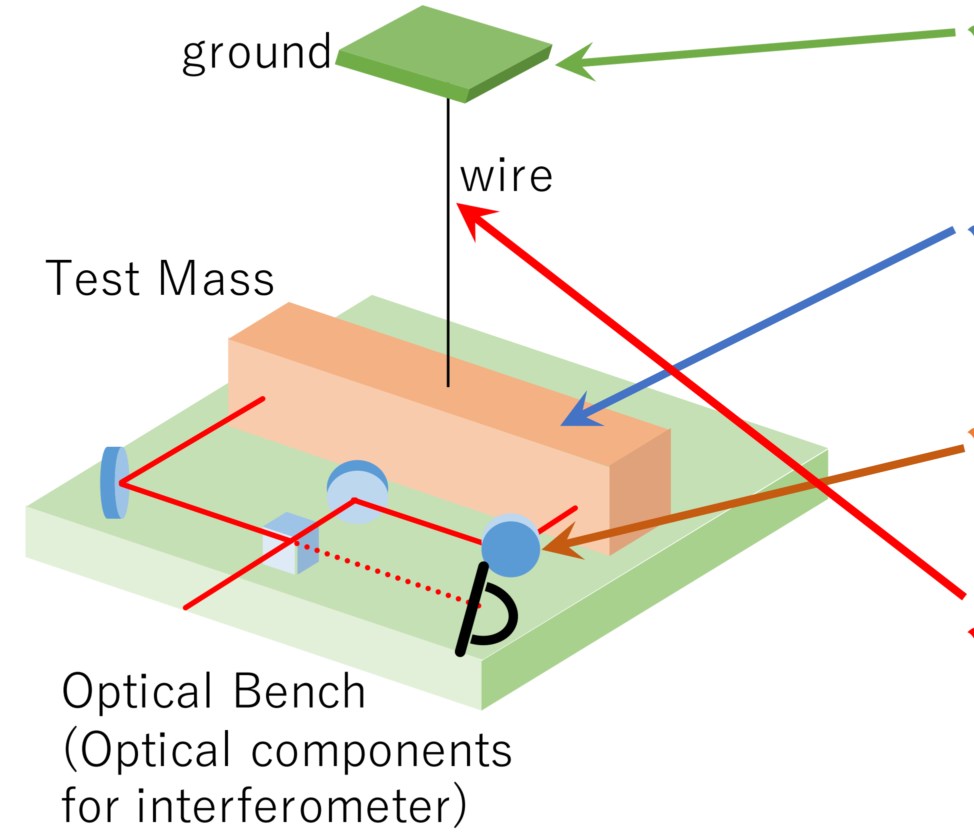
$h \sim 10^{-15}\ /\mathrm{Hz}^{1/2}$ @0.1Hz

Phase-III TOBA Configuration



Main noise sources for Phase-III TOBA

(simplified configuration)



✓Seismic noise

- noise from ground motion

✓Magnetic noise

- noise from external magnetic field fluctuation

✓Sensor noise

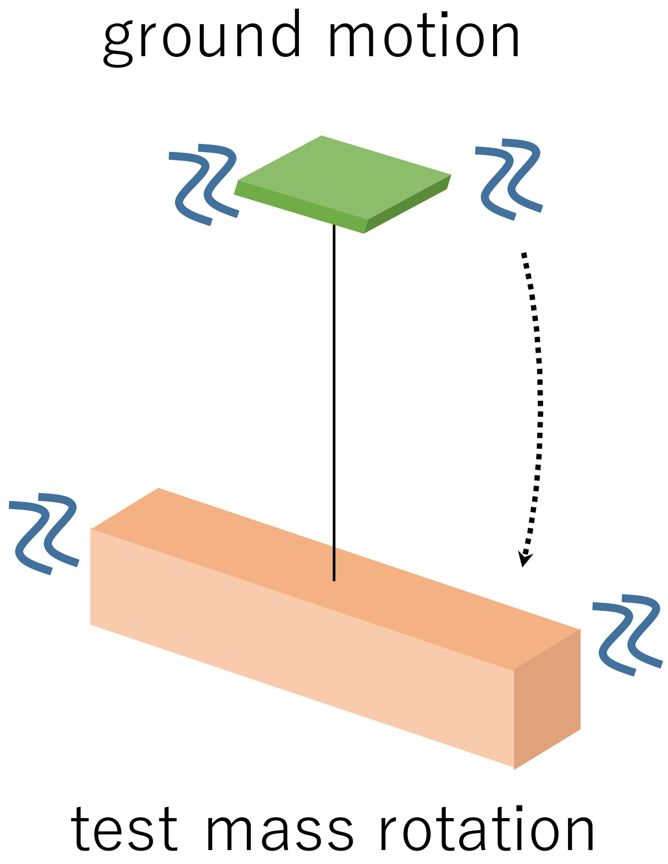
- noise from vibration of the mirrors

✓Suspension thermal noise

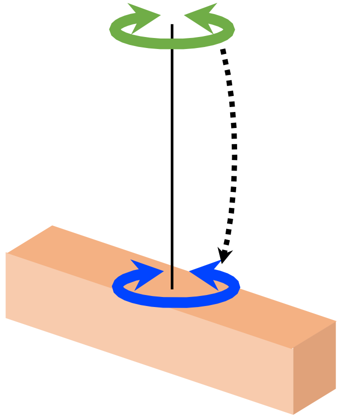
- noise from therma fluctuation via the wire

Seismic noise

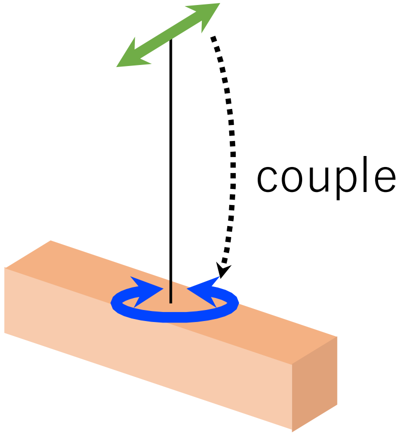
- Noise from seismic ground motion ($\delta x \sim 10^{-6}$ m/Hz$^{1/2}$ @0.1Hz)



- rotational seismic noise
  ⇒ vibration isolation

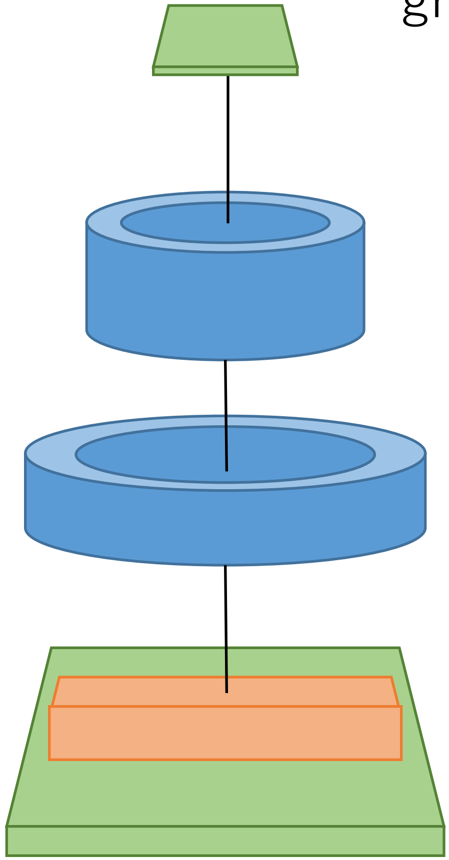


- seismic cross-coupling noise
  ⇒ coupling reduction



Rotational seismic noise

- Vibration isolation with multi-stage torsion pendulum
- Requirement : $\delta\theta < 5\times10^{-16}$ rad/Hz$^{1/2}$



ground(assumption) :

$\delta\theta \sim 10^{-10}$ rad/Hz$^{1/2}$ @ 0.1Hz

⬇

1st intermediate mass:

$\delta\theta \sim 3\times10^{-10}$ rad/Hz$^{1/2}$

⬇

2nd intermediate mass

$\delta\theta \sim 1\times10^{-12}$ rad/Hz$^{1/2}$

⬇

test mass & optical bench

$\delta\theta \sim 1\times10^{-14}$ rad/Hz$^{1/2}$

design completed

⇒ differential rotation

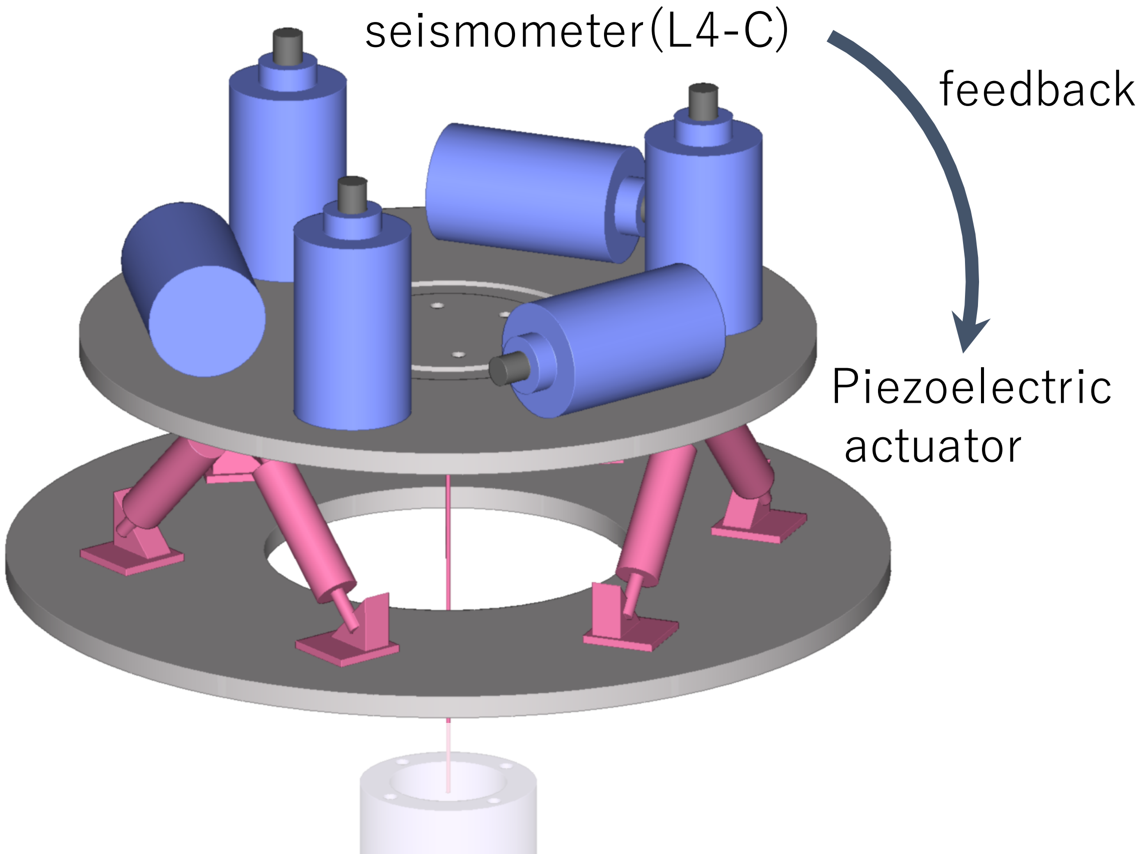
$\delta\theta \sim 1\times10^{-16}$ rad/Hz$^{1/2}$

(common mode rejection)

Active Vibration Isolation Table

- Passive isolation of translational seismic motion at 0.1Hz is very difficult

⇒ active isolation (AVIT) (developped by A. Shoda)



performance will be limited by :

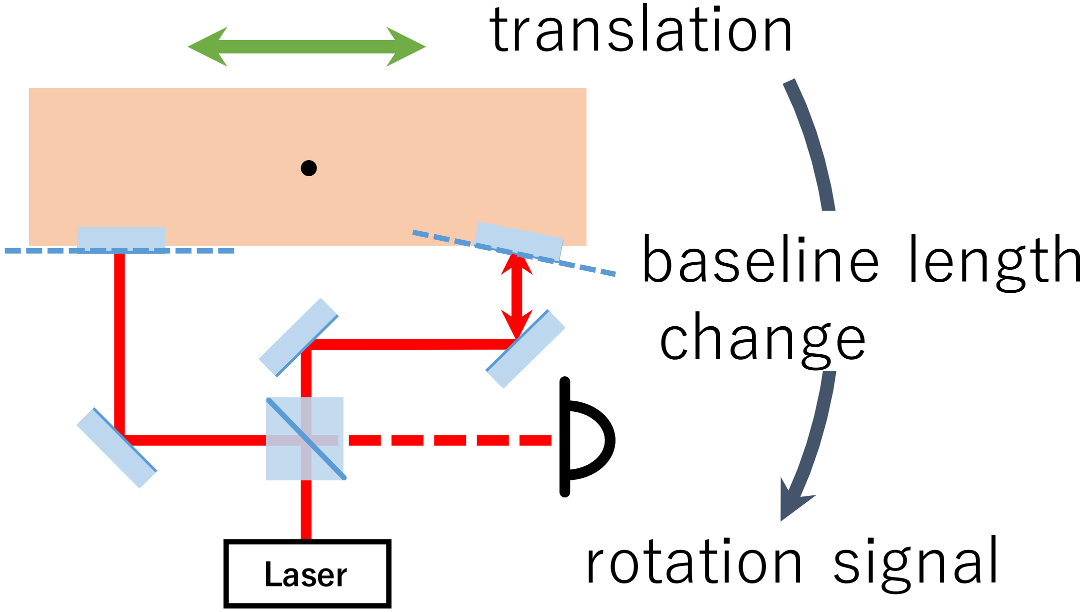
・sensor nosie ($\sim 10^{-7}$ m/Hz$^{1/2}$)

・coupling from tilt

⇒need to solve these problems

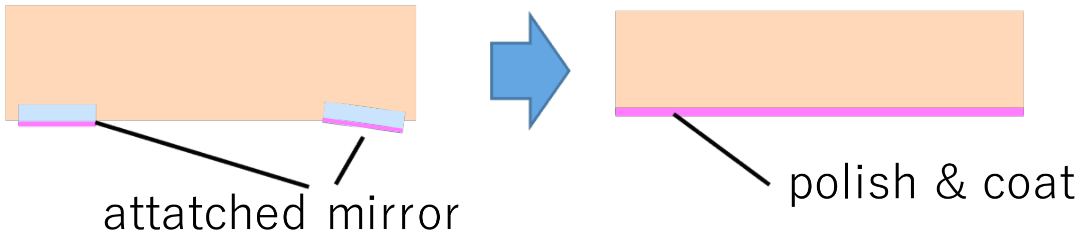
Cross-coupling noise ①

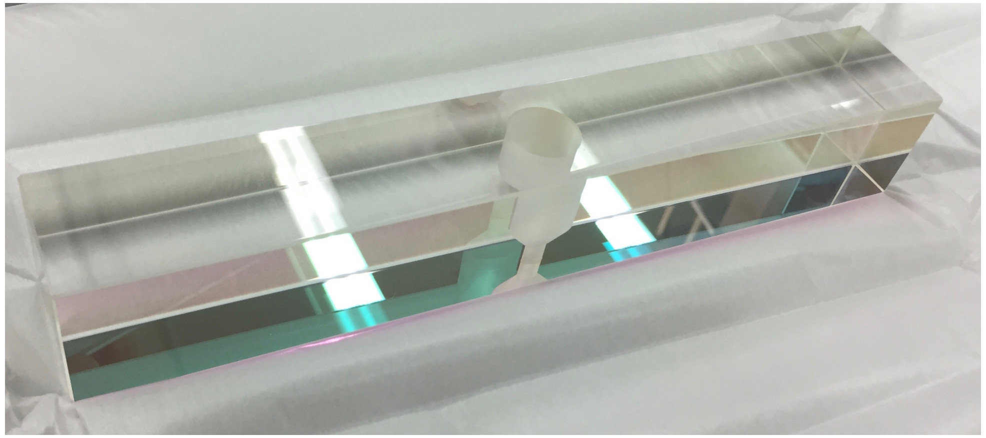
- from the tilt of mirrors on the test mass



Requirement :
(tilt) < 10^{-7} rad

⇒ polished test mass



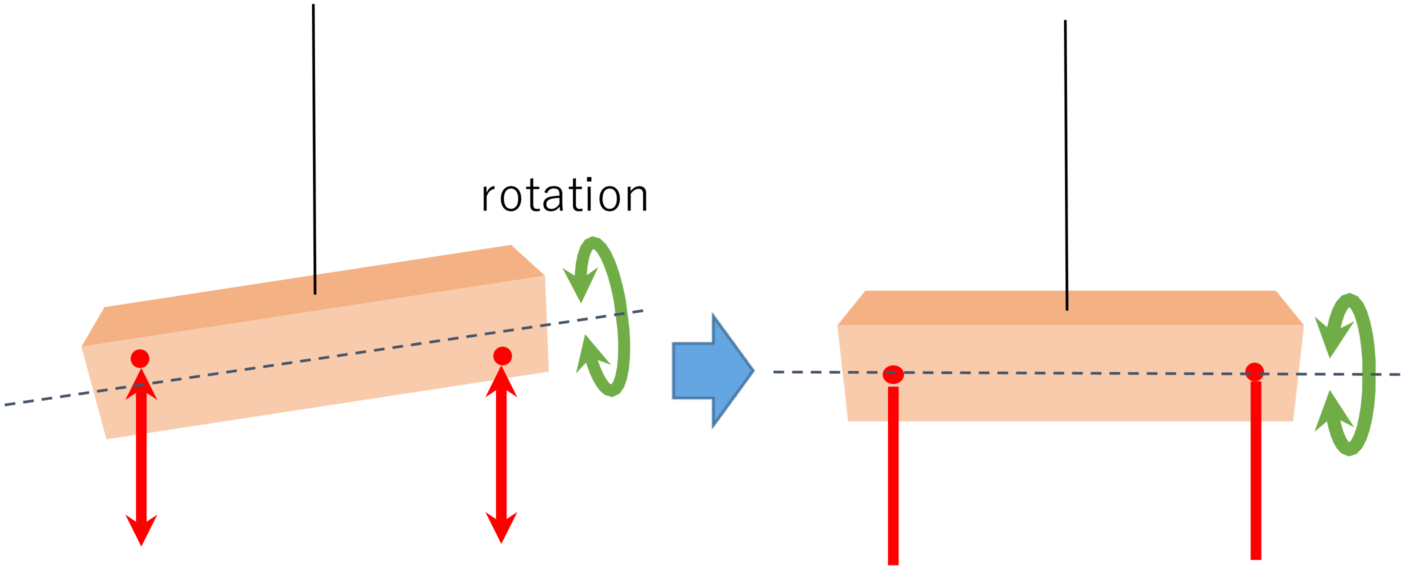


under evaluation

Cross-coupling noise ②

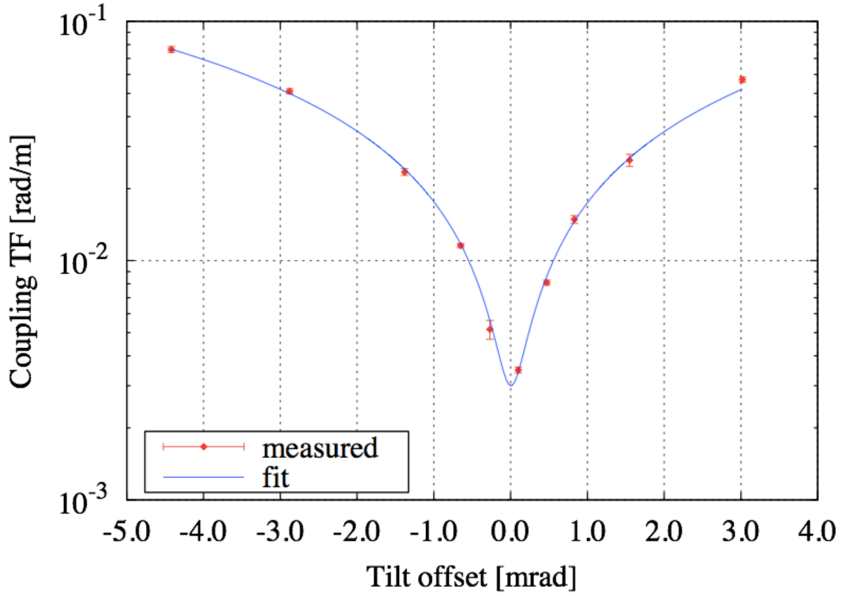
- from other rotation via the tilt of the test mass

⇒adjust the tilt of the test mass



baseline length change

baseline length is constant



Requirement : <u>(tilt) < 30 nrad</u>

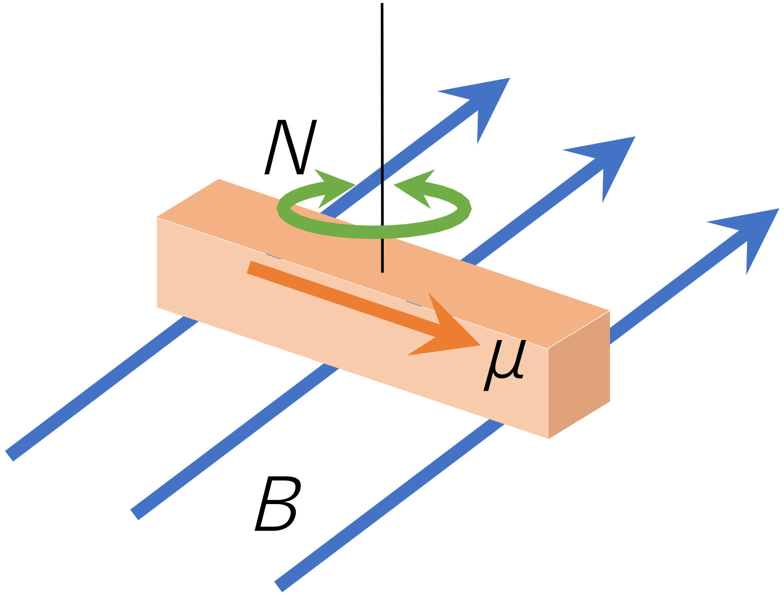
reduction was demonstrated

now : (tilt)~100 μ rad

⇒ need fine tuning

Magnetic noise

- Noise from fluctuation of the environmental magnetic field (via the magnetic dipole moments of the test mass)



$$\underset{\text{torque}}{\vec{N}} = \underset{\text{magnetic moment}}{\vec{\mu}} \times \underset{\text{magnetic field}}{\vec{B}}$$

magnetic moment μ :

- attatched magnets for actuator
- residual magnetization of test mass(not evaluated)

measured magnetic field fluctuation :

$$B = 1.0\times10^{-8}\left(\frac{0.1\ \text{Hz}}{f}\right)\ \text{T}/\sqrt{\text{Hz}}$$

→

required magnetic moment :

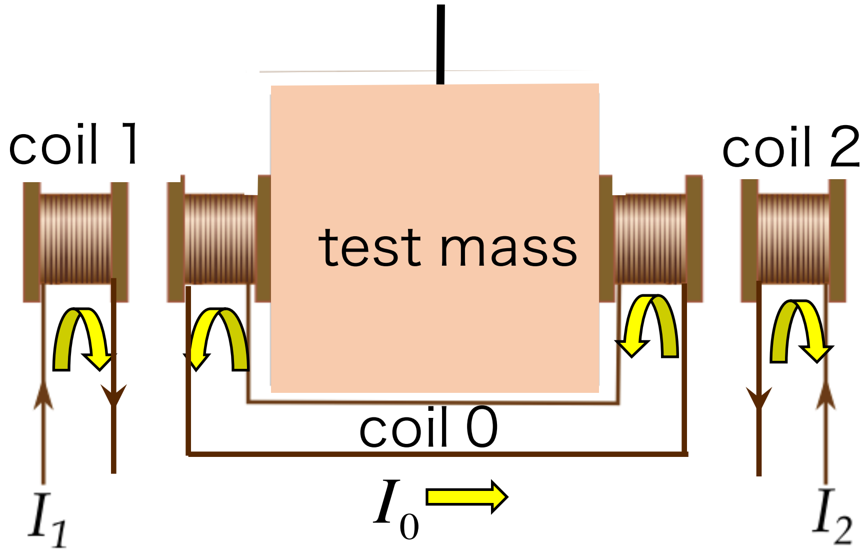
$$\boxed{\mu < 6\times10^{-11}\ \text{A}\cdot\text{m}^{2}}$$

cannot use magnets

⇒ develop new actuator : Coil-Coil actuator

Coil-Coil actuator

- magnetic interaction between drive AC current and induced current



$= i_1 \sin(\omega_d t)$

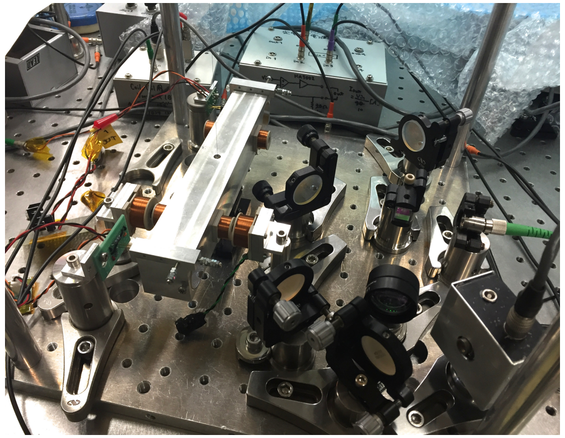
$= i_2 \sin(\omega_d t + \varphi)$

Force : $F \propto {i_1}^2 - {i_2}^2 , \sin\varphi$

amplitude modulation

phase modulation

Coil-Coil actuator is already available
(succeeded to control TOBA)



actuator noise is under evaluation

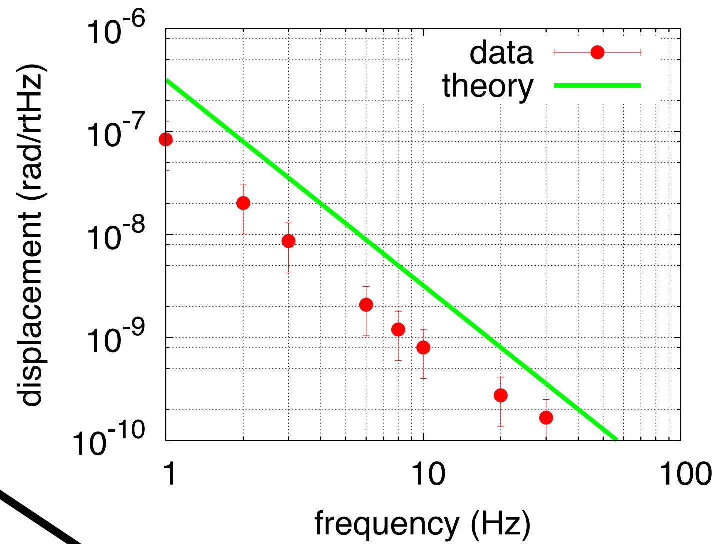
Magnetic noise with Coil-Coil actuator

- magnetic moment of the test mass changes in drive frequency ($\omega_d/2\pi$ ~10kHz)

$$\mu \propto I_0 \propto \sin(\omega_d t)$$

⇒ magnetic field fluctuation around ω_d will be down-converted into torque noise at 0.1Hz

$$N = \mu \times B \;\propto\; \sin(\omega_d t) \times \sin(\omega t) \sim\; \sin(\omega_d - \omega)t$$



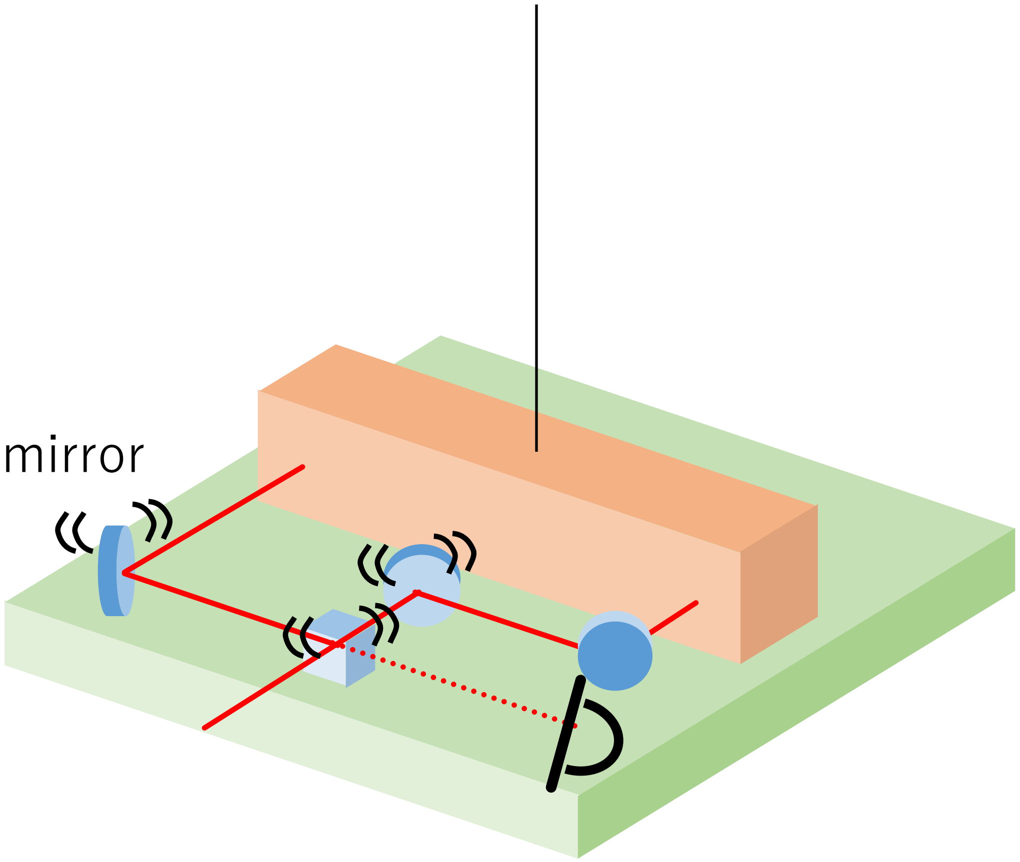
demonstrated by N. Aritomi
(agree with theory except for factor 3 difference)

fluctuation of B may be smaller at higher frequency & easire to shield
⇒ lower torque noise than coil-magnet actuator

※actual magnetic field fluctuation is not measured yet

Sensor noise

- Noise from vibration of optical components(mirror, beam splitter, …)

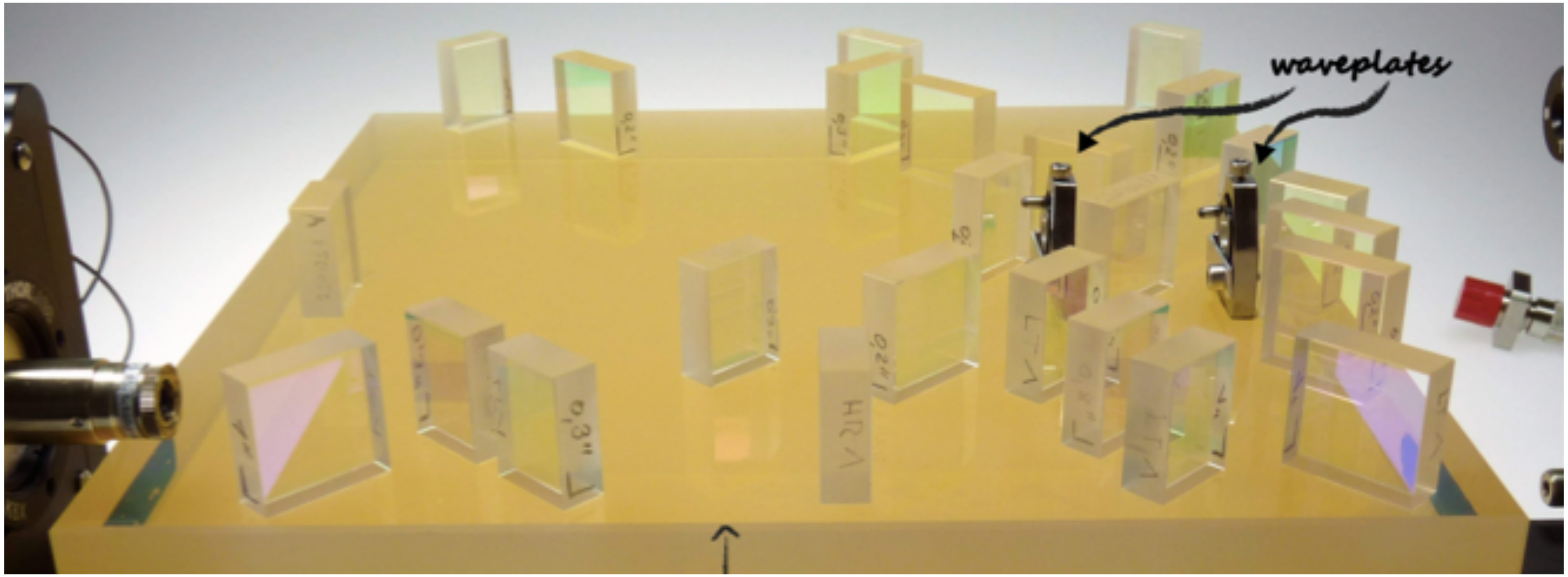


⇒ reduce vibration of mirrors
: develop monolithic optics

Monolithic optics

- mirrors are directly bonded on the plate

  ⇒ responce to vibration is reduced



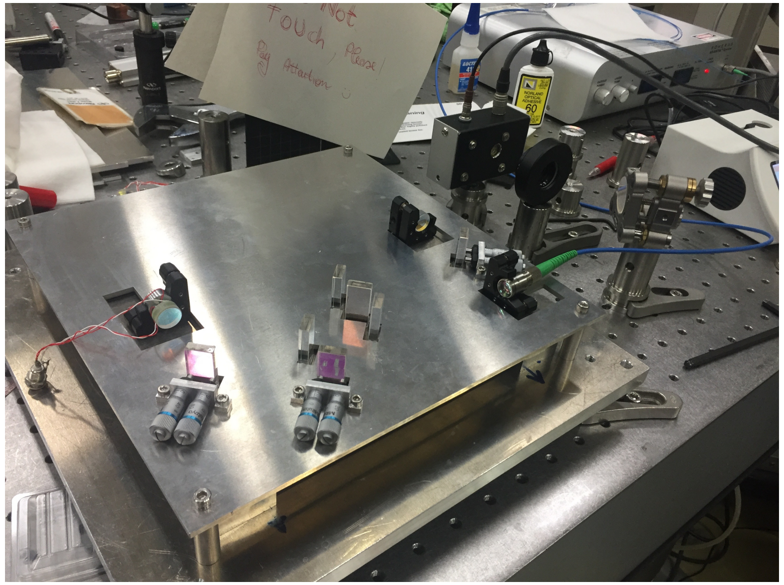
M. Dehne, Doctral thesis (2012)

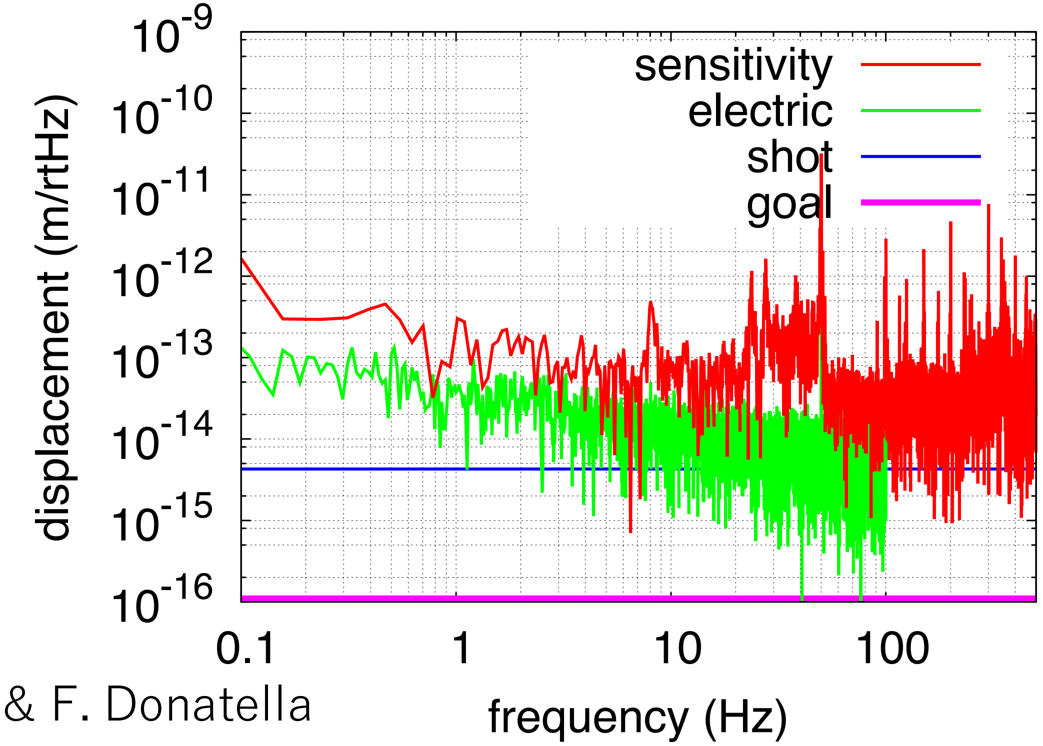
without mirror mount

Progress

- first prototype was made (by N. Aritomi & F. Donatella)
- current sensitivity : $\delta x \sim 1 \times 10^{-12}$ m/Hz$^{1/2}$ @0.1Hz

  (requirement : 1×10^{-16} m/Hz$^{1/2}$)
- Noise sources are under investigation



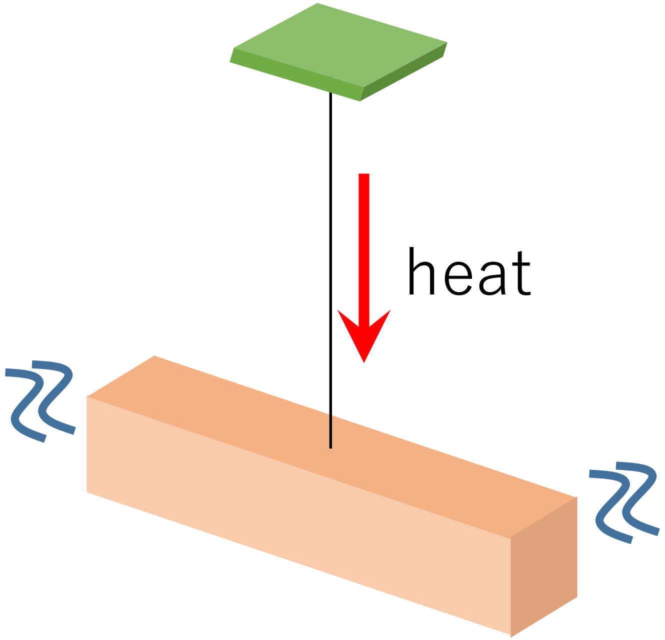


by N. Aritomi & F. Donatella

Suspension thermal noise

not yet

- Noise from thermal fluctuation through a suspension wire



$$\delta\theta = \sqrt{\frac{k_B T}{2\pi^3} \frac{f_0{}^2 \phi}{I f^5}}$$

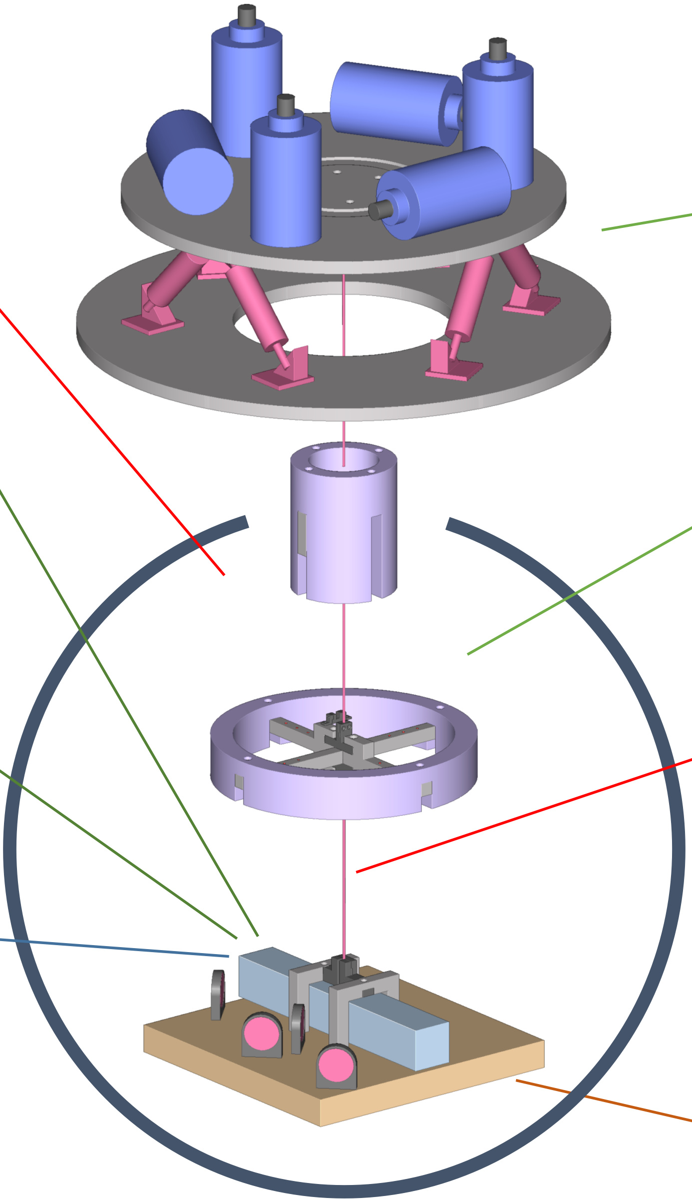
T : temperature
f_0 : resonant freq.
ϕ : mechanical loss of wire
I : moment of inertia

Requirement (in the case of I=0.06, f_0=2mHz) :
$\underline{T < 4K}$ & $\underline{\phi < 3 \times 10^{-8}}$

⇒ cooling & low loss wire
- construct cryogenic system
- material search for the wire
  (silicon, sapphire, fused silica,...)

Summary

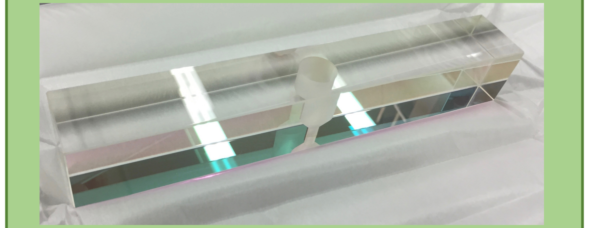
Summary of Phase-III TOBA Configuration



cryogenic

Active Vibration Isolation Table
(seismometer + PZT hexapod)

Polished Test Mass

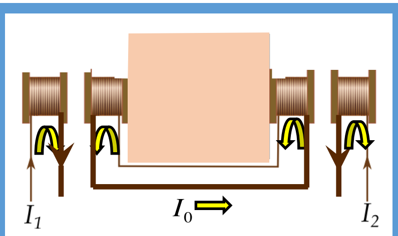


Passive Vibration Isolation
(3-stage torsion pendulum)

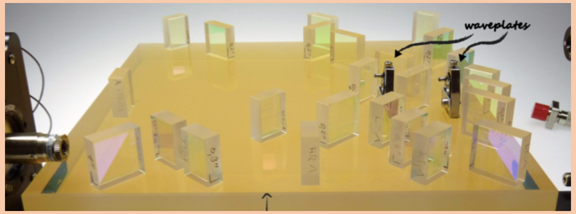
tilt control

low loss suspension wire

Coil-Coil actuator



Monolithic Optical Bench



Summary of progress

noise source	**reduction method & requirement**	**current status**	**residual task**
seismic noise	vibration isolation	design completed partly constructed	full construction & evaluation
	polished test mass	available	evaluation
	tilt adjustment	demonstrated	fine tuning
magnetic noise	coil-coil actuator	available	noise estimation
sensor noise	monolithic optics	first prototype was made	noise hunting
suspesion thermal noise	cooling low-loss wire	not yet	all

easy hard

Future plan (rough)

	2016	2017			2018			2019~	
rotational isolation				construction & evaluation					
cross-coupling reduction	test polished test mass fine tilt adjustment								
coil-coil actuator	noise estimation								
monolithic optics	noise hunting & sensitivity improvement								
suspension thermal noise					construct cryogenic system wire material search				

Thank you for listening