Torsion-bar Antenna for Astronomy and Geophysics

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Outline

- What is Torsion-bar Antenna (TOBA)?
    - Astronomy
    - Geophysics
- Development
    - Design of Phase-II TOBA
    - Sensitivity of Phase-II TOBA
- Future Plan

Torsion Pendulum

Torsion pendulum used in Cavendish's experiment

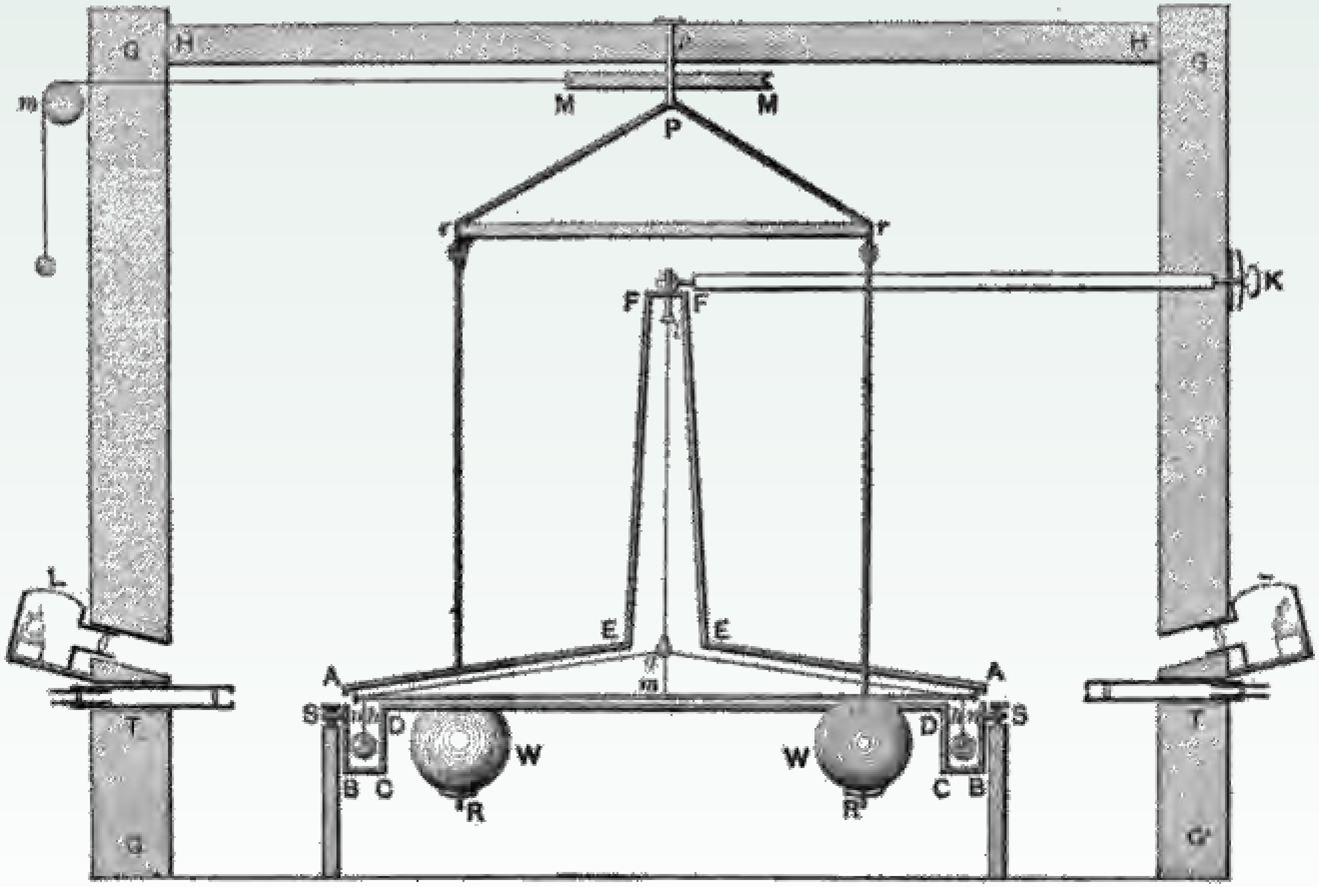
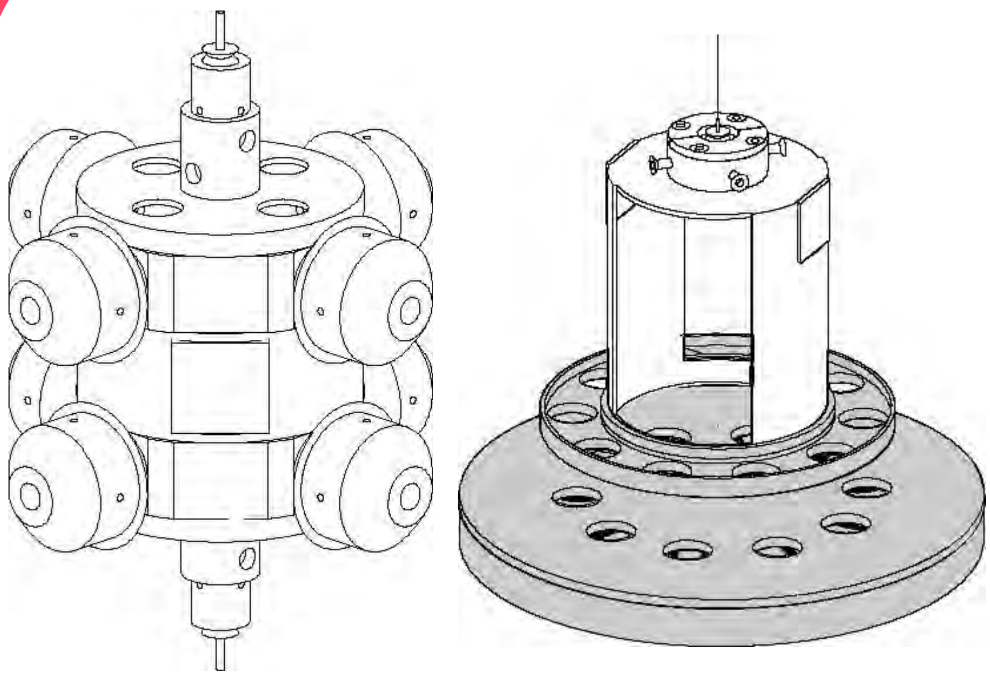


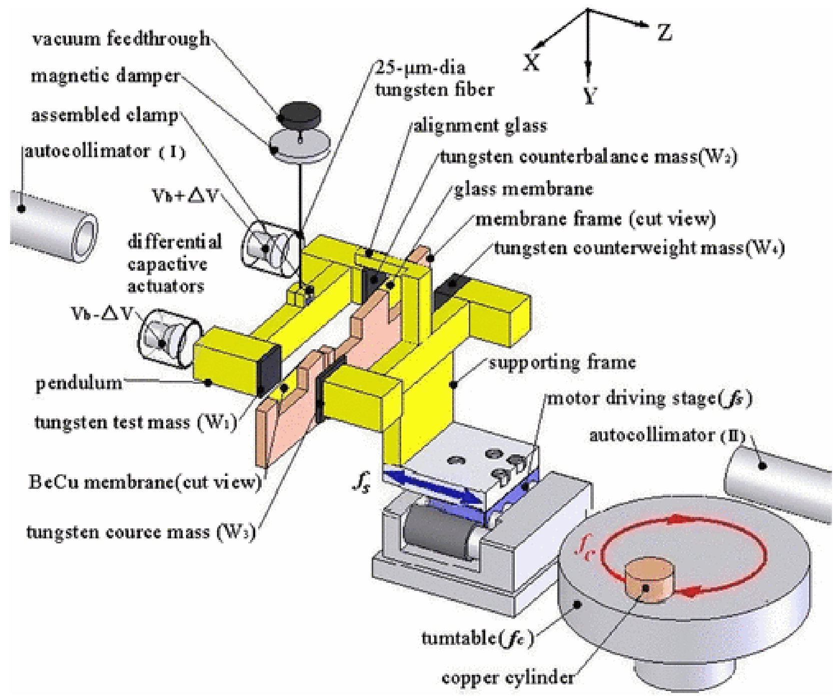
Fig. 1

Torsion Pendulum

Torsion pendulum used in Cavendish's experiment



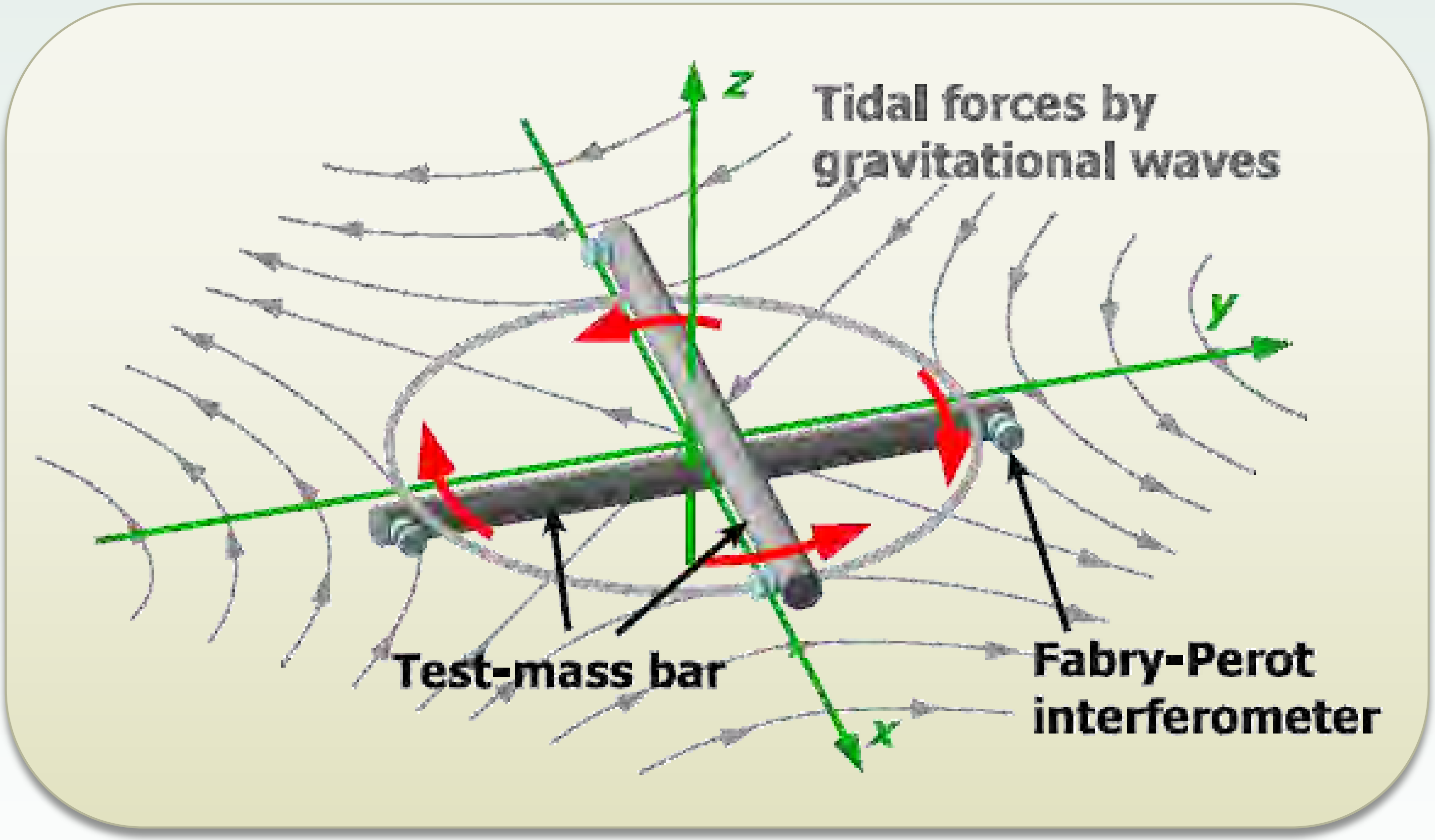
Eot-Wash group



Huazhong University

Torsion-bar Antenna

TOBA for the LF (0.01-10 Hz) gravitational wave detection



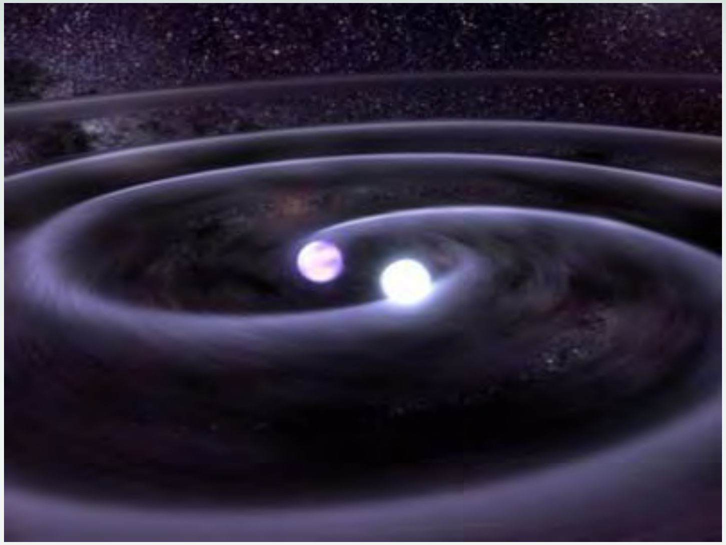
Sensitive to gravitational waves & gravity gradient

Gravitational Waves

Ripple of the space and time

Emitted from moving astronomical objects with the heavy mass

Ex.) Neutron star binaries,
Black hole binaries,
Supernovae…



New observation method of the universe

Information that electro-magnetic waves do not carry

Ex.) Radius of neutron stars,
State inside the supernovae…

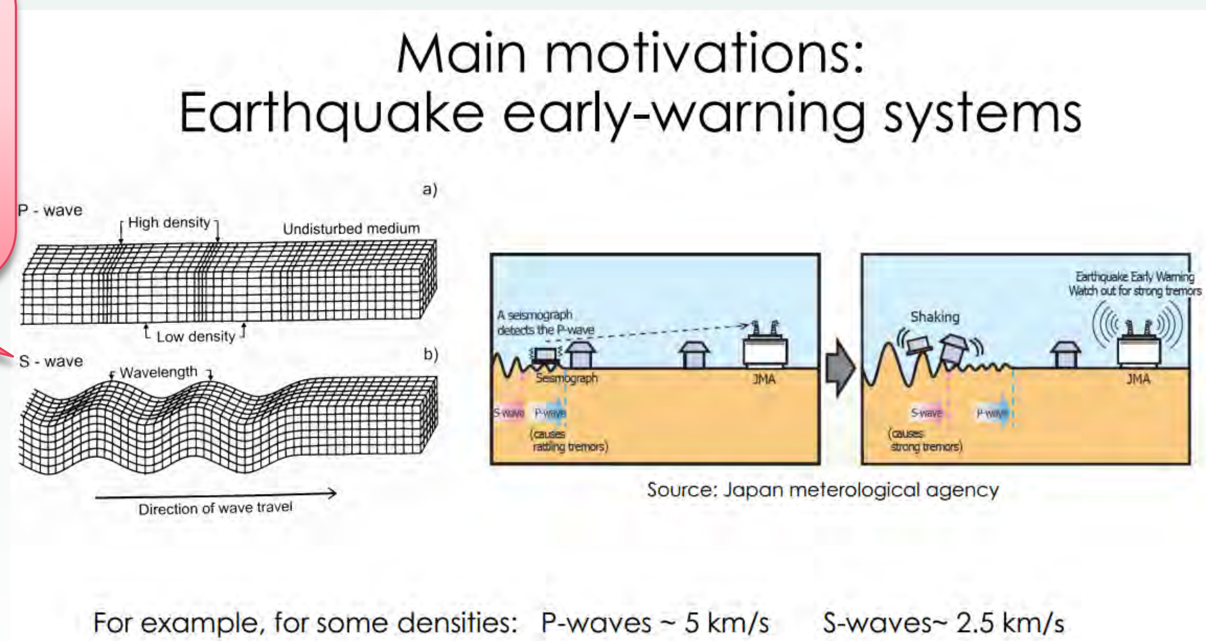
= **Gravitational wave astronomy**

Geophysics

Free masses move according to the gravity gradient

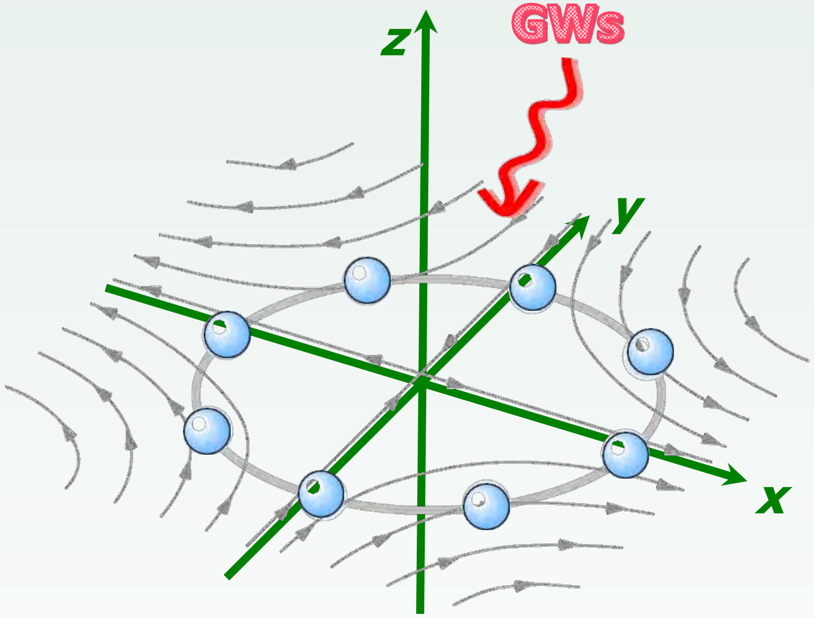
Not Yet Observed !

Gravity gradient signal from earthquakes arrives earlier than seismic waves



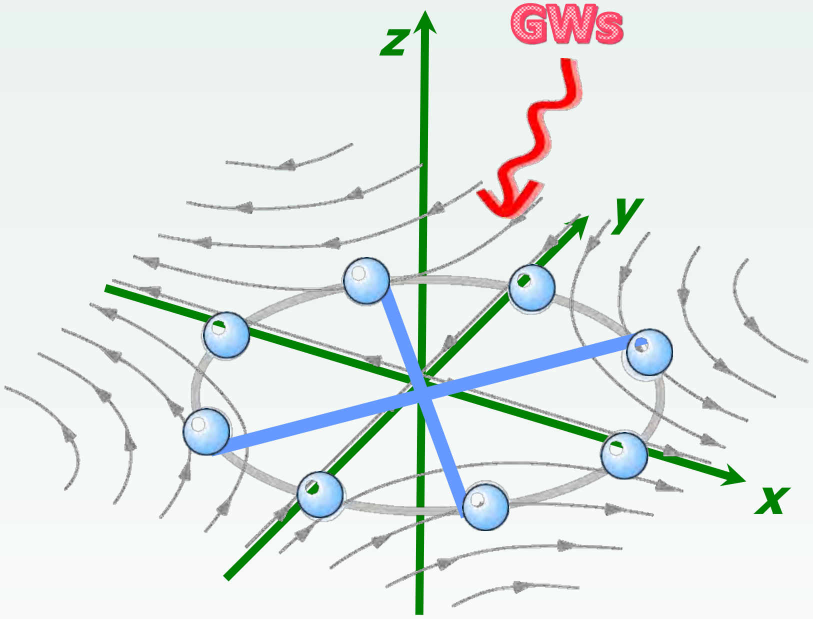
M. Barsuglia, GWADW2014 slide

Principle



Principle

TOBA



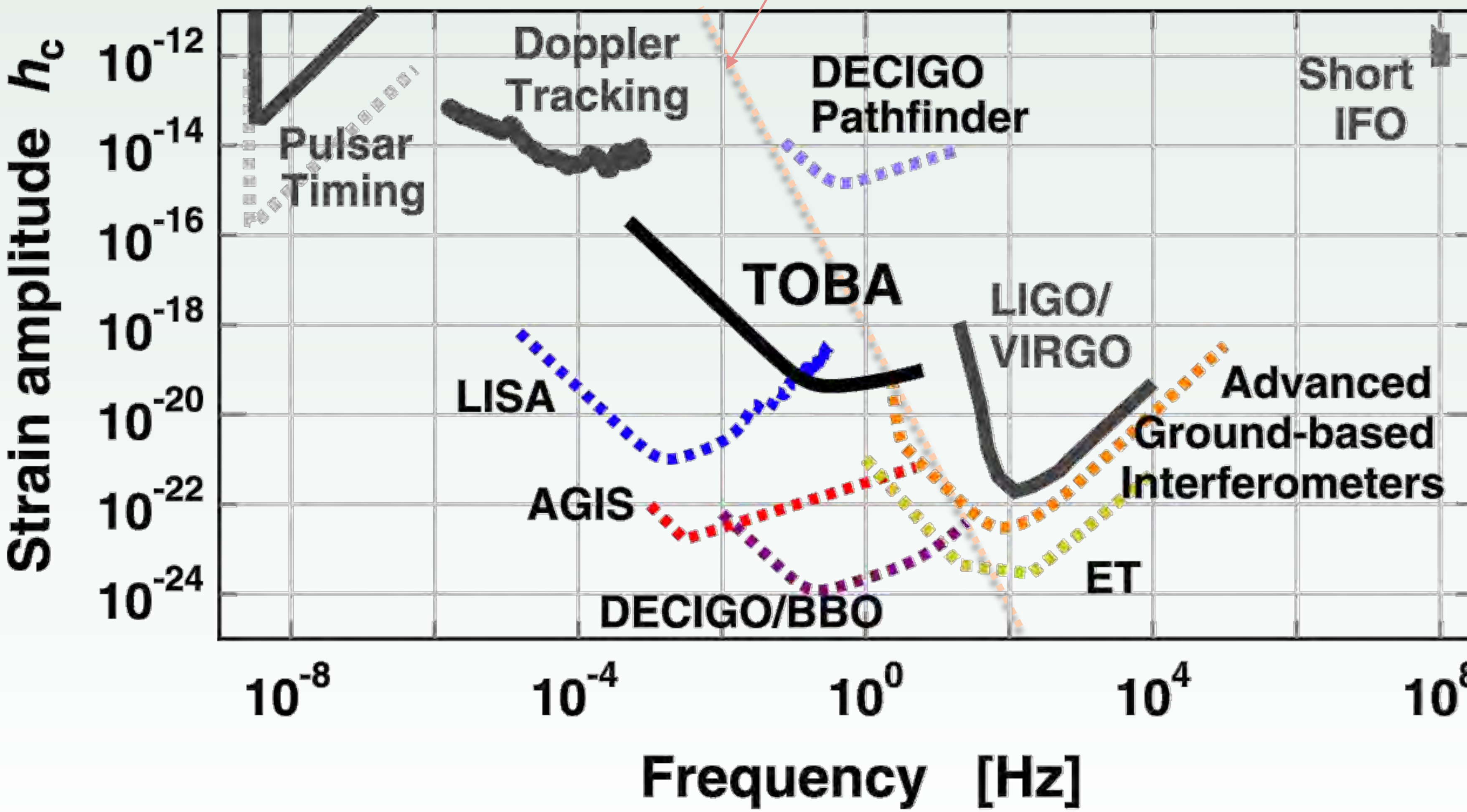
Angle $h \sim \delta\theta \sim \frac{\delta L}{L}$

GW Detectors and targets

Target Sensitivity

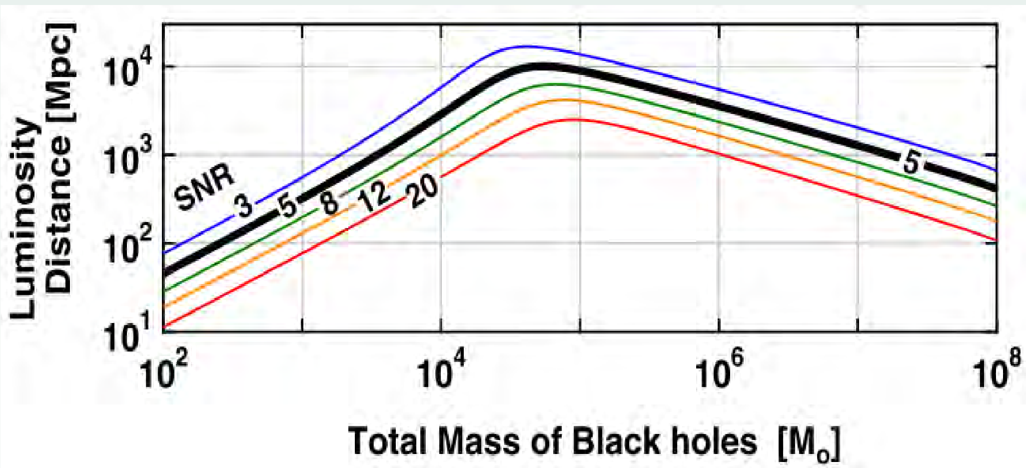
Signal from the gravity gradient
(Only for ground-based detectors)

(Example)



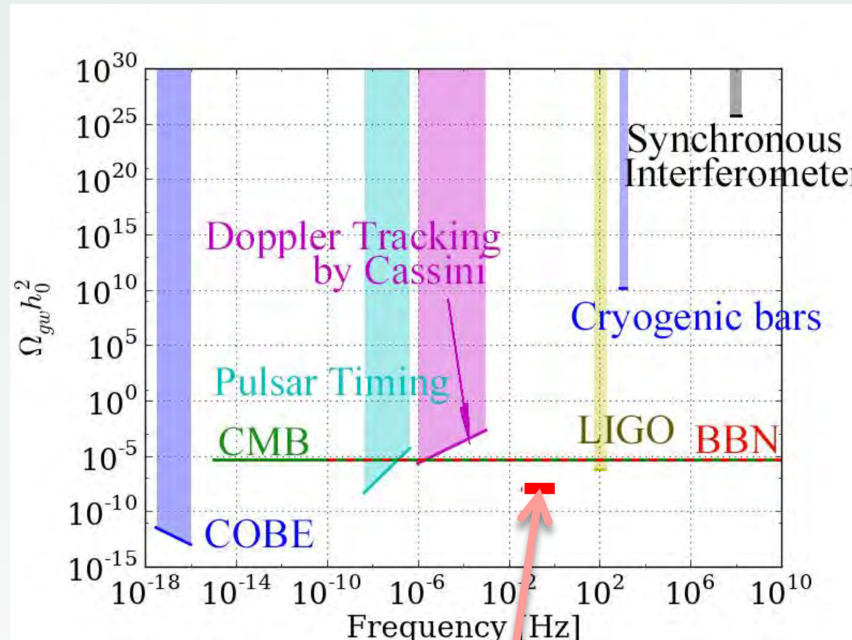
Astronomical targets

Black Hole Binaries



Mechanism of Super Massive BH, & galaxies

Stochastic GW background

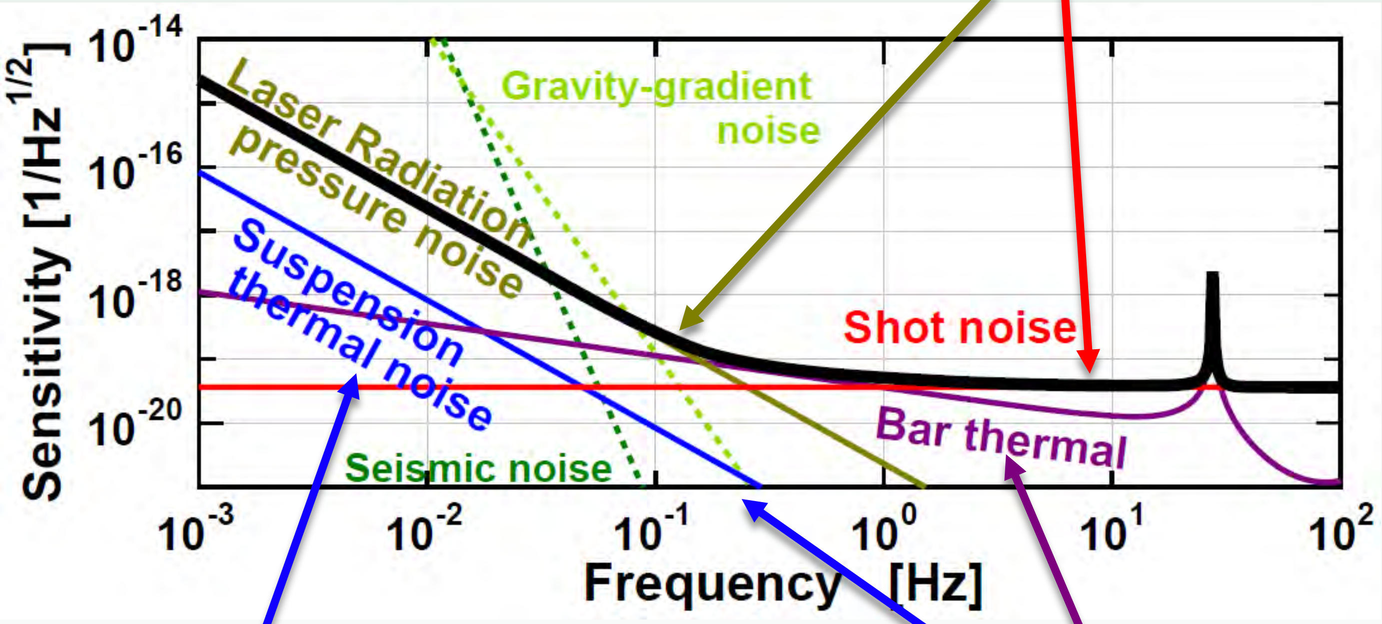


One year observation

Cosmology

What do we need?

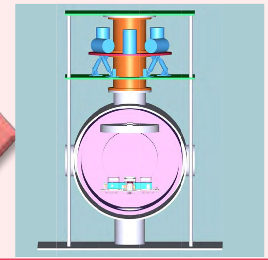
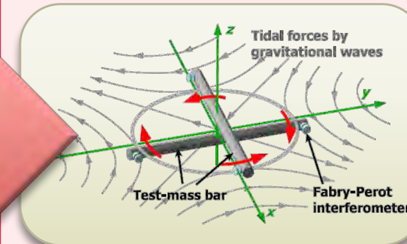
Bar length: 10m
Fabry-Perot Interferometer
Laser Power: 10W



Low loss suspension：
damping factor $\gamma=10^{-10}$

Cryogenic：4K

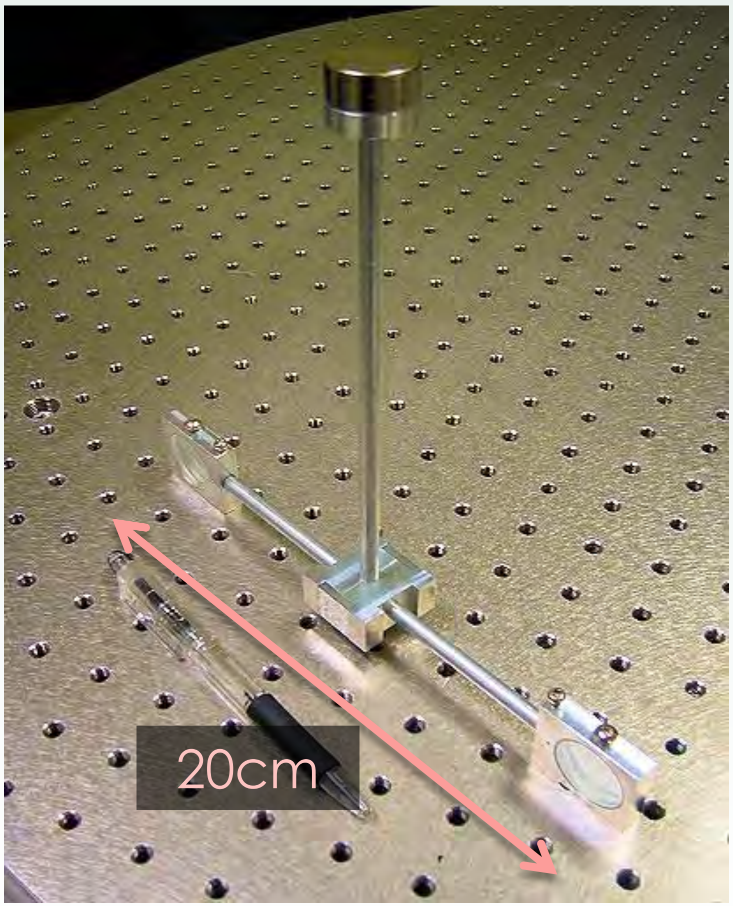
Roadmap

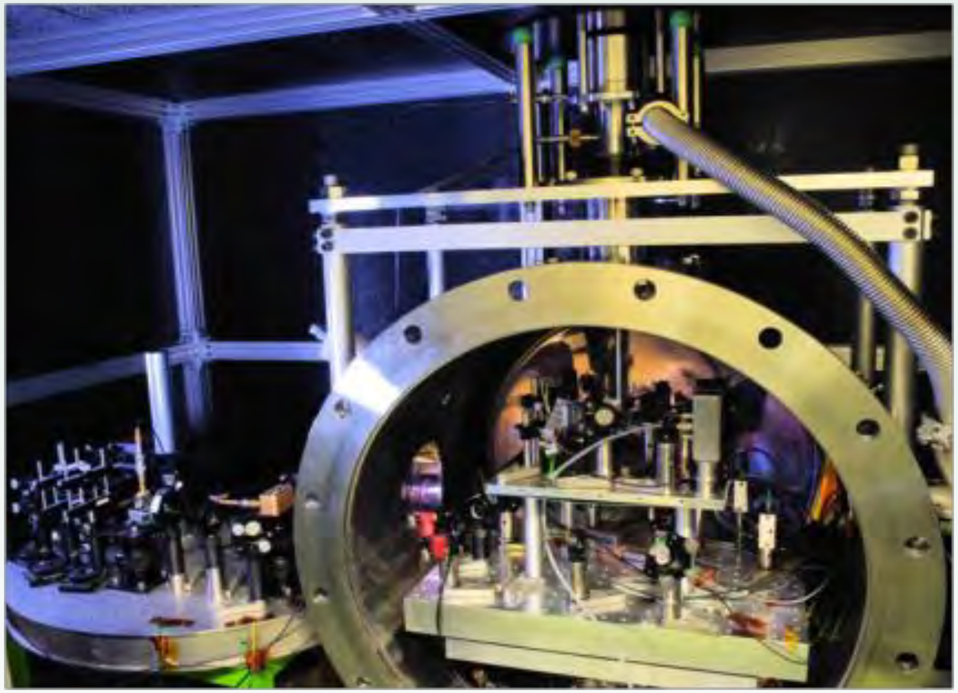
		Phase-I	Phase-II		Final
					
Susp.	TM size	Small (20cm)	Small(25cm)		Large(10m)
	TM #	1	2		2
	Multi-Output	×	○	…	○
	Vibration isolation	×	○ Passive+Active		○
	Low loss susp.	△	×		○
Sensors		Michelson	Michelson		Fabry-Perot
Cryogenic		×	×		○

Phase-I	Phase-II	Final
h ~ 10^{-8} @ 1Hz	h ~ 10^{-10} @ 1Hz	h ~ 10^{-19} @ 1Hz
Principle test	Suspension system	GW astronomy
First observation	IMBH first obs.	

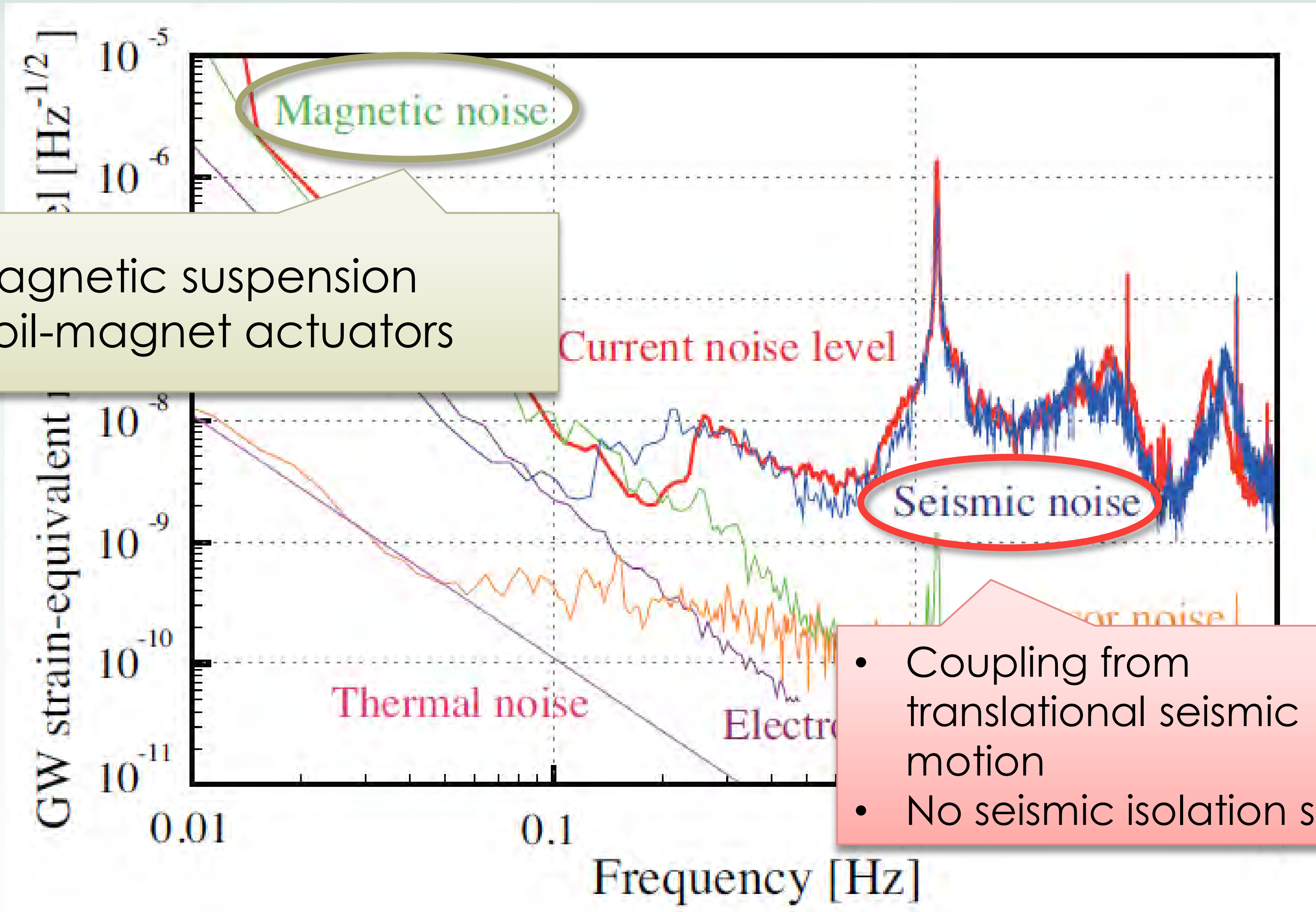
Previous experiment

Small prototype for the principle test and first observation





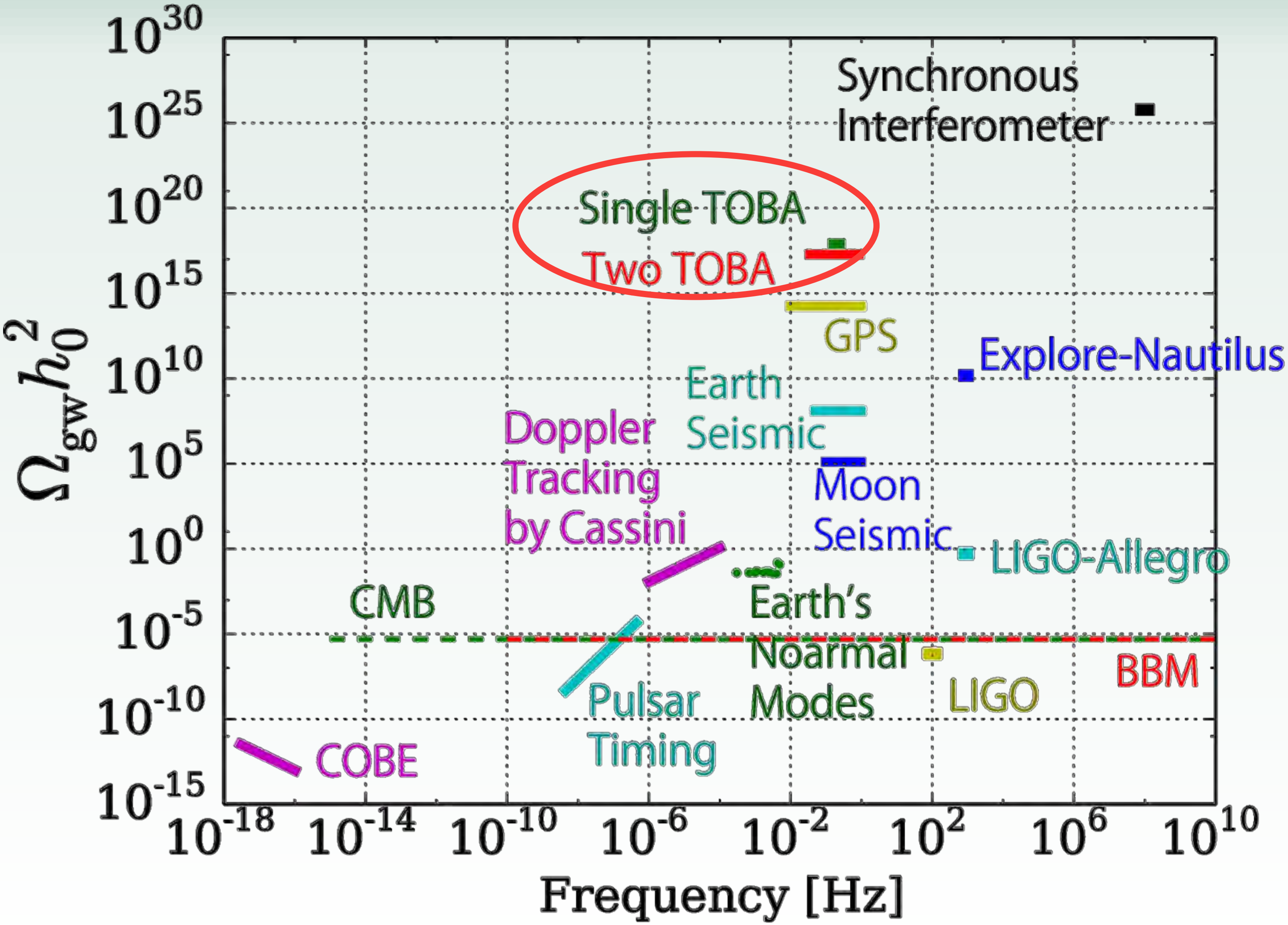
Prototype sensitivity



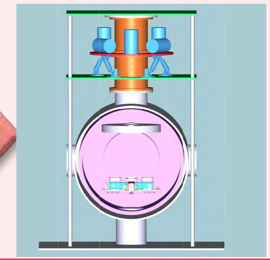
- Magnetic suspension
- Coil-magnet actuators

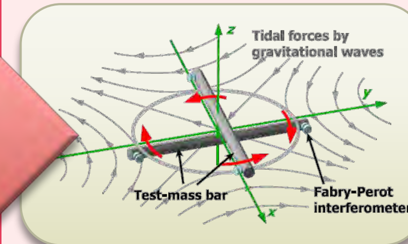
- Coupling from translational seismic motion
- No seismic isolation system

Stochastic GW background search



Roadmap





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	Low loss susp.	△	×		○
Sensors		Michelson	Michelson		Fabry-Perot
Cryogenic		×	×		○

h ~ 10^{-8} @ 1Hz
Principle test
First observation

h ~ 10^{-10} @ 1Hz
Suspension system
IMBH first obs.

h ~ 10^{-19} @ 1Hz
GW astronomy

Phase-II TOBA

- ✓ Multi-output system
- ✓ Common mode noise rejection
- ✓ Passive vibration isolation
- ✓ Active vibration isolation

Conventional detectors

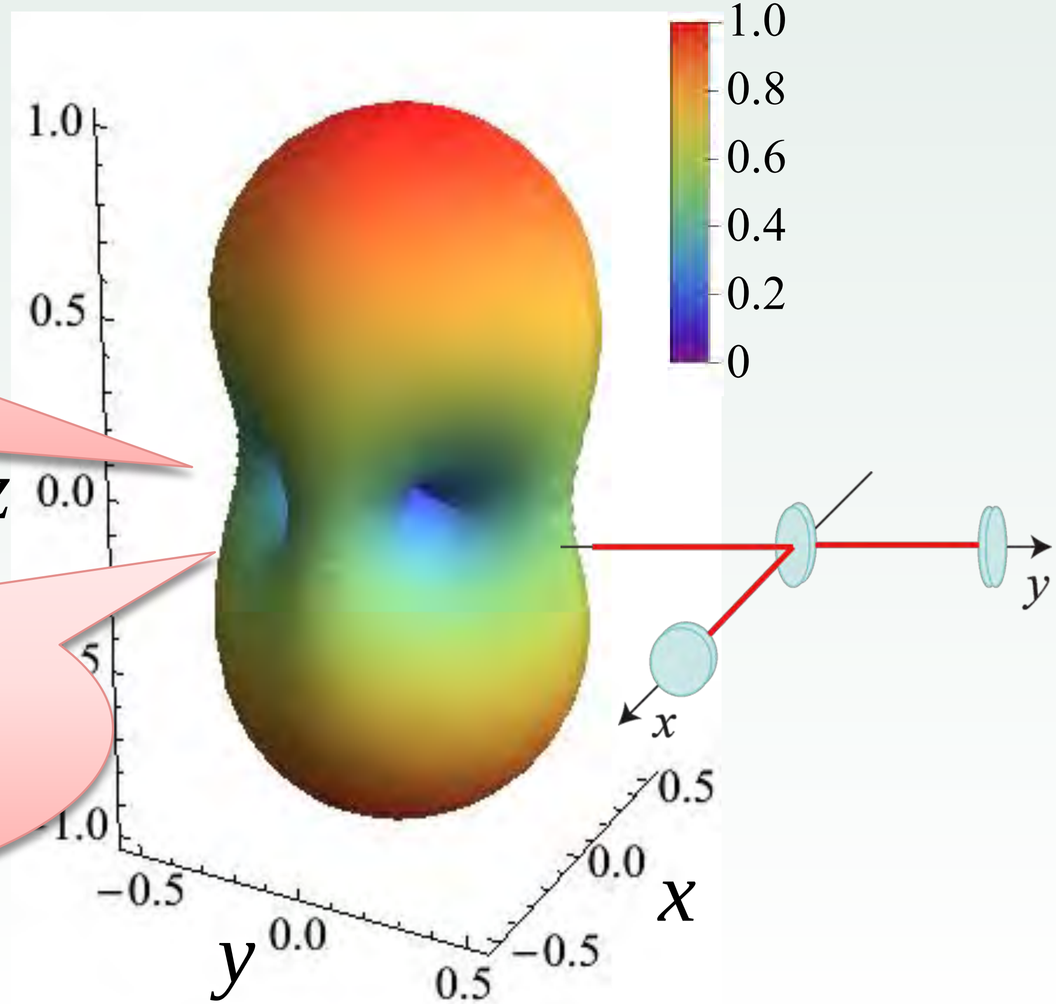
Antenna Pattern

Sensitivity of the detector depends on the direction of sources

In case of laser interferometers

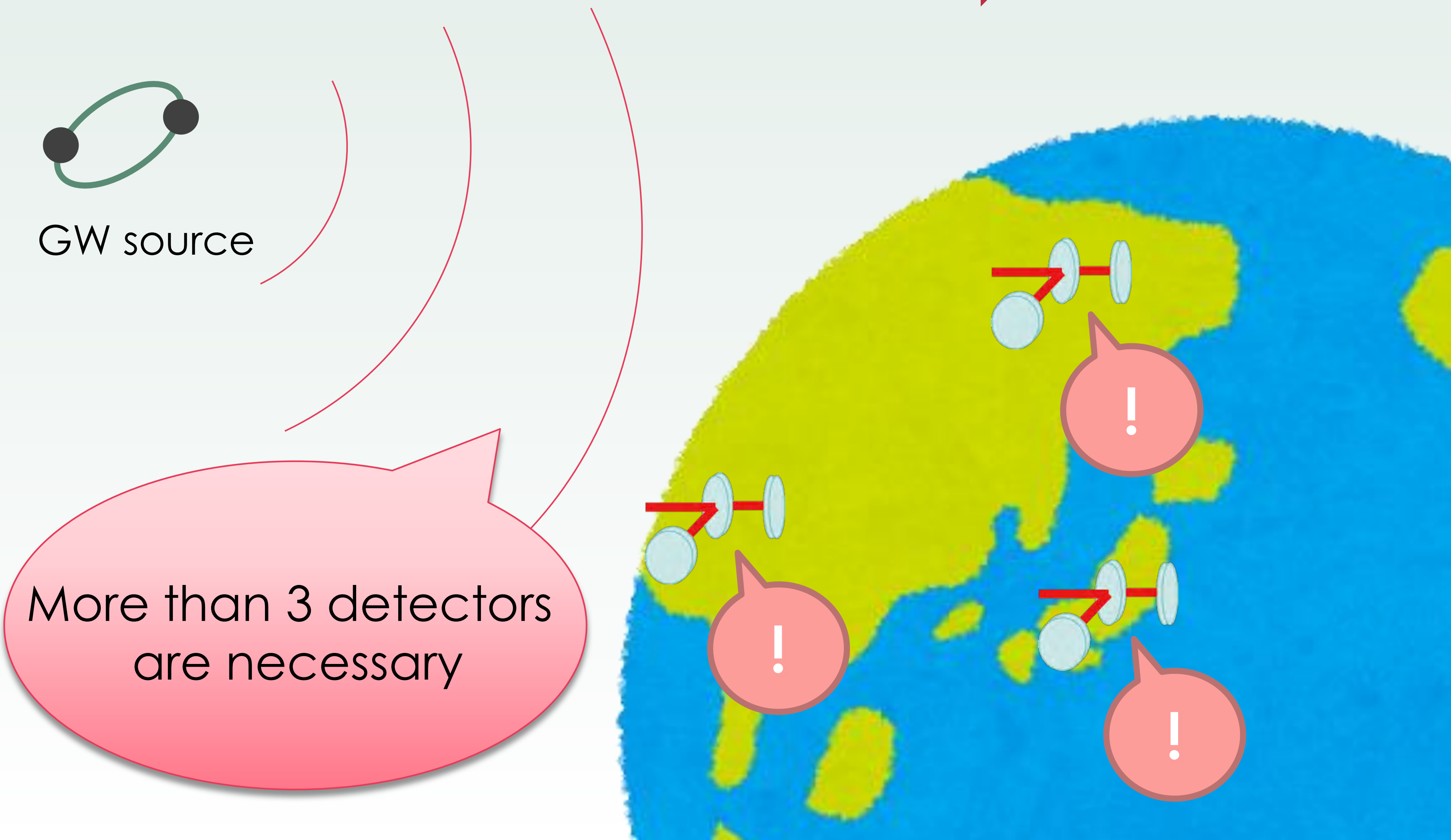
Dead angle
↓
You will miss some events

Poor directivity
↓
You do not know from where the signal comes.



Source Identification

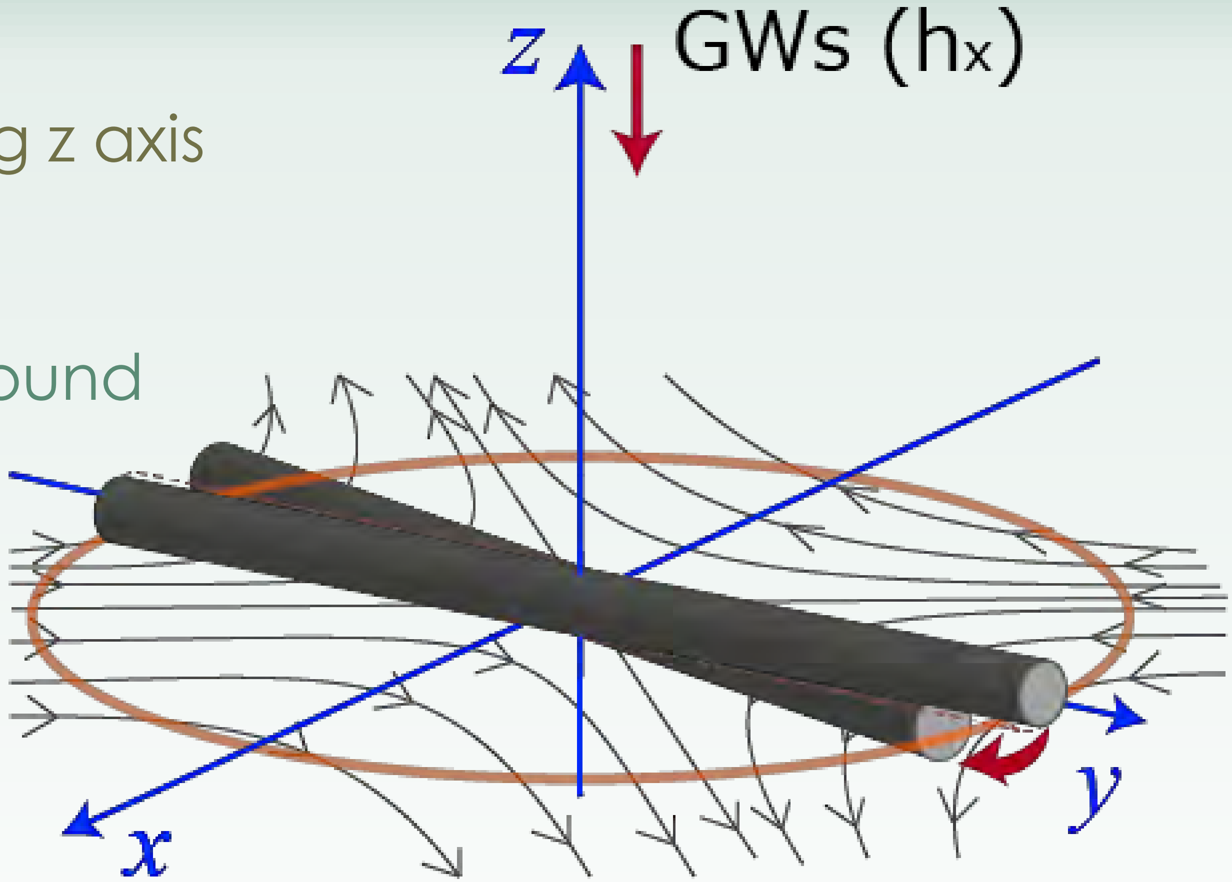
Detection + Sky position of the source ⇨ GW astronomy



Multi-Output System

GWs along z axis

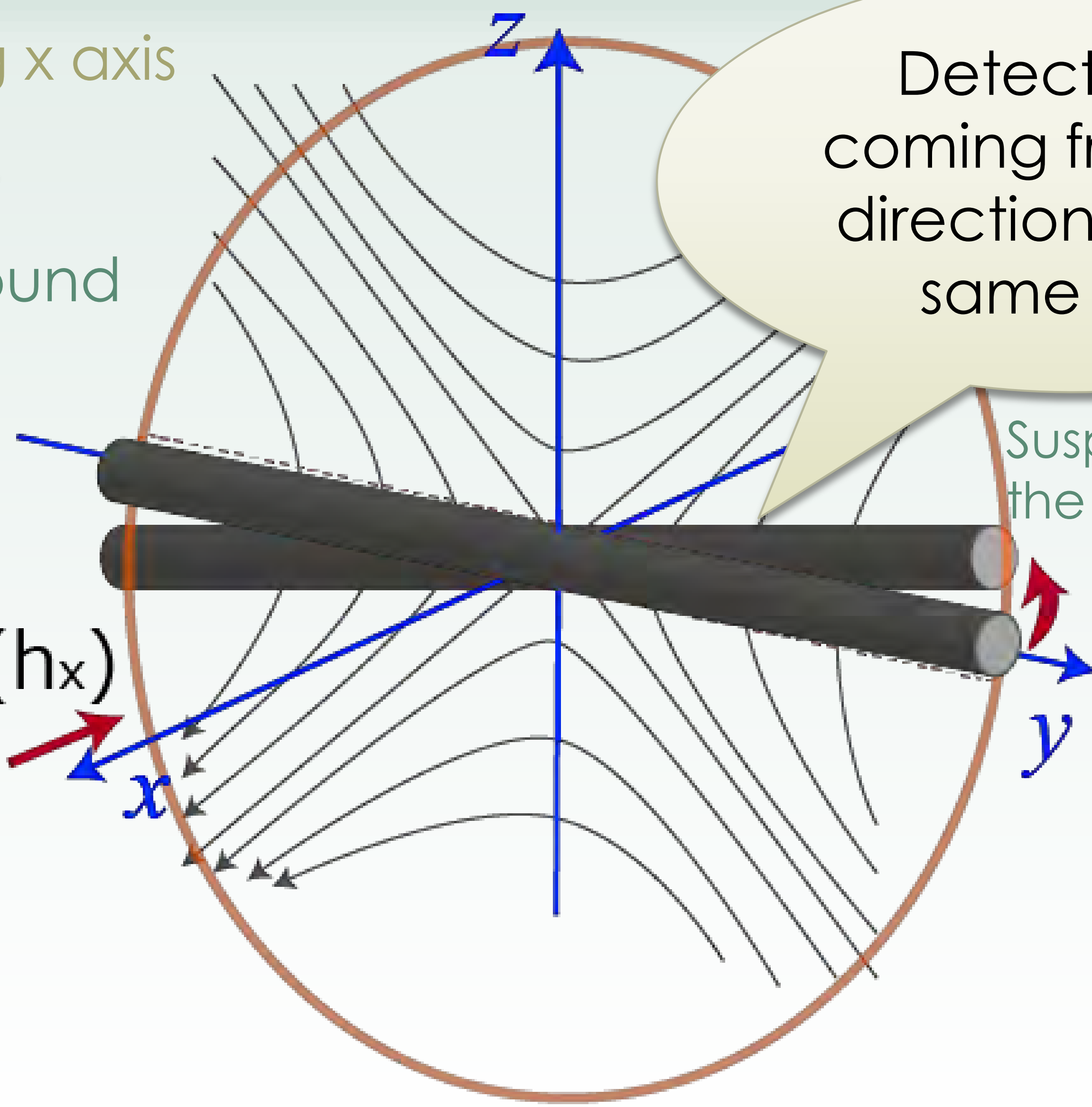
Rotate around z axis



Multi-Output System

GWs along x axis

Rotate around x axis

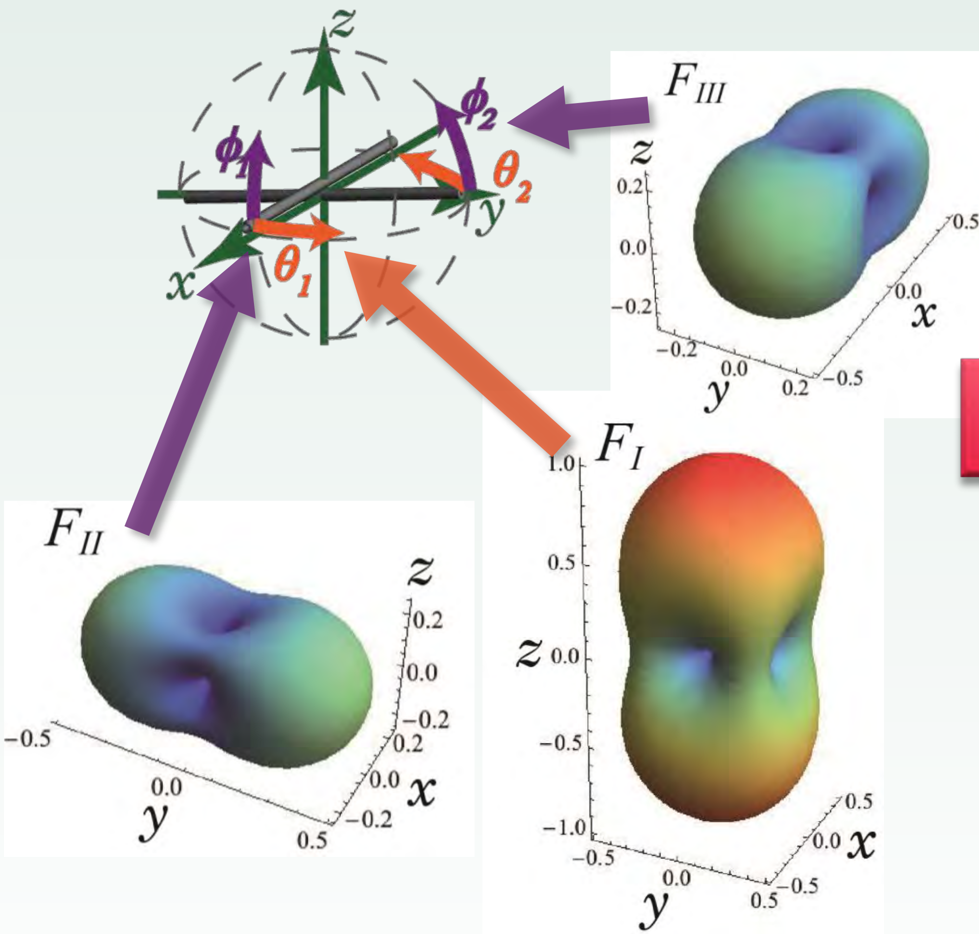


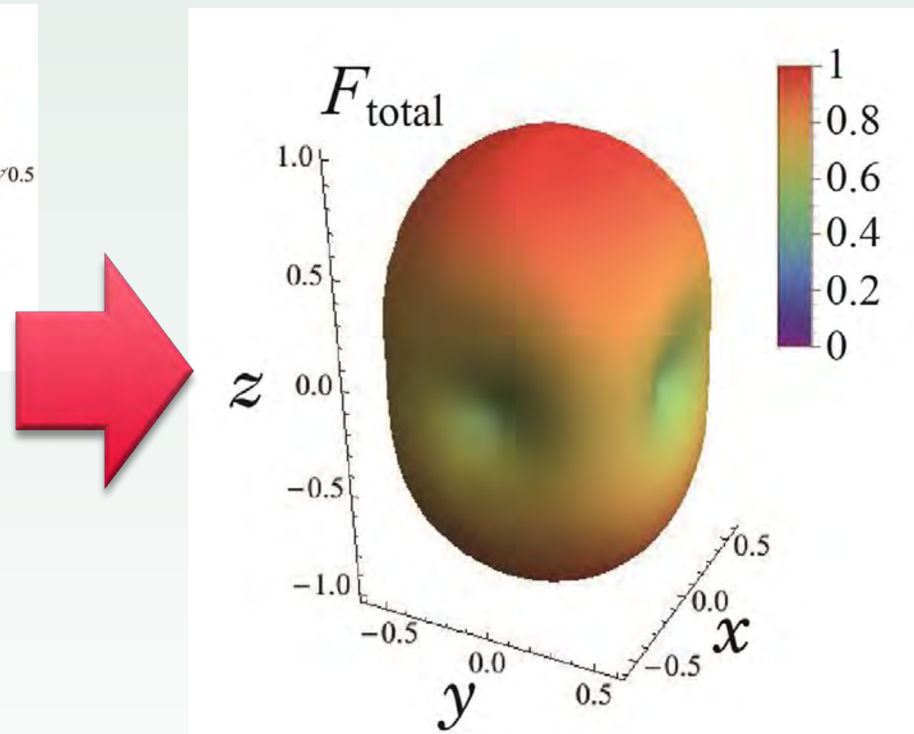
GWs ($h_\times$)

Detect GWs coming from two directions at the same time

Suspend TMs near the COMs

Antenna Pattern





※ assume that signals from horizontal rotation is two times better than others

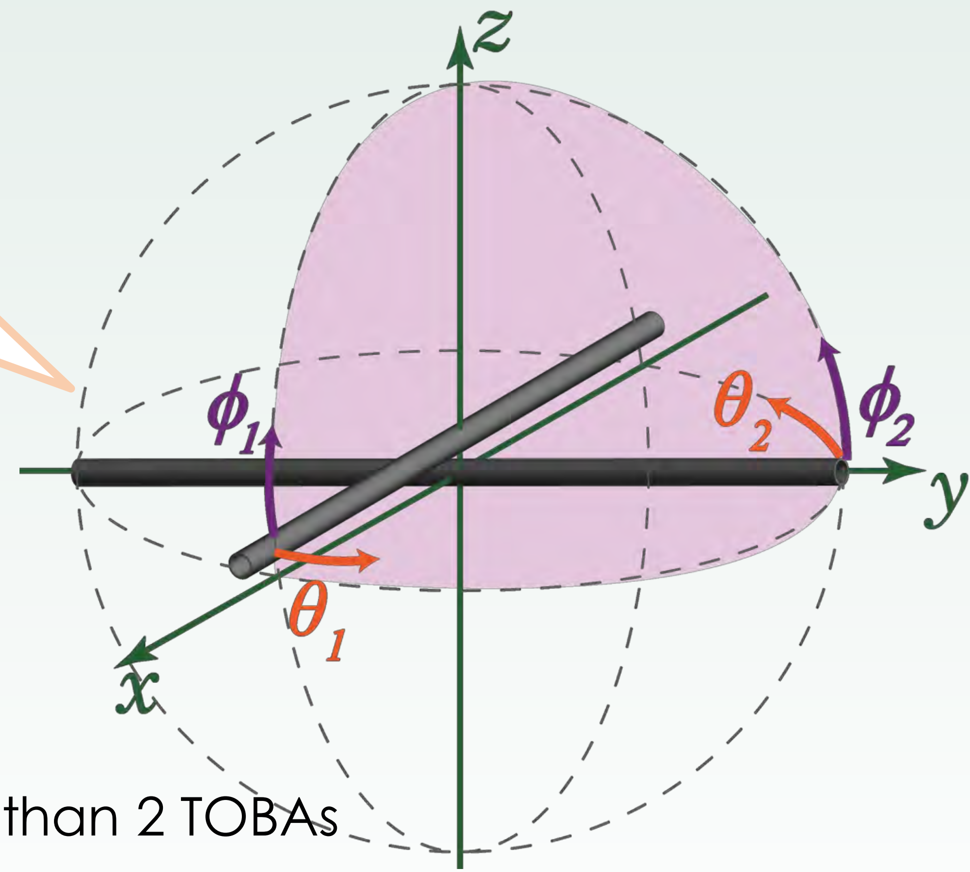
The detection volume ∝ event rate

× 1.7

Direction Identification

narrow down the sky position of the source only with a single detector

One point in one quadrant



8 points for the all sky

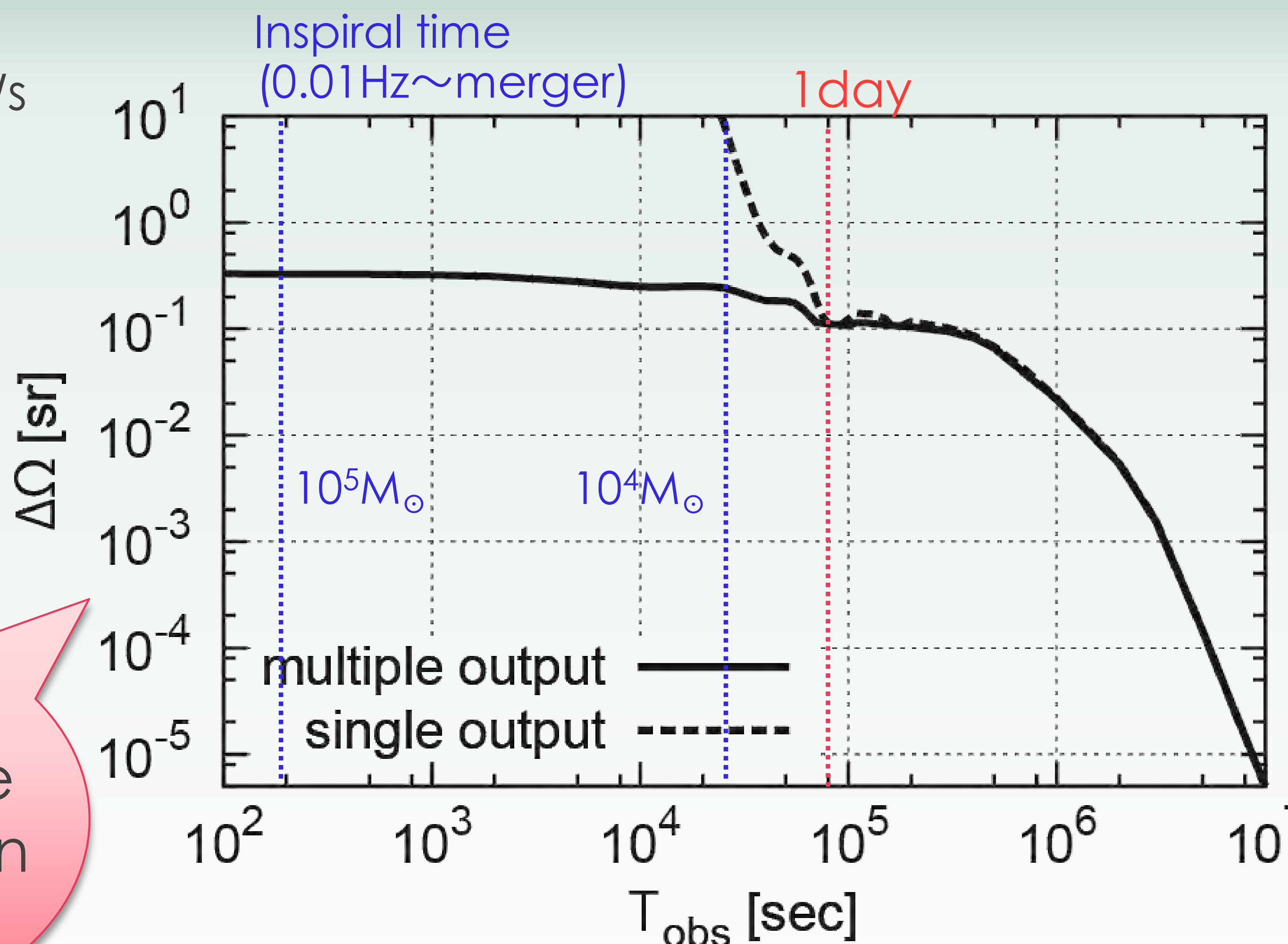
+

Follow up with electromagnetic waves or More than 2 TOBAs

→ Identify the sources

Angular resolution

Continuous GWs



Useful when the obs. Time is shorter than 1 day

Calculated by K. Eda

K. Eda, A. Shoda +, Phys. Rev. D. **90**, 064039 (2014)

Angular Accuracy

In case of IMBH binaries

Mass of the stars ($M_\odot$)	Inspiral time (0.01Hz→merger)	Angular resolution ($\Delta\Omega$ [sq-deg.])	
		Single-output	Multi-output
$10^4 - 10^4$	4×10^4 sec	---	221
$10^4 - 10^5$	5×10^3 sec	---	1260
$10^5 - 10^5$	2×10^2 sec	---	847

Calculated by K. Eda

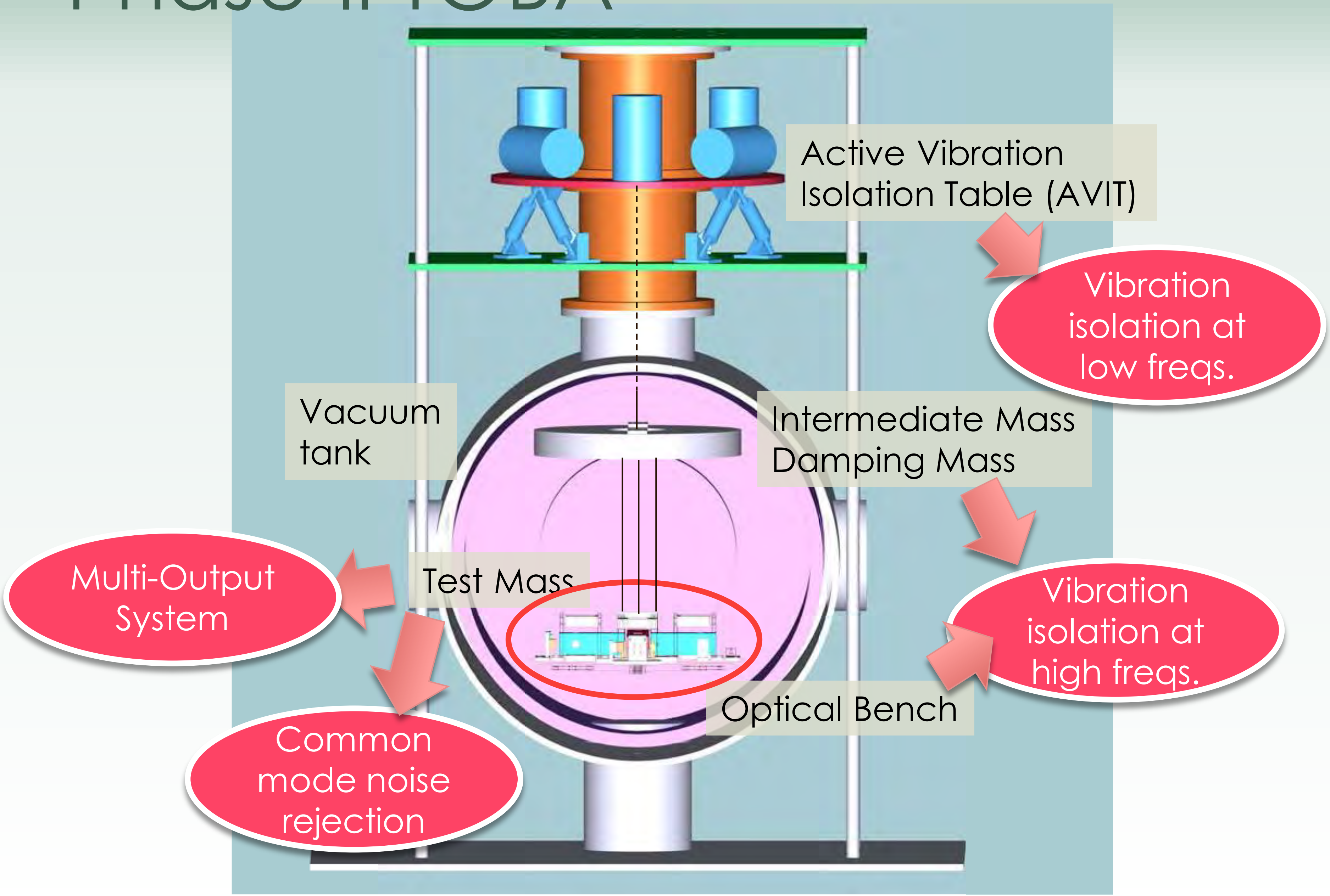
Astronomy & Geophysics with less detectors

K. Eda, A. Shoda +, Phys. Rev. D. **90**, 064039 (2014)

Phase-II TOBA

- ✓ Multi-output system
- ✓ Common mode noise rejection
- ✓ Passive vibration isolation
- ✓ Active vibration isolation

Phase-II TOBA

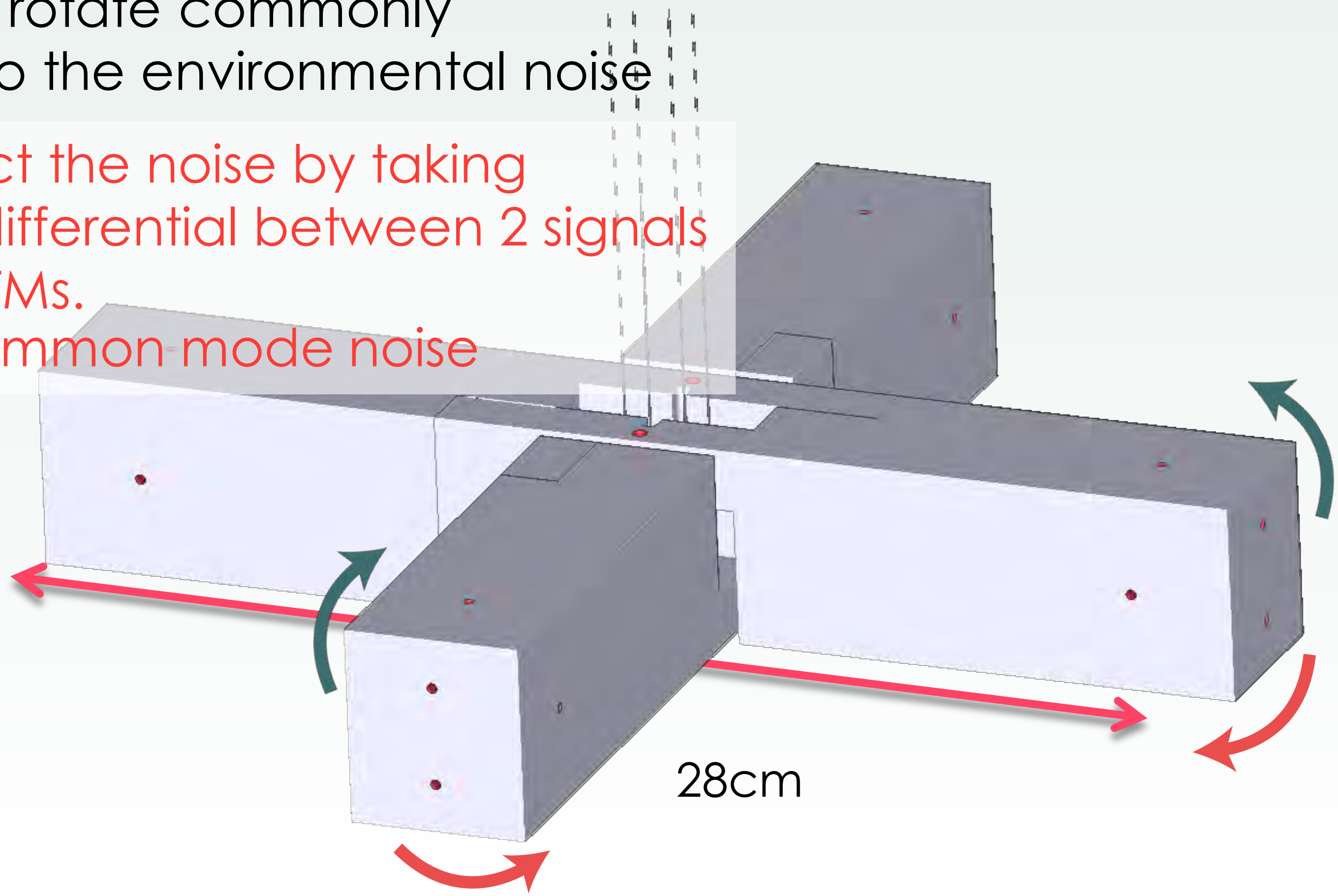


Common mode noise rejection

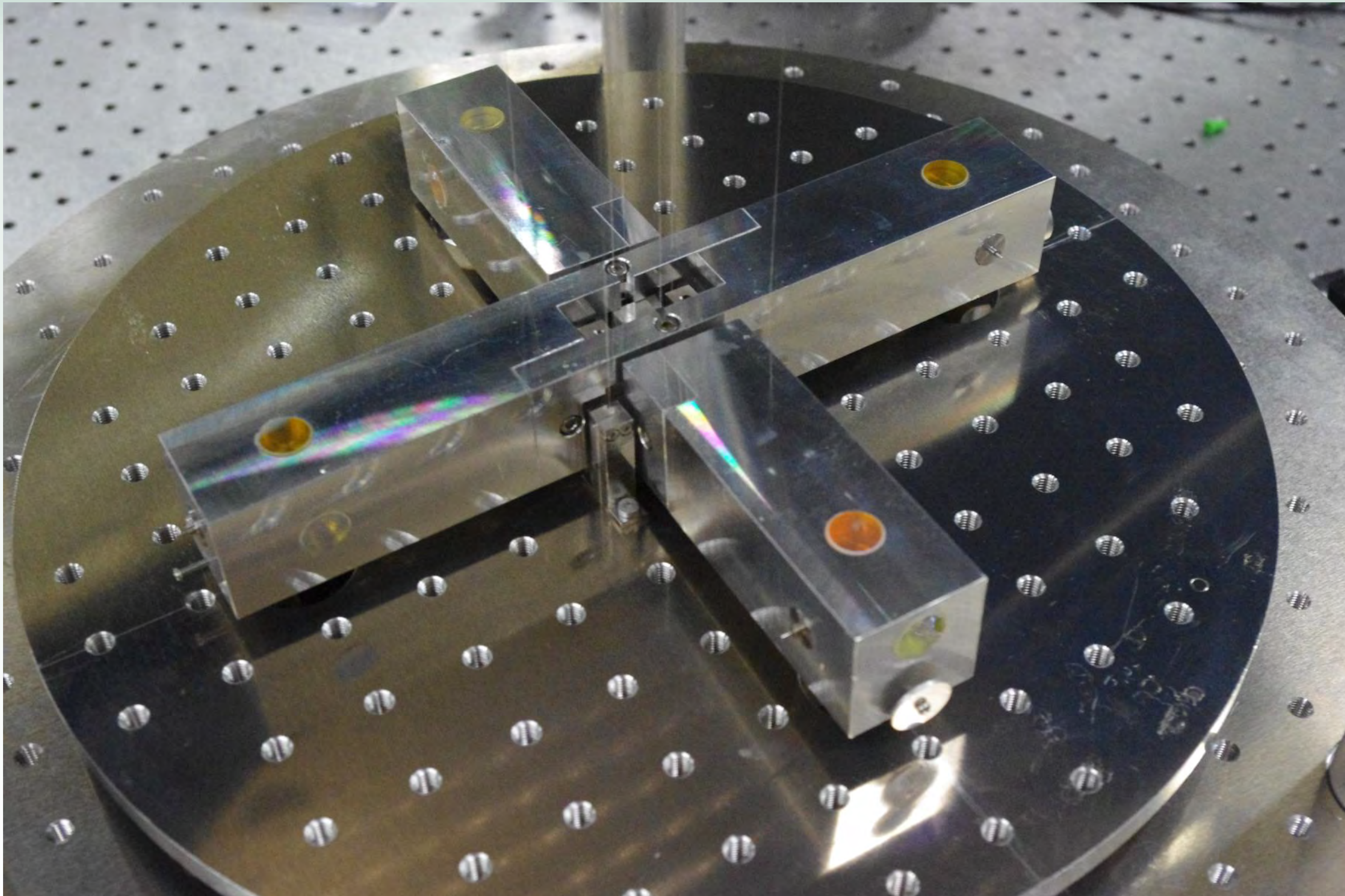
- Suspension points near COM
  ⇨ Multi-output System

Res. Freq.
horizontal： 0.1 Hz
vertical： ～0.15 Hz

- COMs of 2 TMs at the same point
  ⇨ 2 TMs rotate commonly due to the environmental noise
  ⇨ Reject the noise by taking the differential between 2 signals of 2 TMs.
  ＝Common mode noise

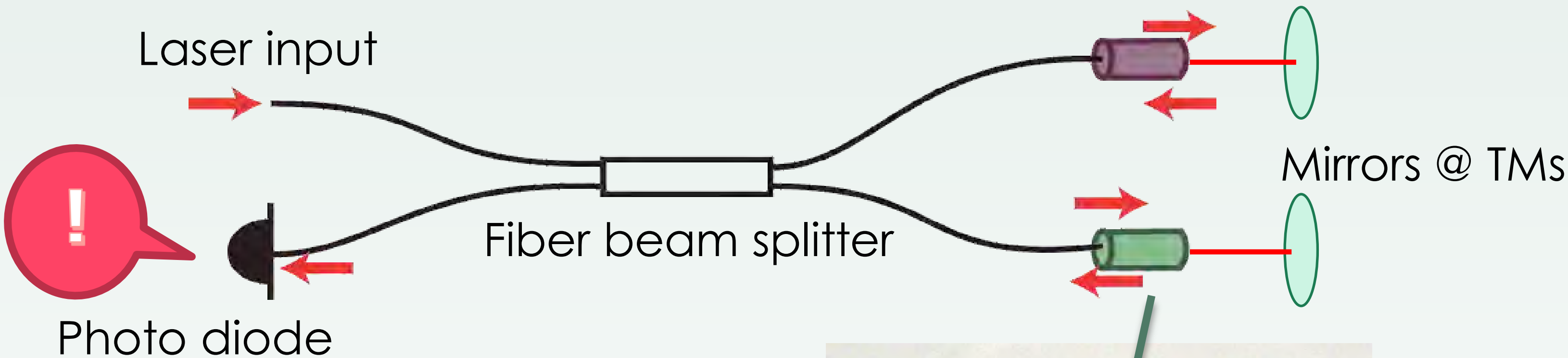


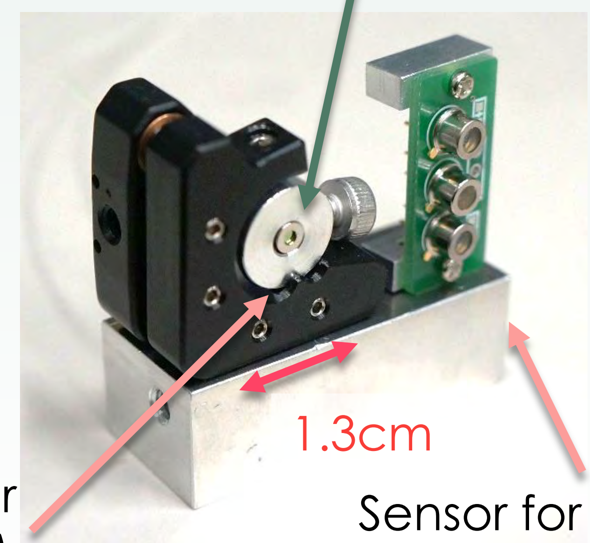
Test Mass



Sensor

Fiber Michelson interferometer → Save space

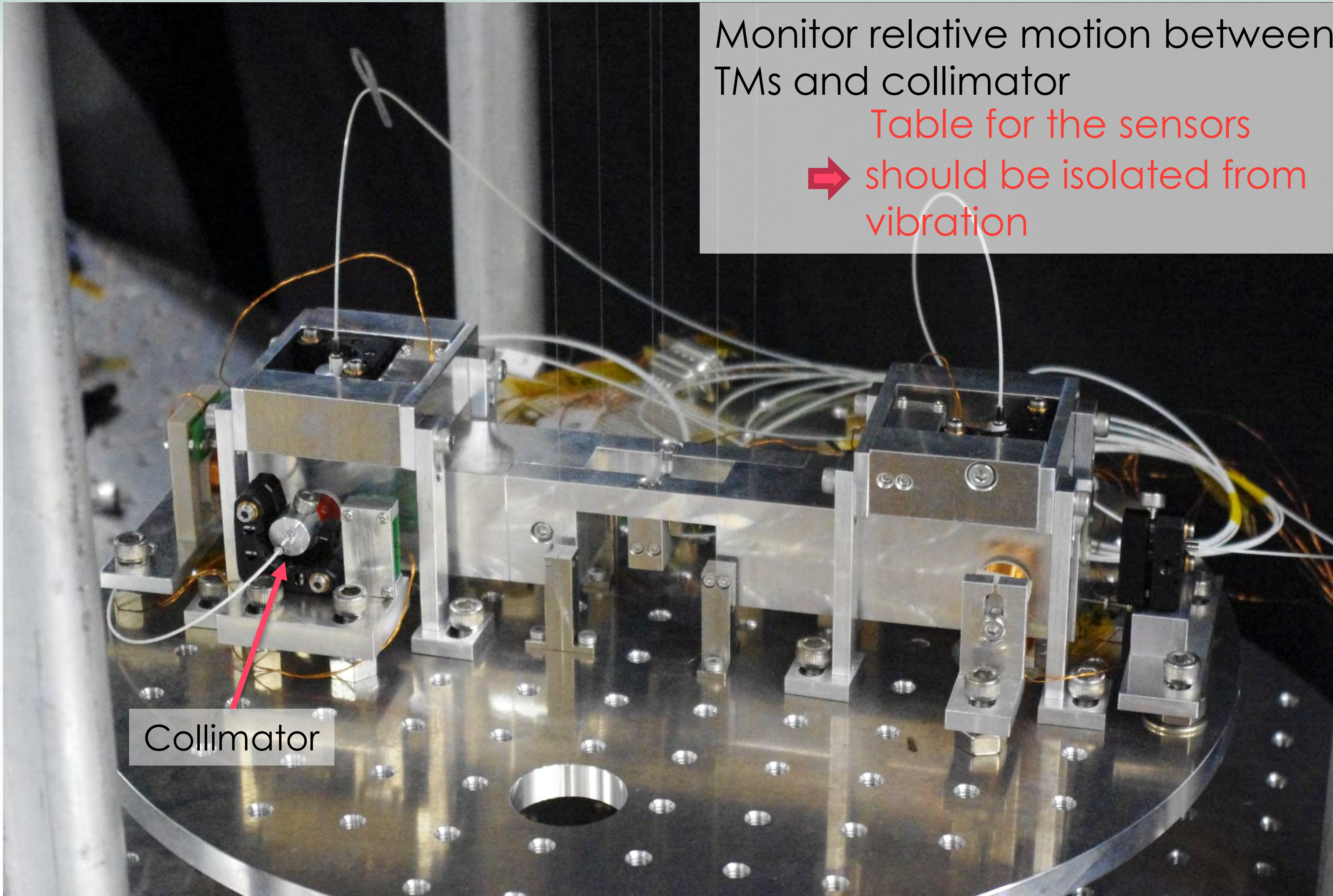




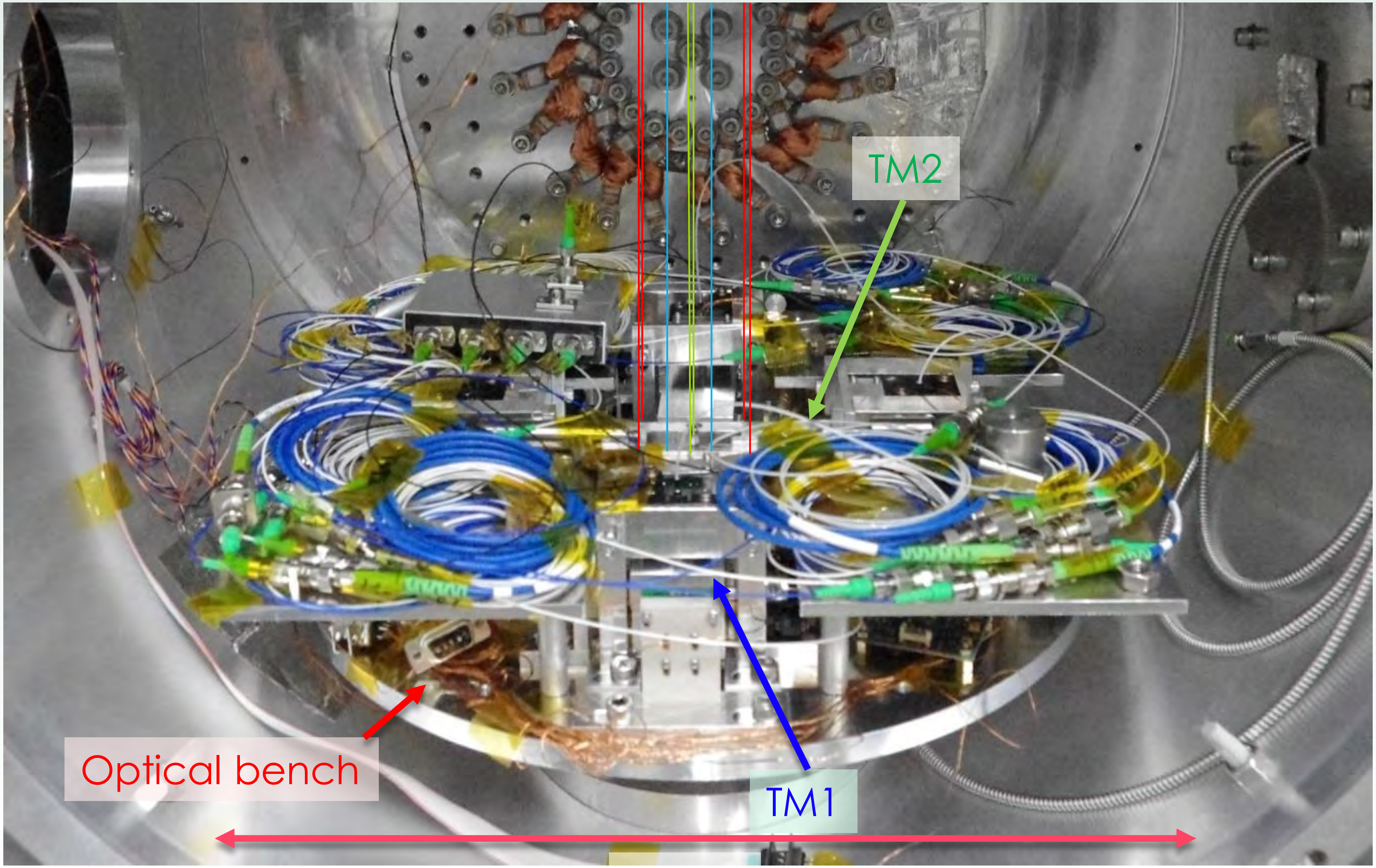
Optical Bench

Monitor relative motion between TMs and collimator

➡ Table for the sensors should be isolated from vibration

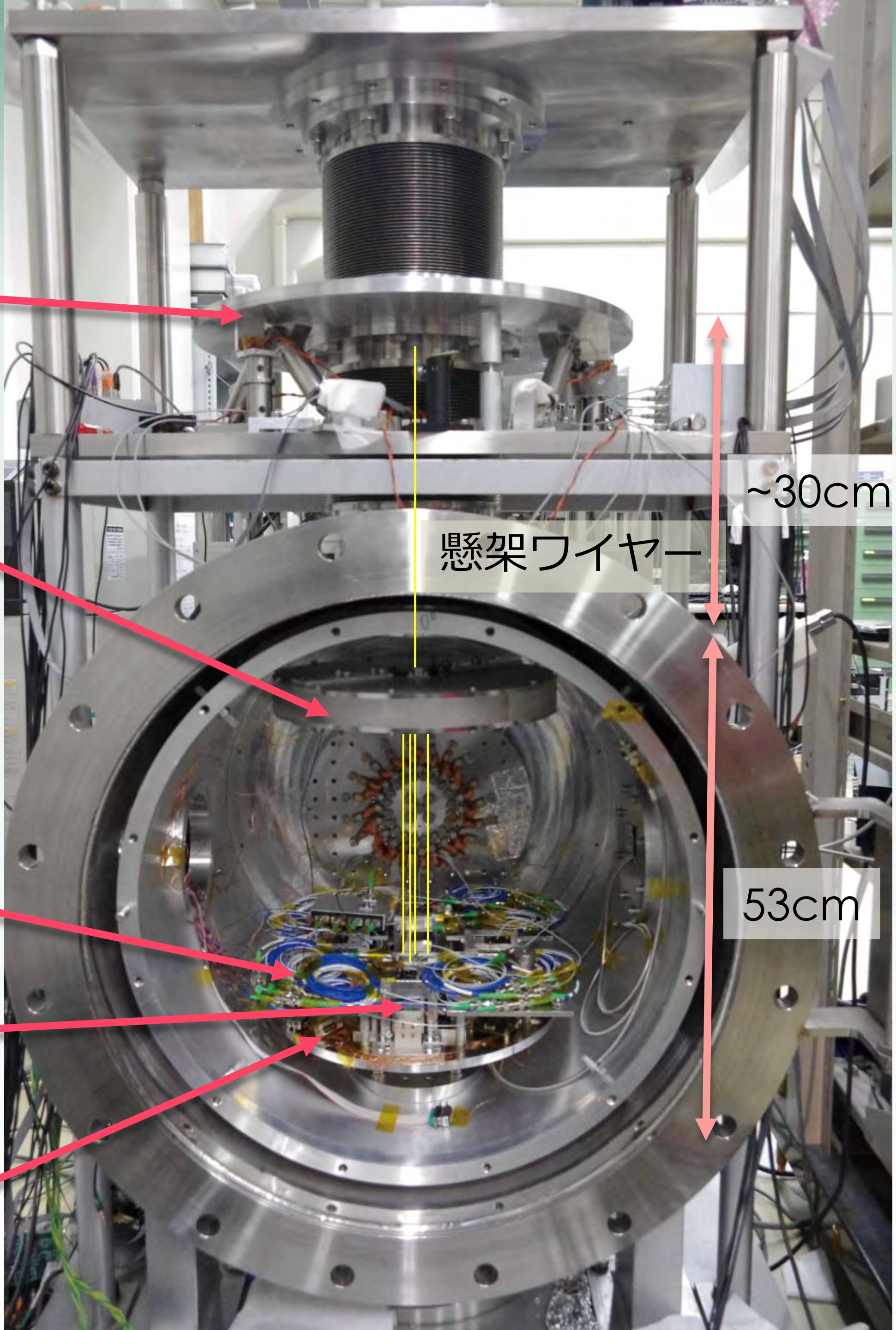


Optical Bench



33cm

Suspension



AVIT

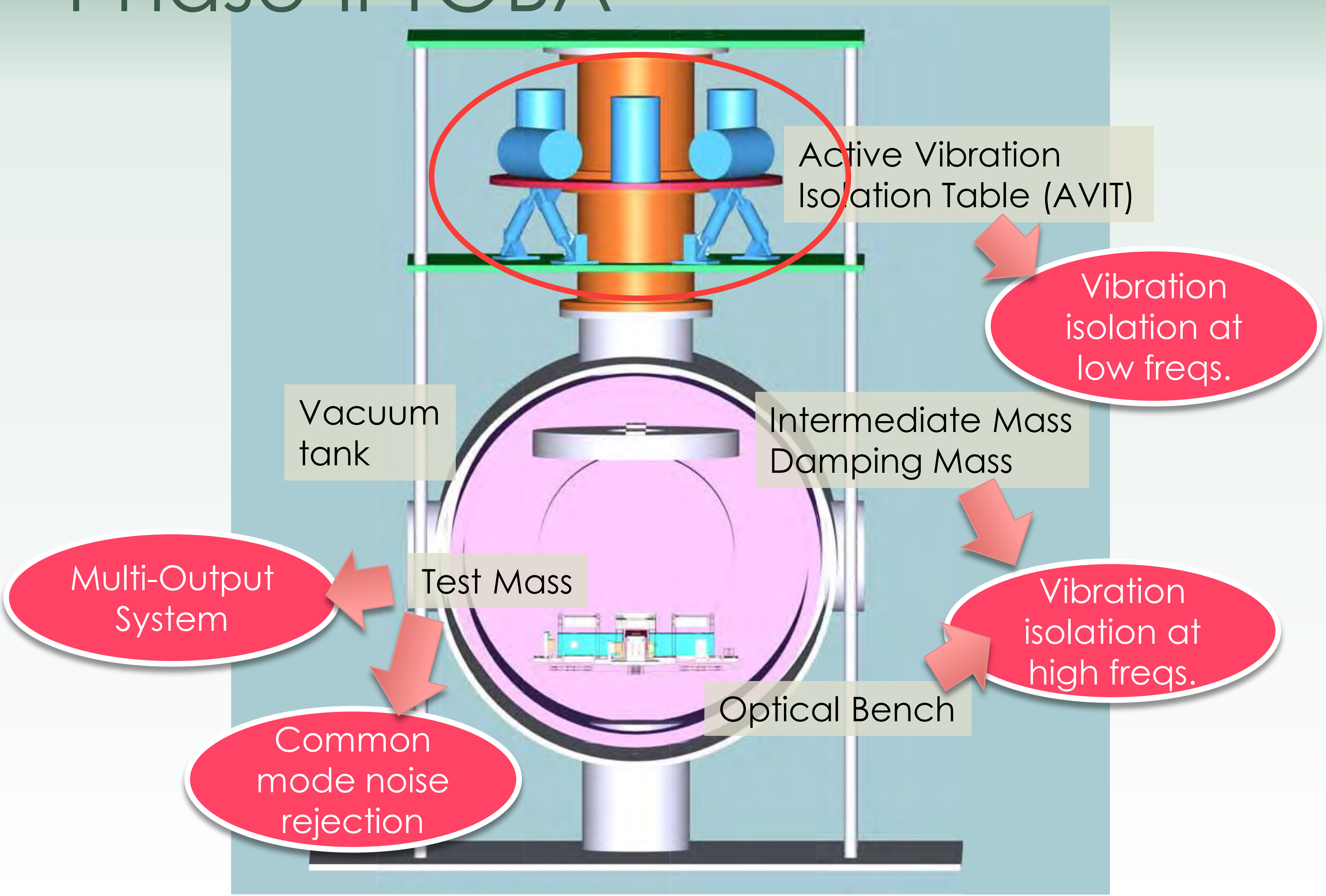
Intermediate mass
Damping mass

Optical fibers

TMs

Optical bench
(sensors)

Phase-II TOBA



Active vibration isolation table

Passive vibration isolation : Works only above <u>Res. Freq.</u> of the pendulum

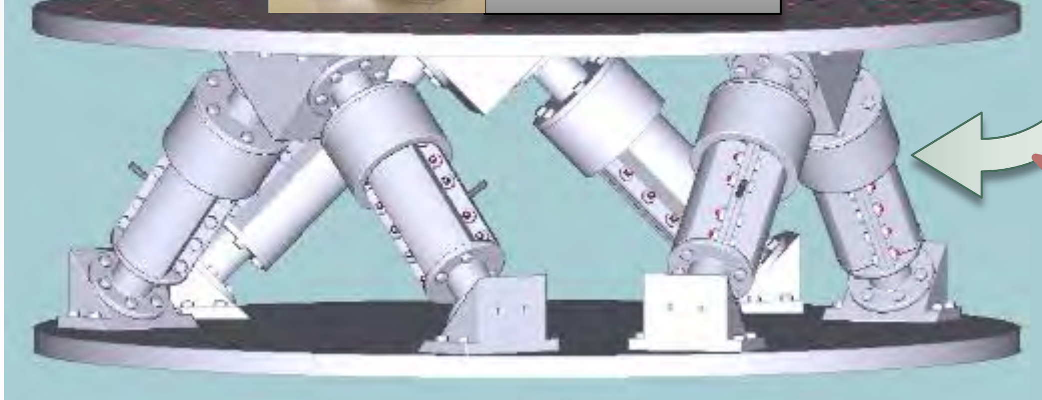
～1Hz

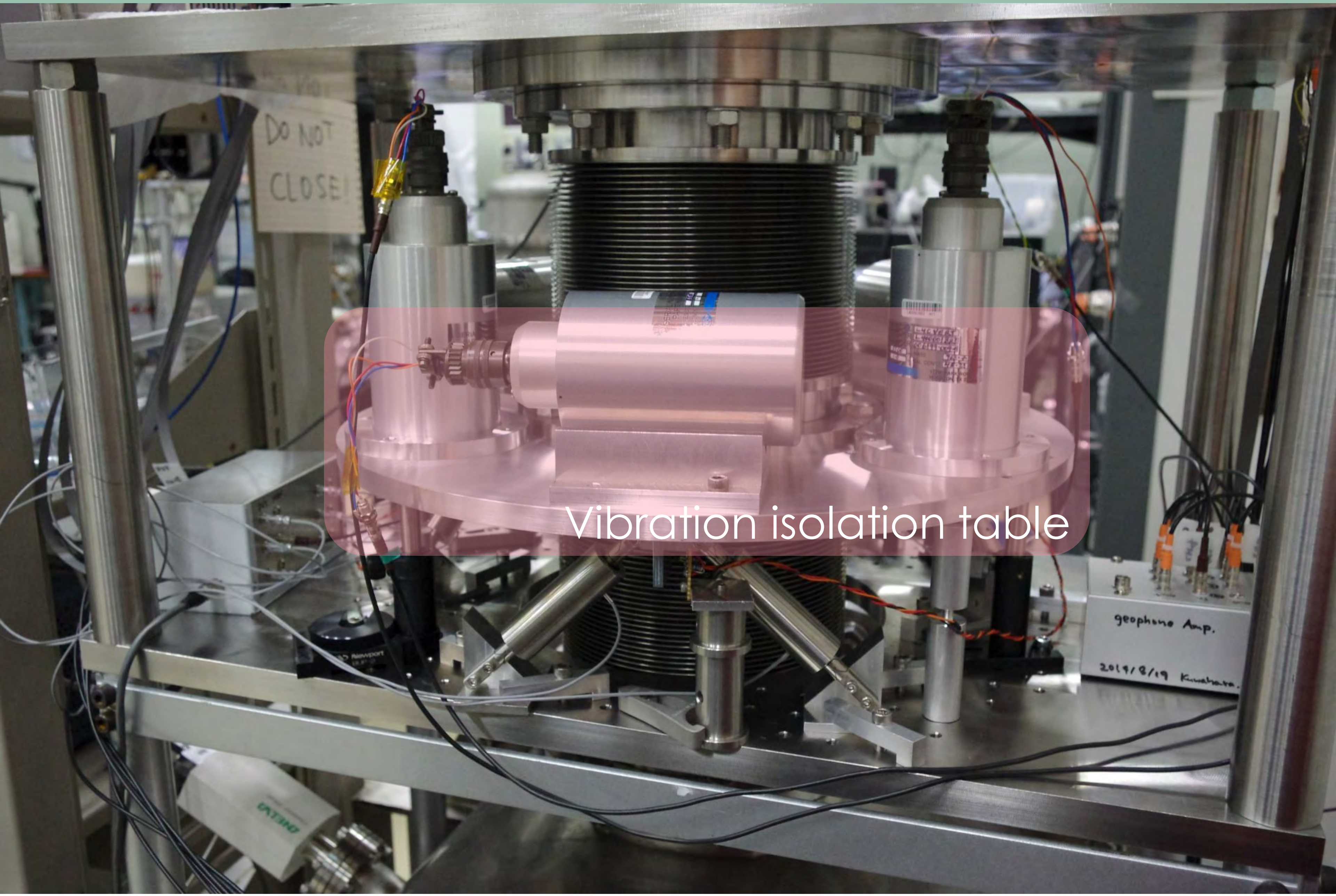
Vibration Isolation at low freqs.

goal : 10^{-8} m /rtHz @ 1Hz

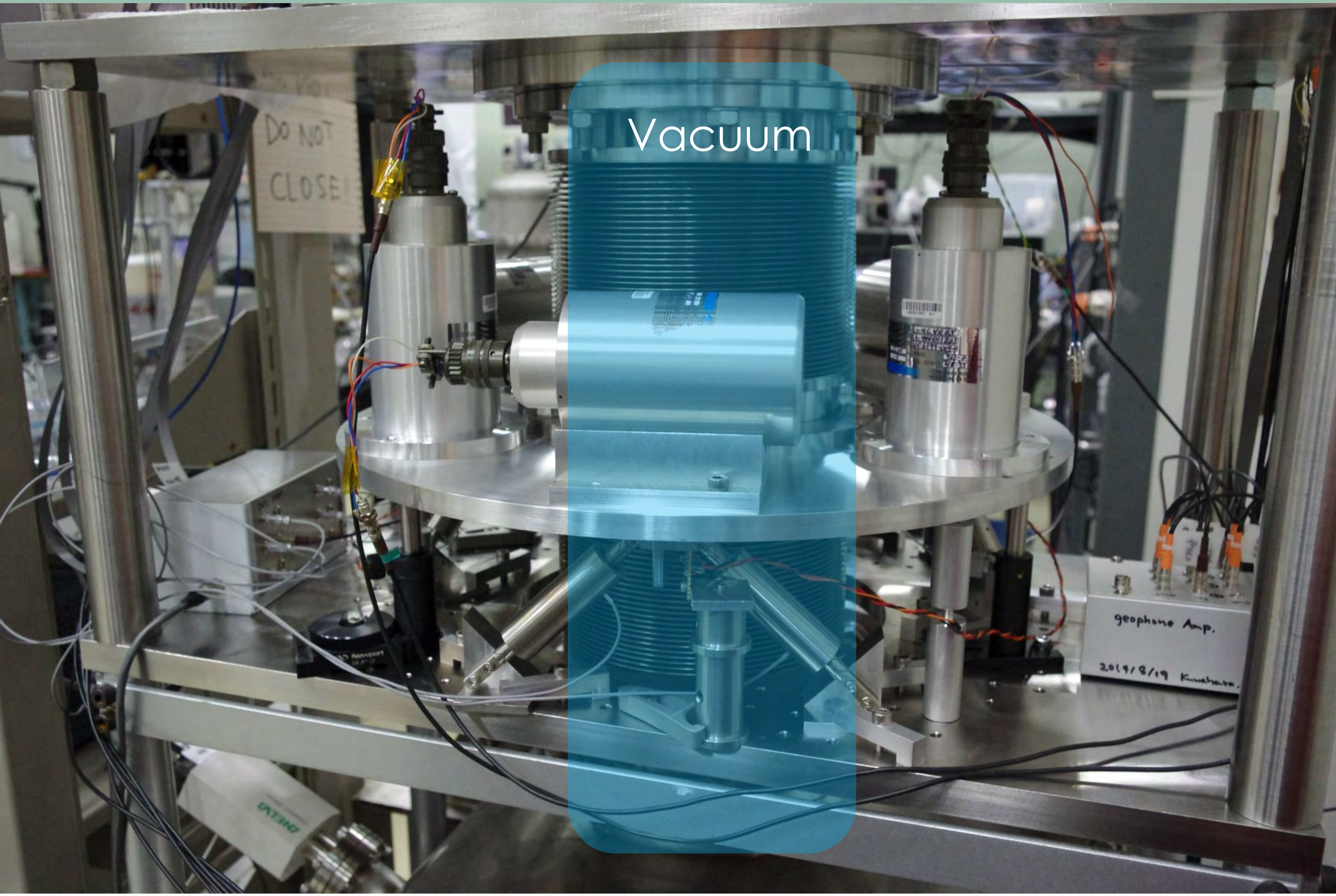
(offline decoupling rate : 1/10)

Active vibration isolation table

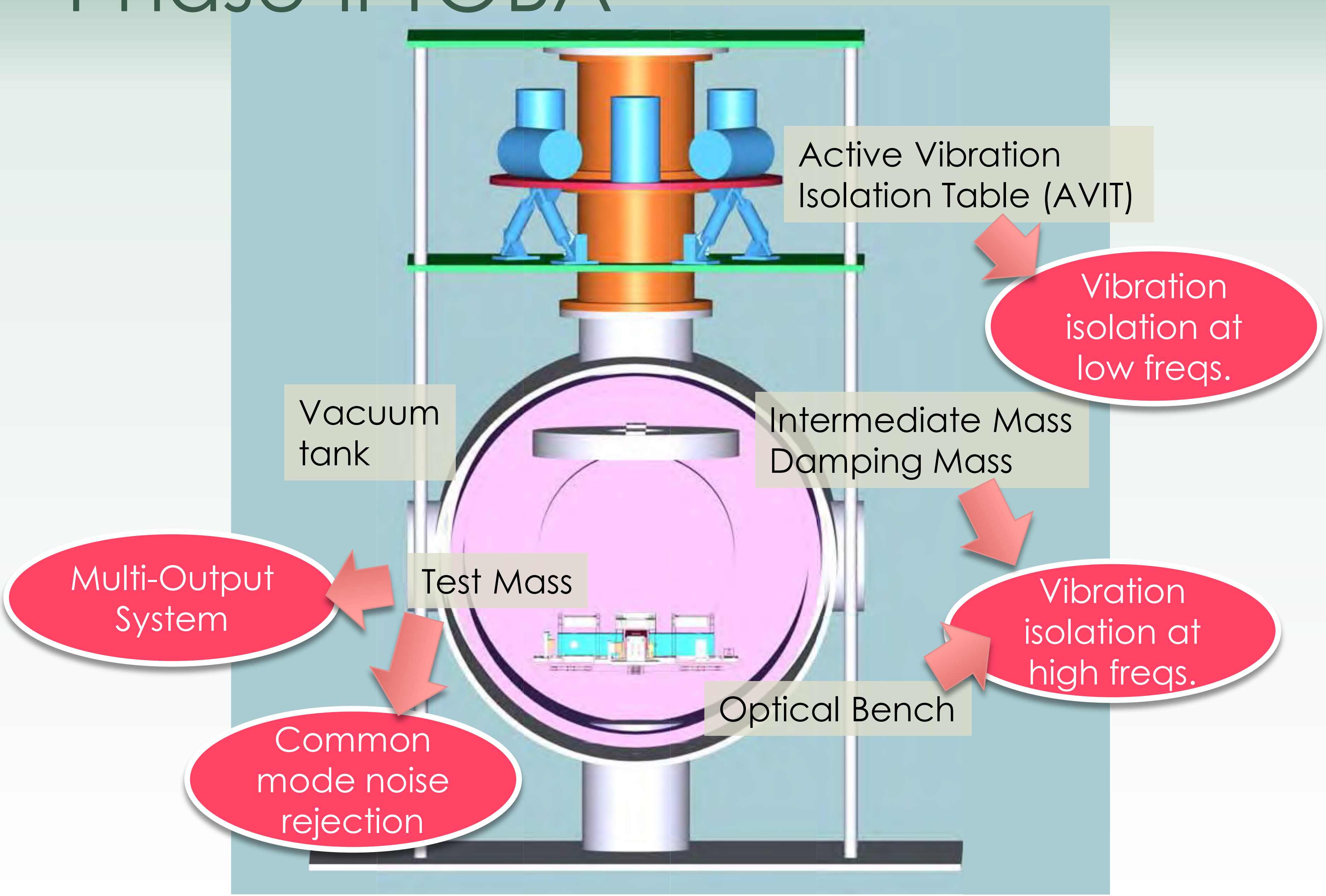



DO NOT
CLOSE!
Vibration isolation table
geophone Amp.
2014/8/19 Kuwahara

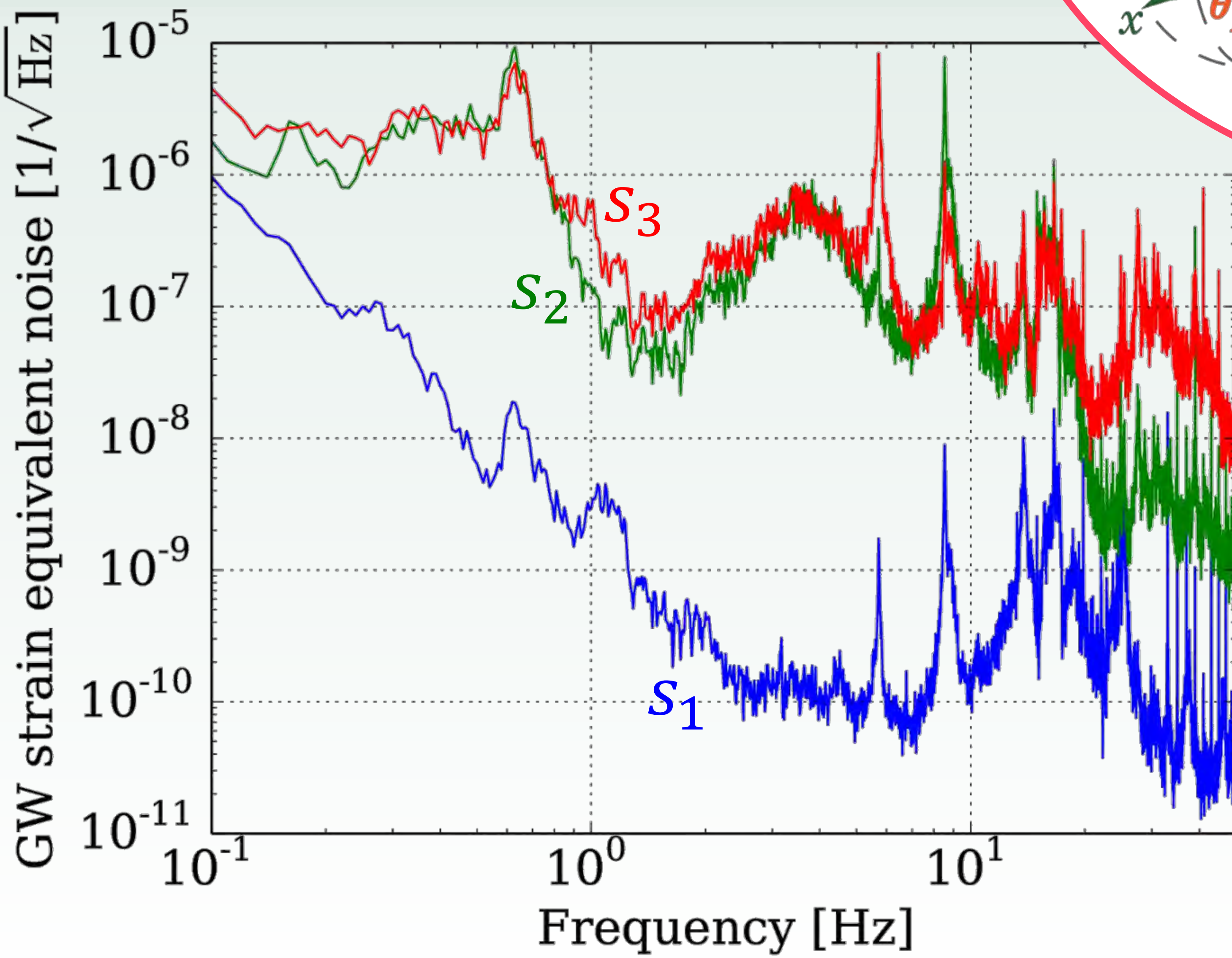

DO NOT
CLOSE!
Geophone
PZT
geophone Amp.
2014/8/19 Kuwahara.

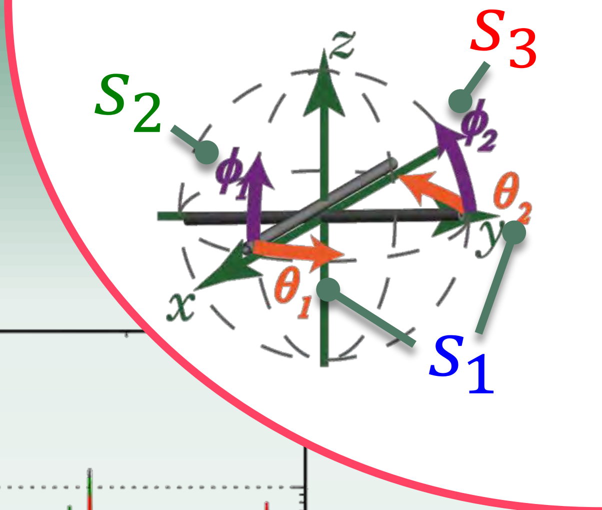

Vacuum
DO NOT CLOSE!
geophone Amp.
2014/8/19 Kuwahara

Phase-II TOBA



Sensitivity

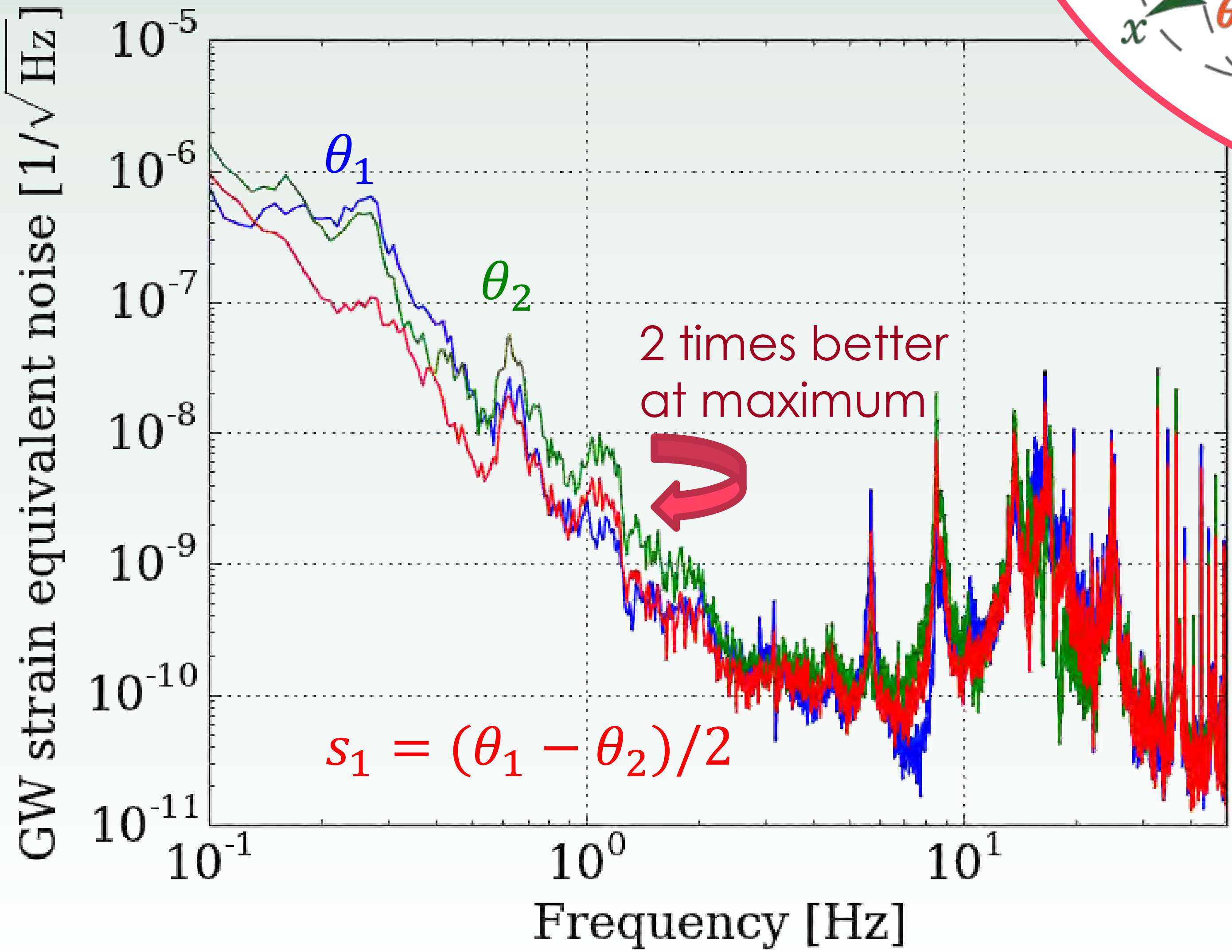


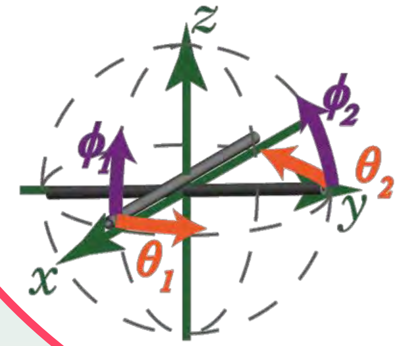


Phase-II TOBA

- ✓ Multi-output system
- ✓ Common mode noise rejection
- ✓ Passive vibration isolation
- ✓ Active vibration isolation

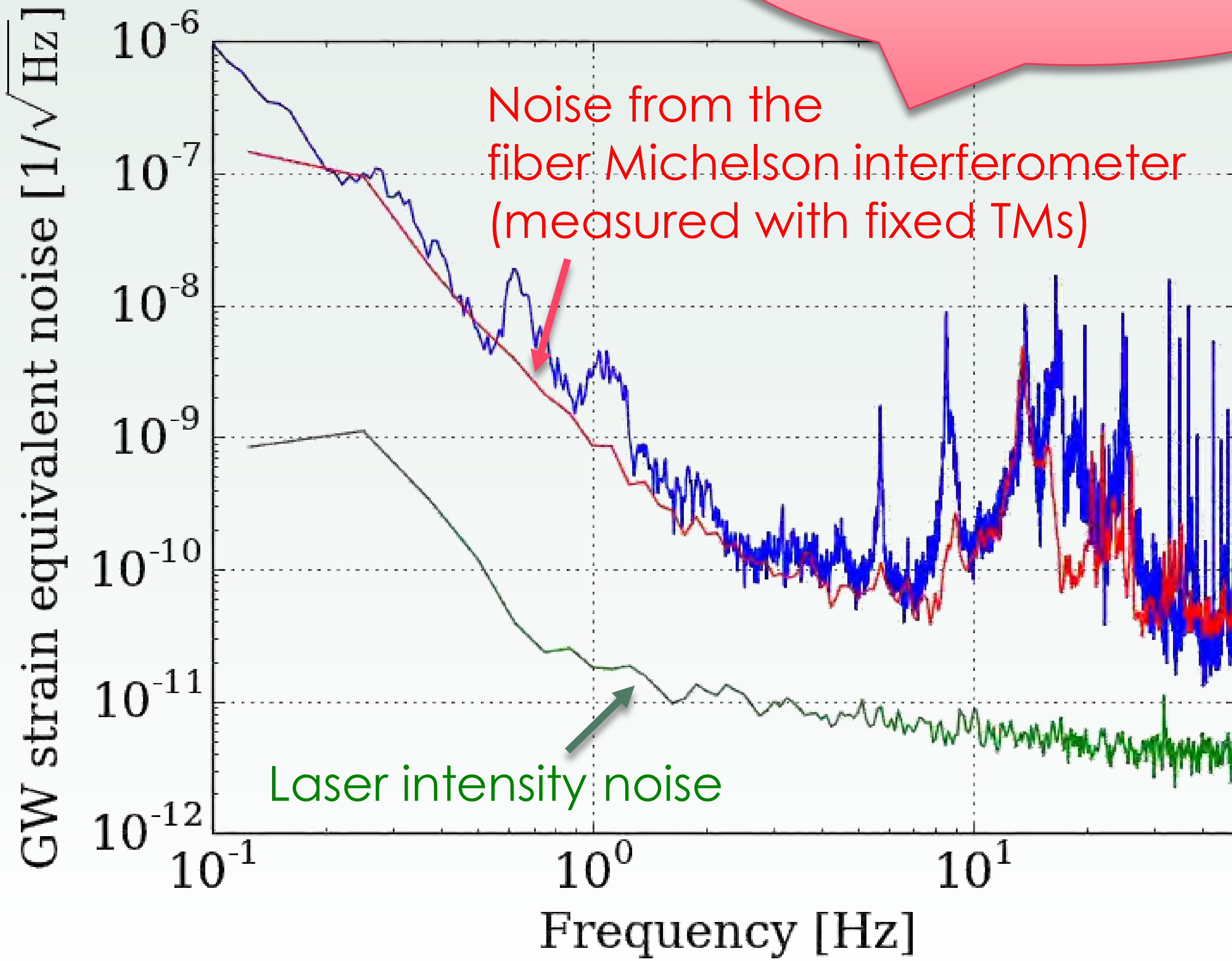
Common mode noise rejection





Sensor noise

The sensitivity is limited by the sensor noise



Phase-II TOBA

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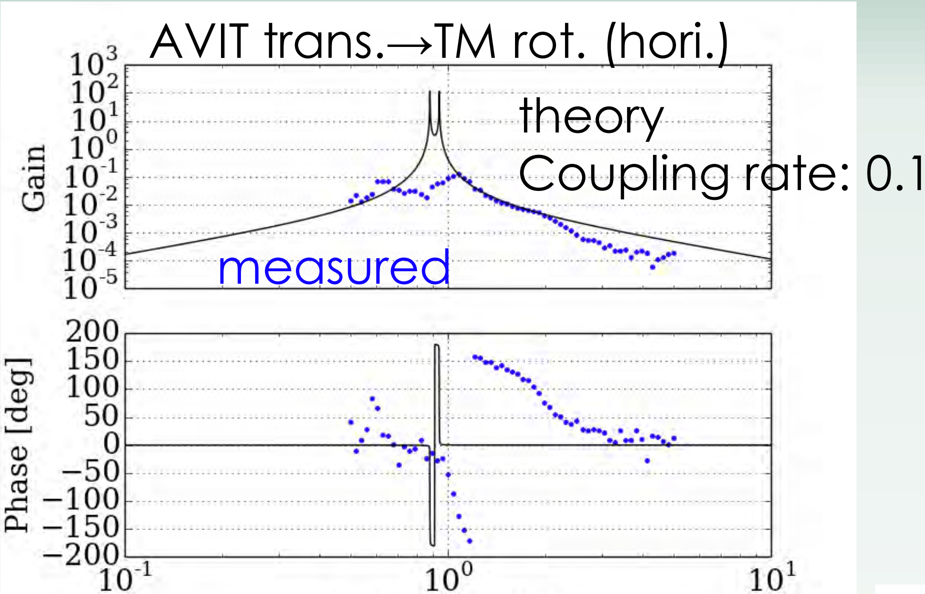
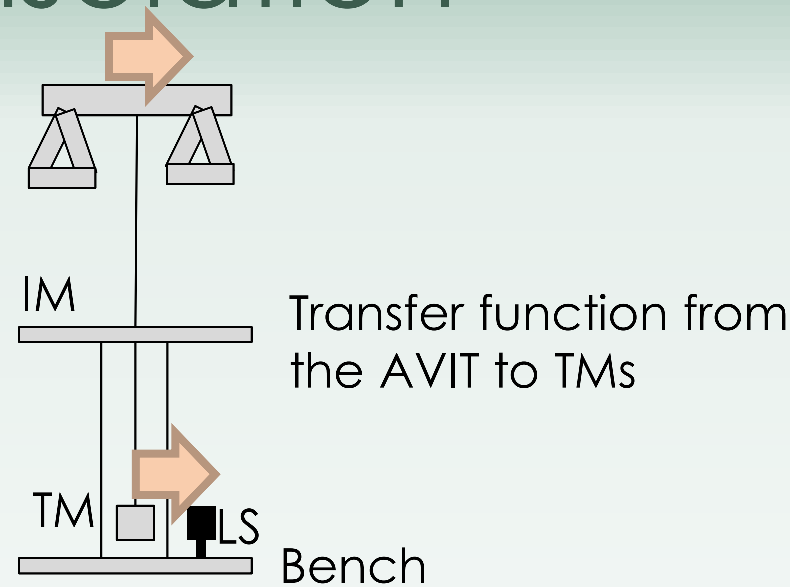
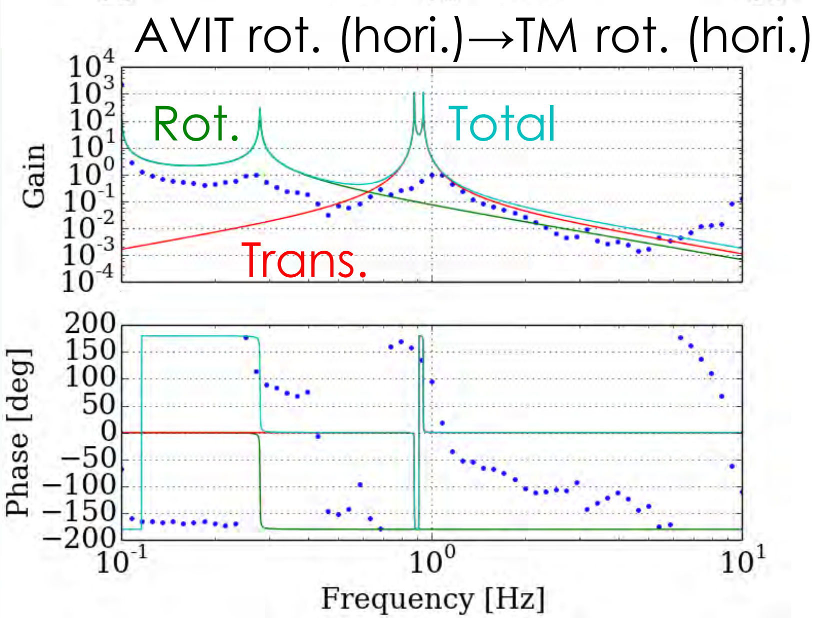
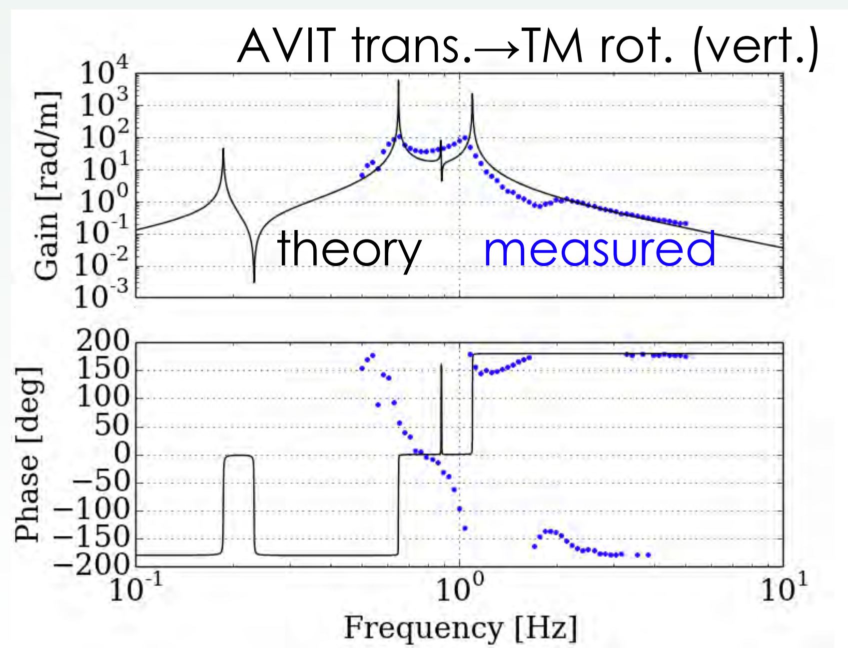
Passive vibration isolation

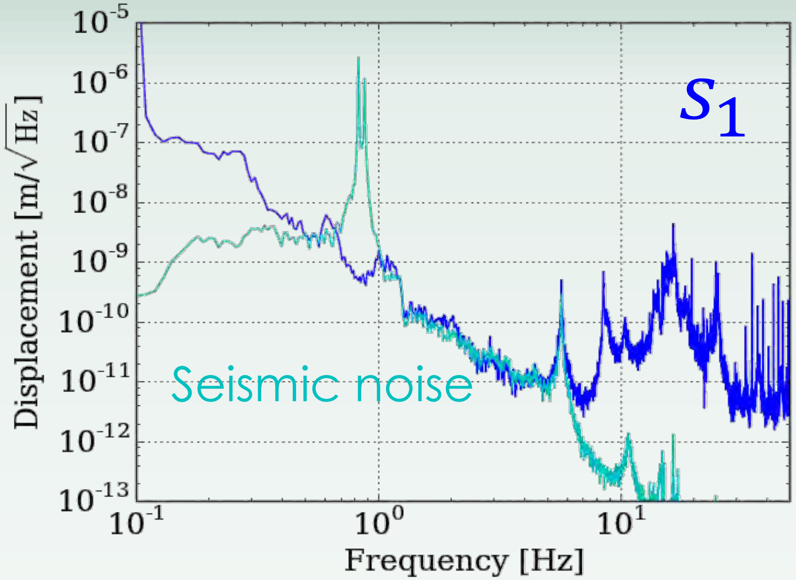




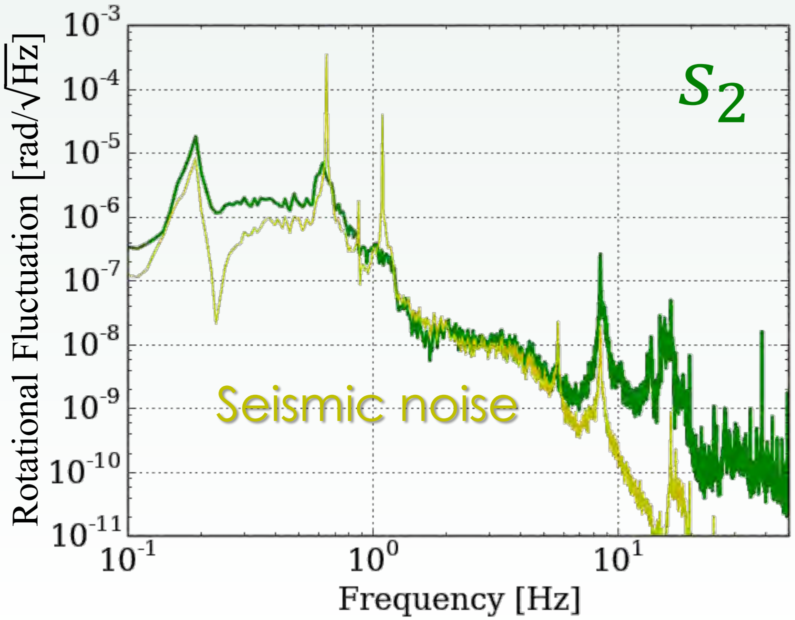


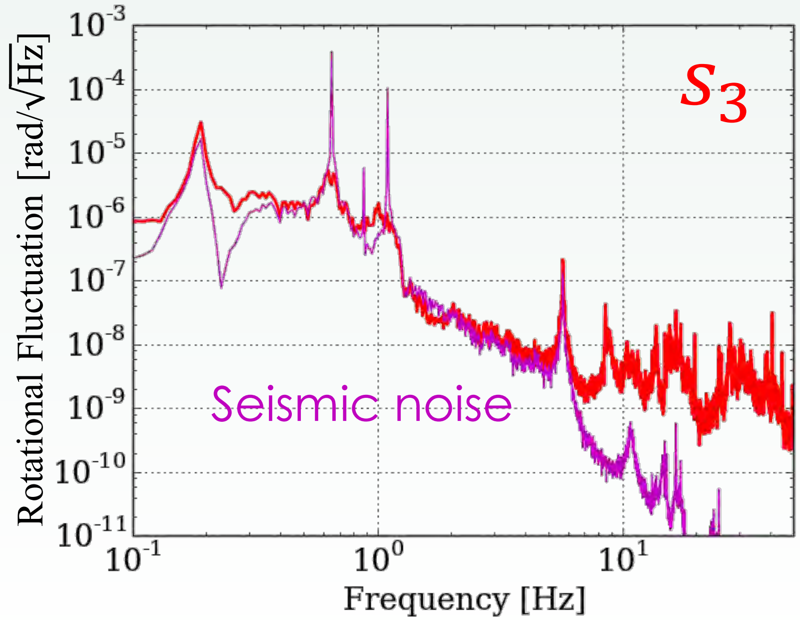


Seismic noise



The sensitivity is limited by the seismic noise below ~7Hz

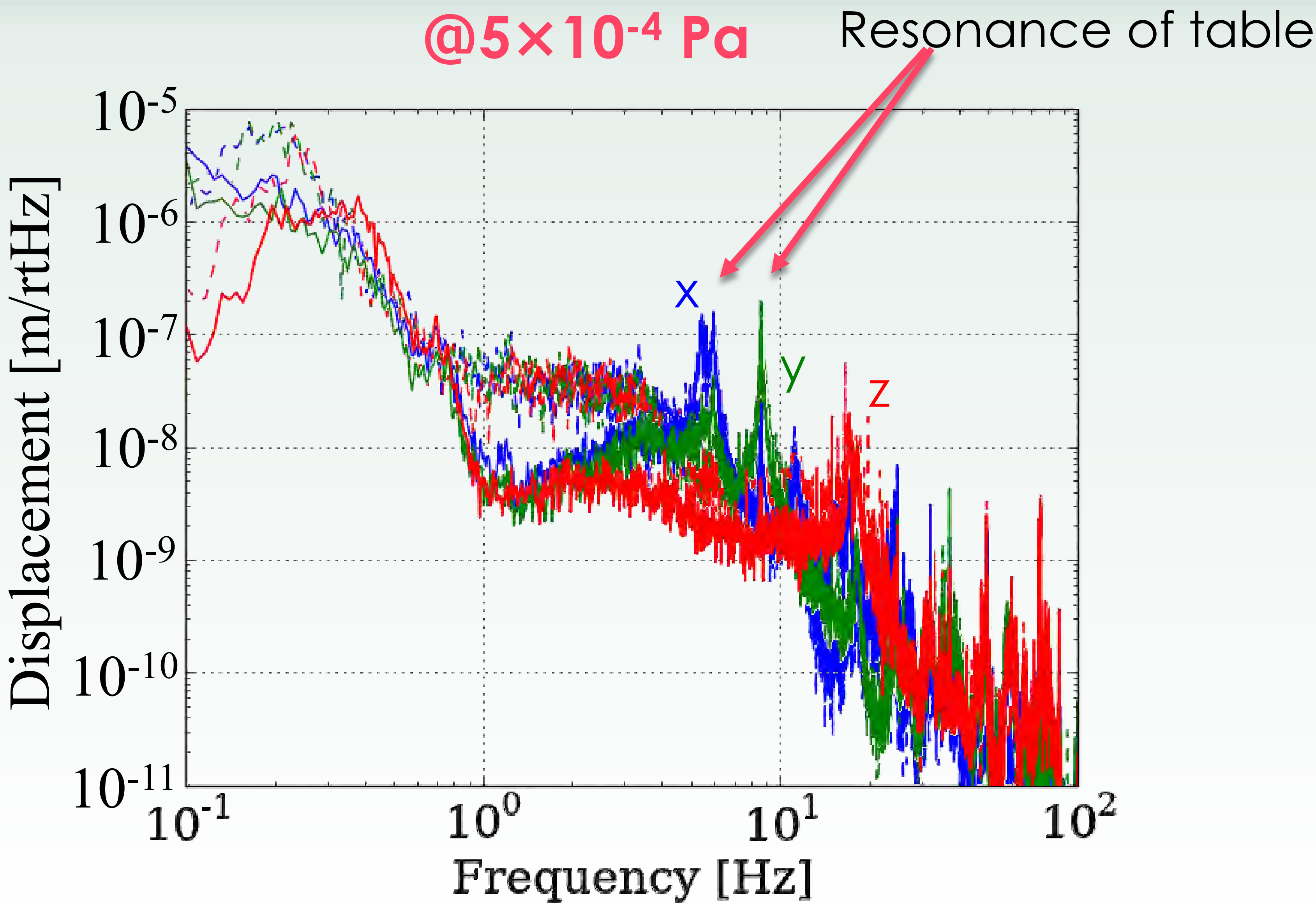




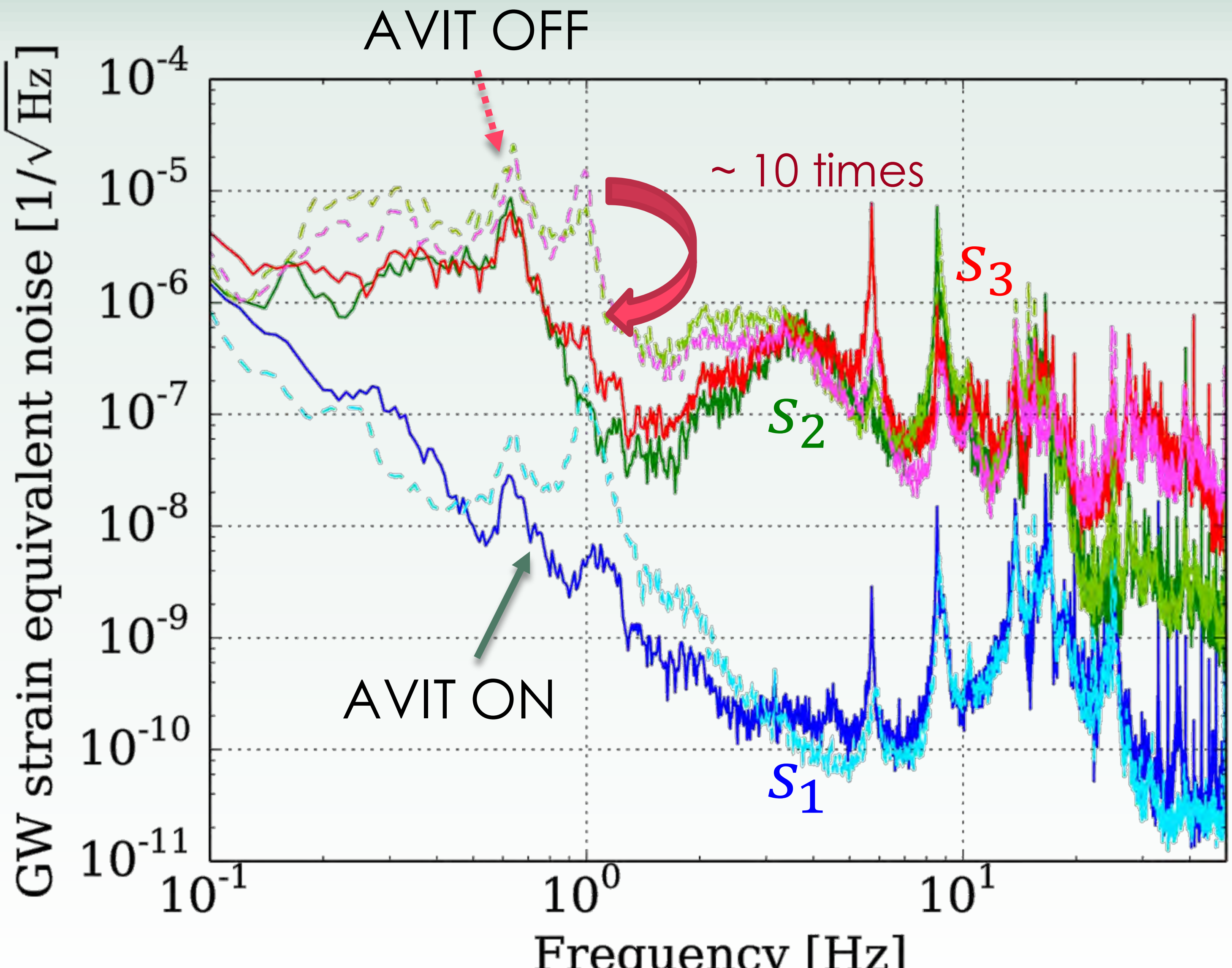
Phase-II TOBA

- ✓ Multi-output system
- ✓ Common mode noise rejection
- ✓ Passive vibration isolation
- ✓ Active vibration isolation

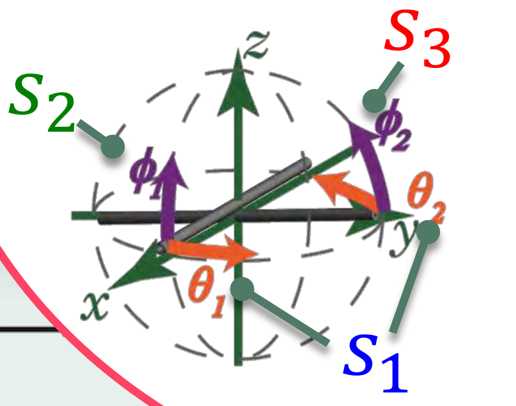
AVIT performance



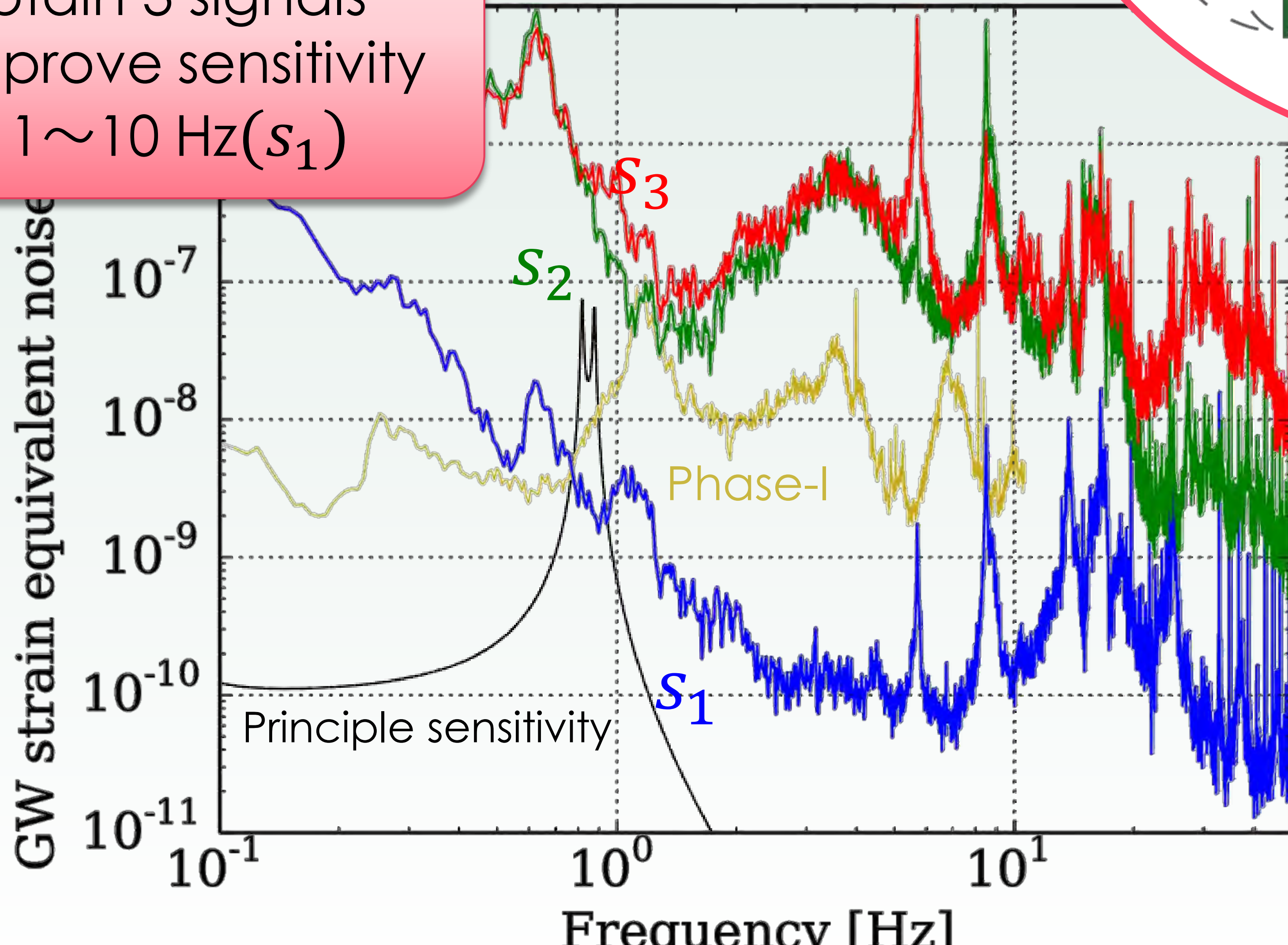
Sensitivity improvement by AVIT



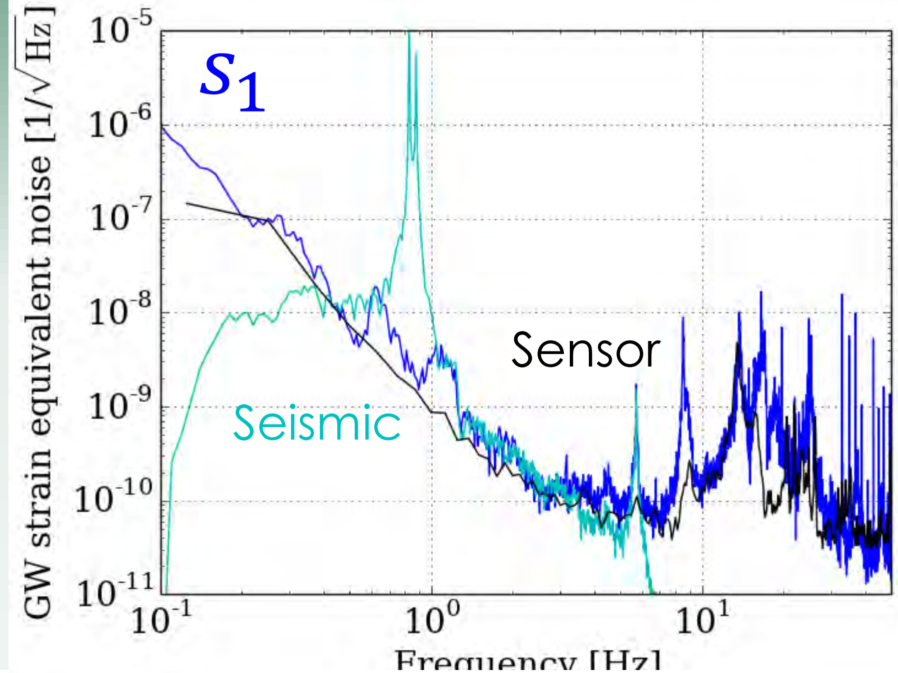
Sensitivity summary

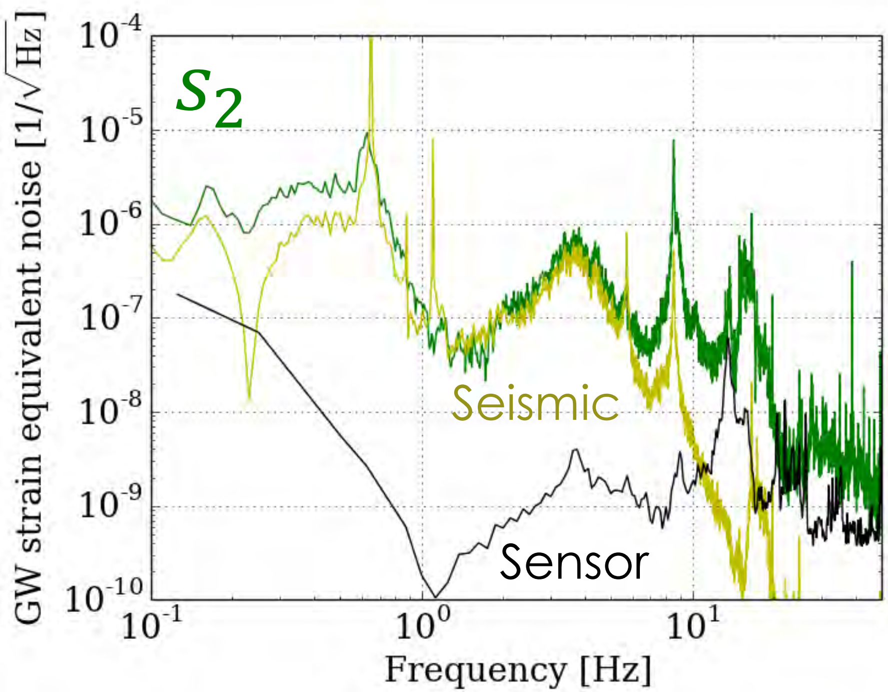


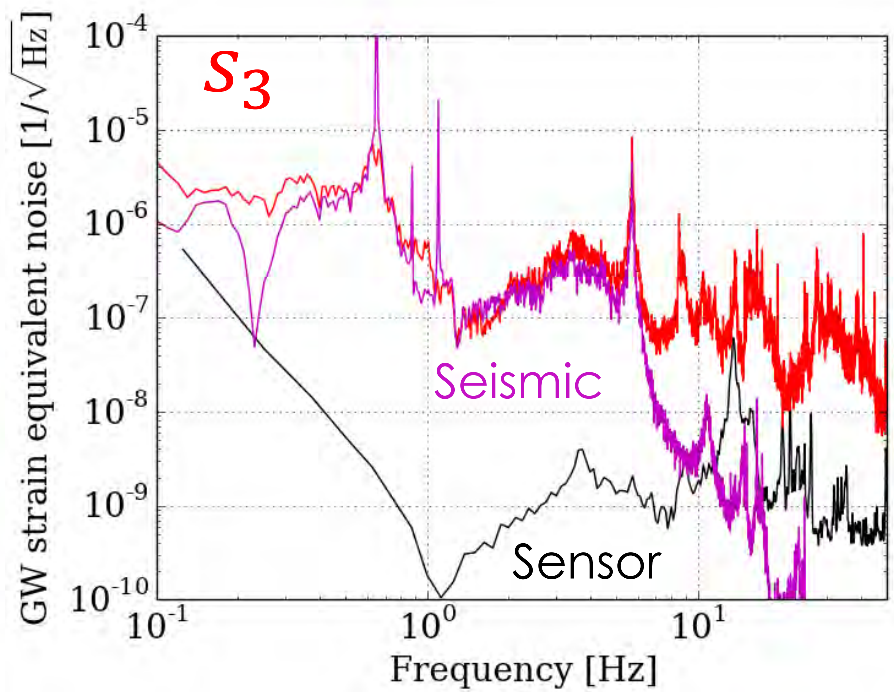
- Obtain 3 signals
- Improve sensitivity at 1～10 Hz(s_1)



Noise sources





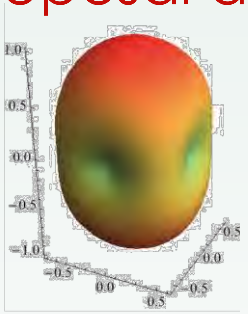


Summary

We developed Torsion-bar Antenna (TOBA) for GW astronomy and earthquake early alert system

Establish the new suspension system

- Proposal and Introduction of Multi-Output System



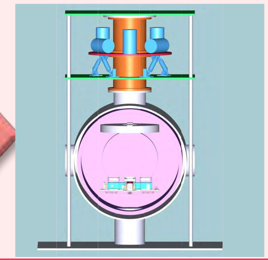
Improvement of the event rate
& angular resolution

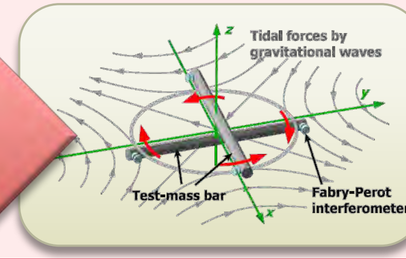
- Development of the vibration isolation system

Passive isolation → Above 1Hz

Active isolation → Around 1Hz

Future Plan





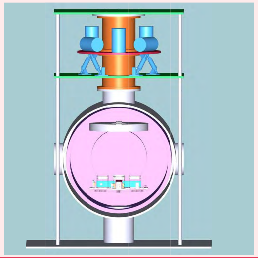
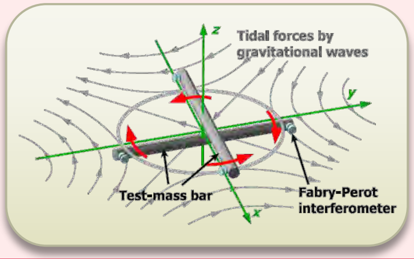
		Phase-I	Phase-II		Final
Susp.	TM size	Small(20cm)	Small(25cm)		Large(10m)
	TM #	1	2		2
	Multi-Output	×	○	…	○
	Vibration Isolation	×	○ Passive+Active		○
	Low loss susp.	△	×		○
Sensors		Michelson	Michelson		Fabry-Perot
Cryogenic		×	×		○

$h \sim 10^{-8}$ @ 1Hz
Principle test
First observation

$h \sim 10^{-10}$ @ 1Hz
Suspension system
IMBH first obs.

$h \sim 10^{-19}$ @ 1Hz
GW astronomy

Future Plan

		Phase-II	Phase-III	Final
				
Susp.	TM size	Small(25cm)	Middle(1m)	Large(10m)
	TM #	2	2	2
	Multi-Output	○	○	○
	Vibration Isolation	○ Passive+Active	○ Passive+Active	○
	Low loss susp.	×	○	○
Sensors		Michelson	Michaelson	Fabry-Perot
Cryogenic		×	○	○

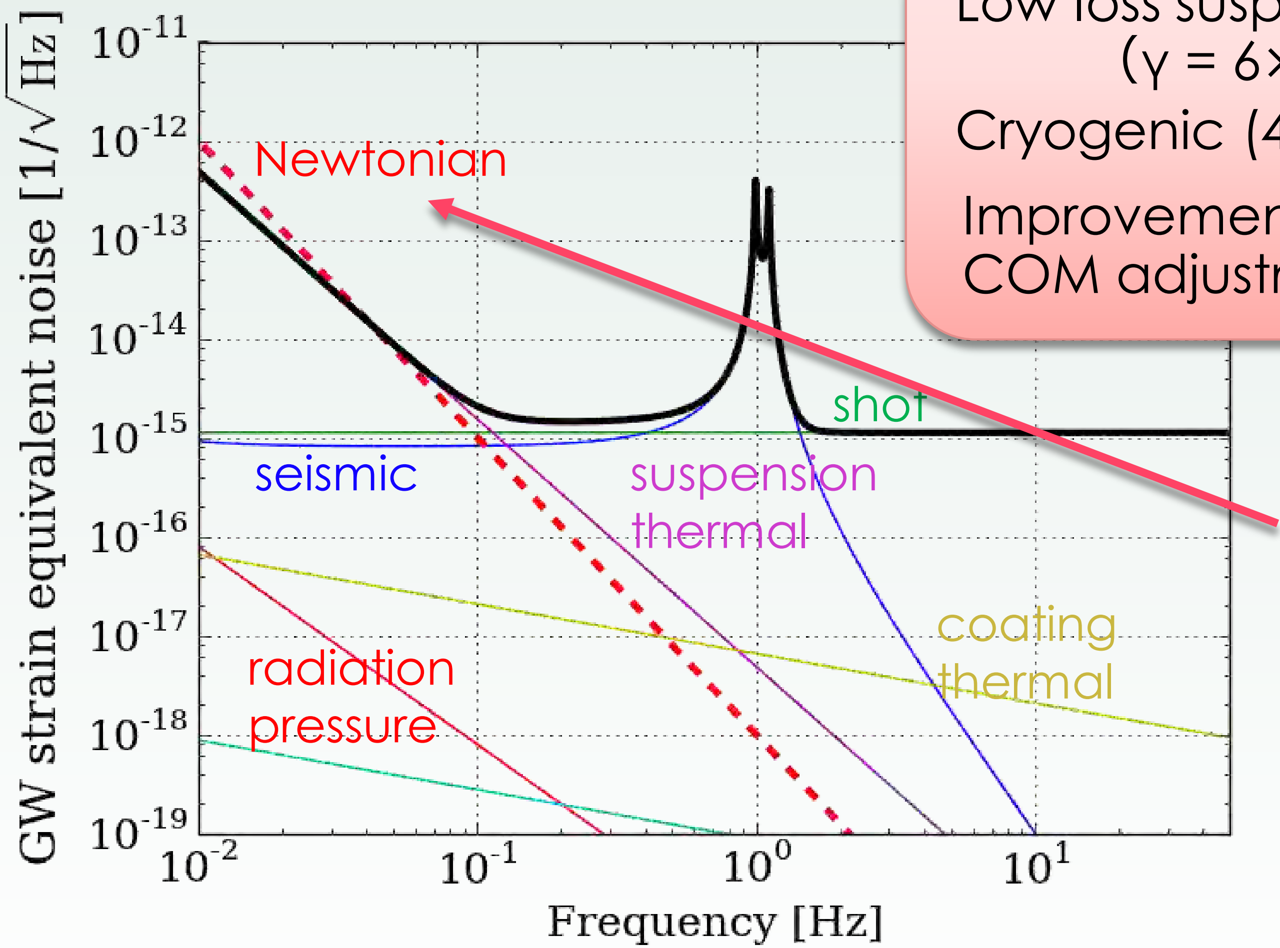
h ~ 10^{-10} @ 1Hz
Suspension system
IMBH first obs.

h ~ 10^{-15} @ 1Hz
Earthquake early alart

h ~ 10^{-19} @ 1Hz
GW astronomy

Future Plan

Phase-III TOBA : observe IMBH binaries in our galaxies



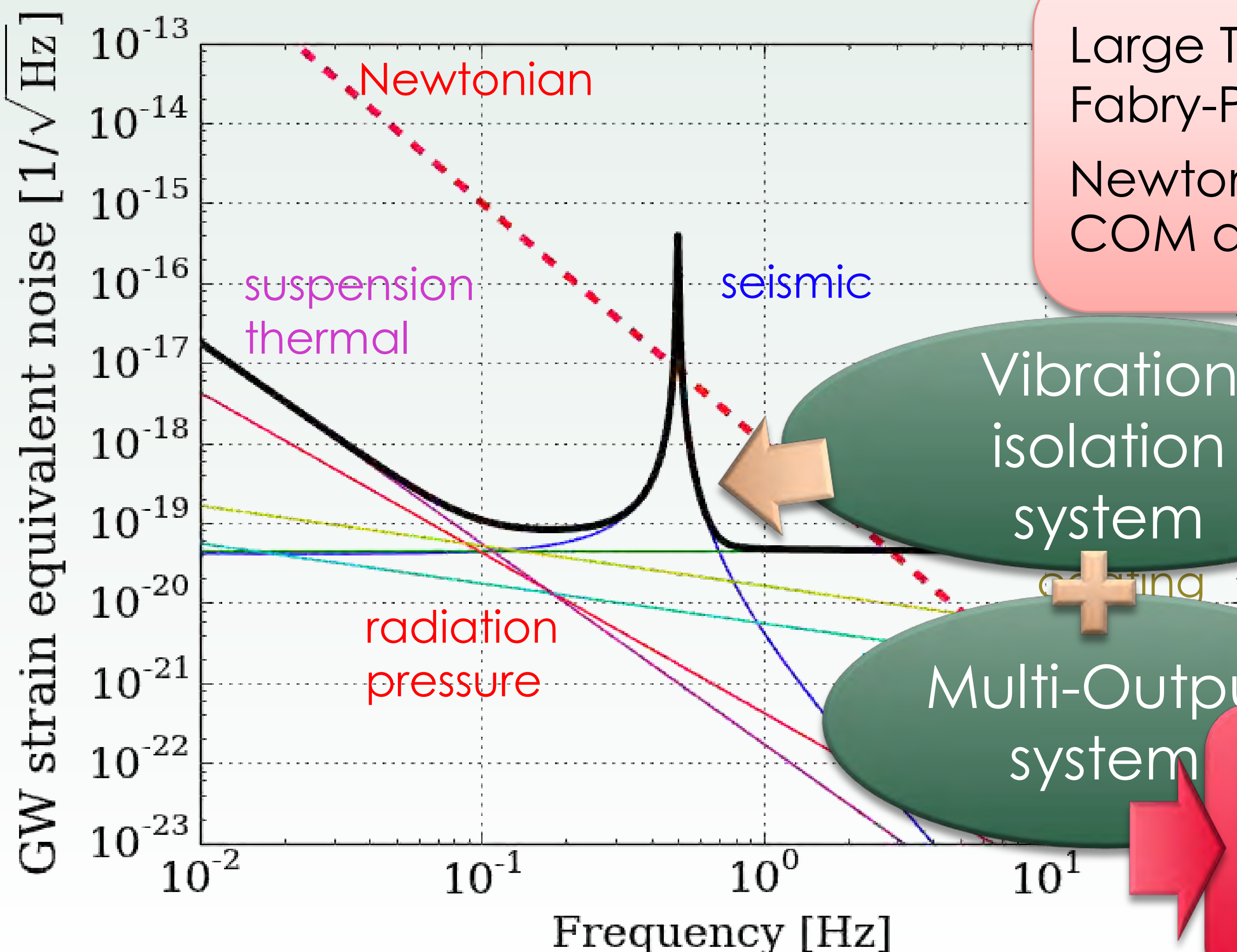
Low loss suspension ($\gamma = 6\times10^{-7}$)
Cryogenic (4K)
→ Thermal noise reduction

Improvement of AVIT & OB
COM adjustment : 1mm

earthquake early alert

Future Plan

Final TOBA : observe IMBH binaries within 10Gpc



Large TMs
Fabry-Perot interferometer

Newtonian noise reduction
COM adjustment : 0.1mm

Vibration isolation system

+

Multi-Output system

Low frequency GW astronomy
+
Earthquake Alert

BACKUP

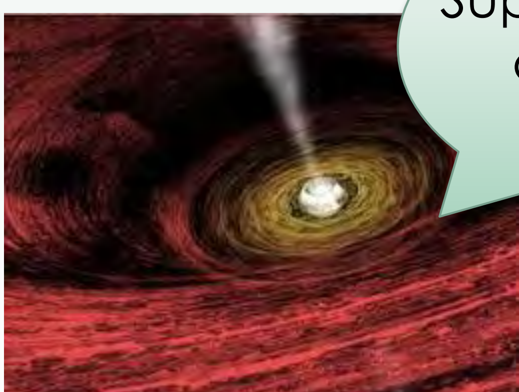
Intermediate Mass Black Hole Binaries

IMBH: black holes with the mass of $10^2 \sim 10^6\ M_\odot$

Observed with the X-ray

M82

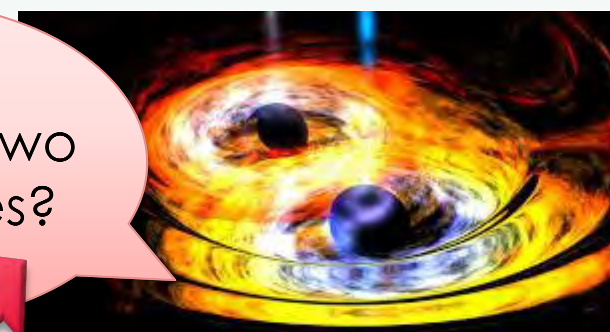
Keys for the mystery of super massive black holes



Super Eddington accretion?

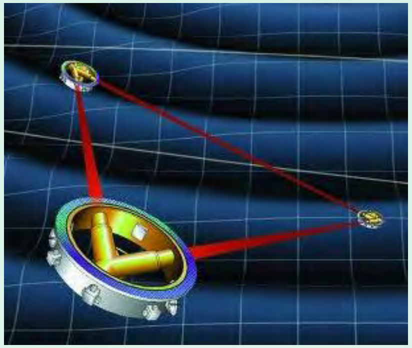
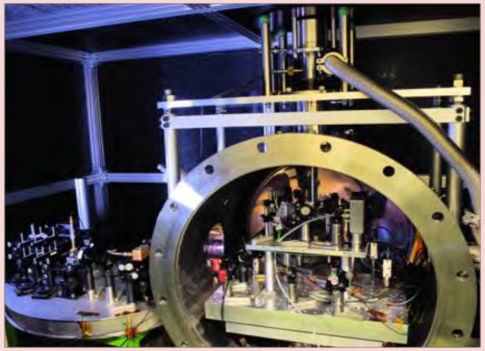
?

Merger of two black holes?



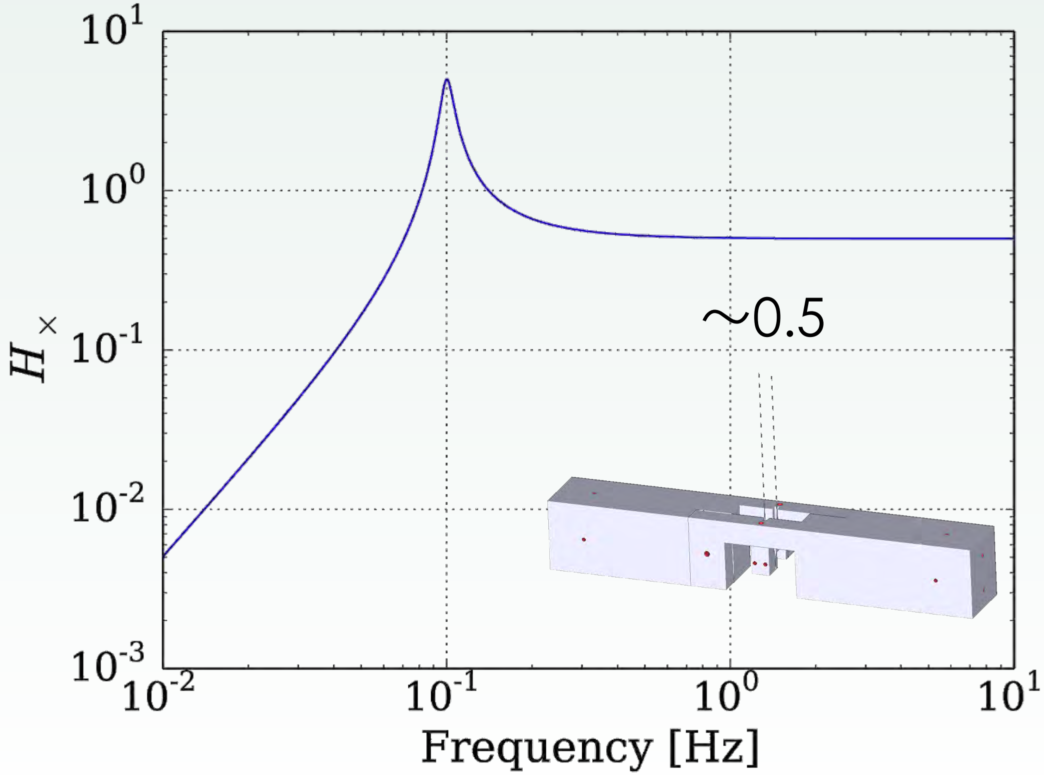
GW sources

Others vs TOBA

	Ground-based interferometers	Space interferometers	TOBA
			
Freq.	10-1000 Hz (Res. Freq. ~ 1Hz)	1m -10 Hz	0.1-10 Hz (Res. ~ a few mHz)
Feature	High sensitivity Large(3km) Updatable	High sensitivity Large(～1000km) Unable to update	Low sensitivity Small(～10m) Updatable

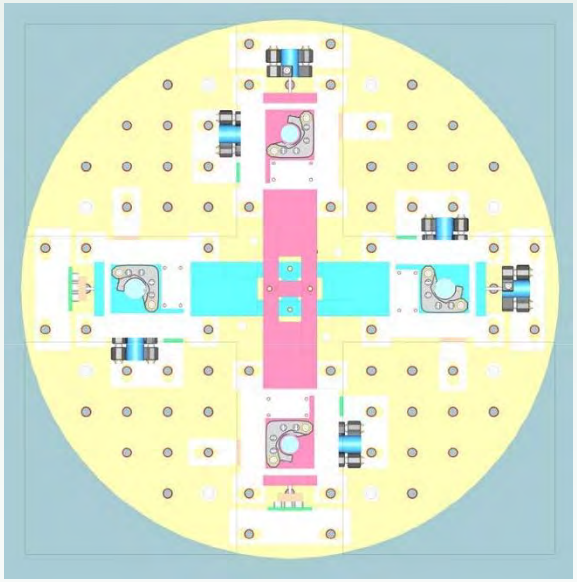
Rotation→Strain

$$\theta(\omega) = \frac{q_+}{2I} H(\omega) h(\omega)$$

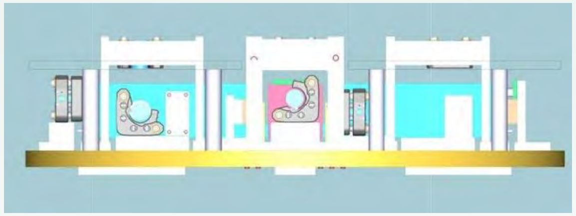


Rotation→Strain

Optical Bench also moves



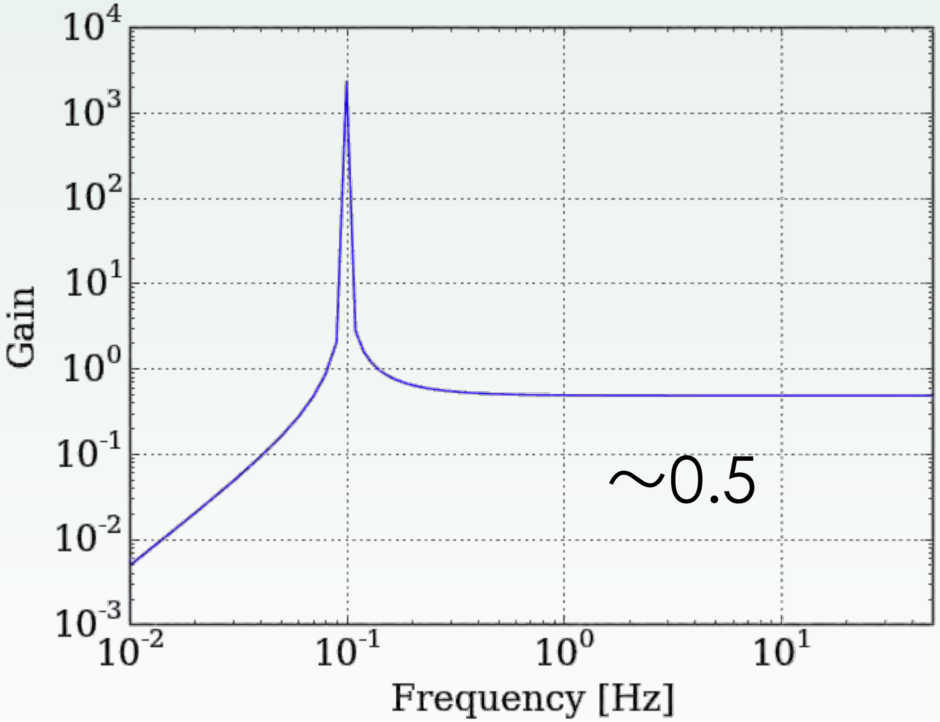
$q_+ = 0$



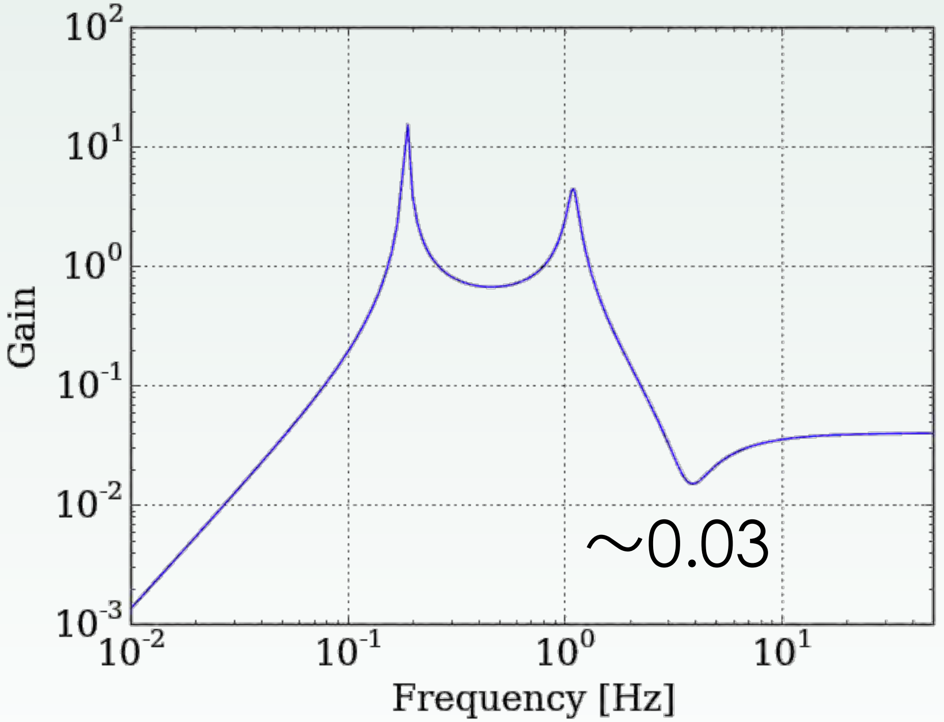
$q_+ \neq 0!$

Rotation→Strain

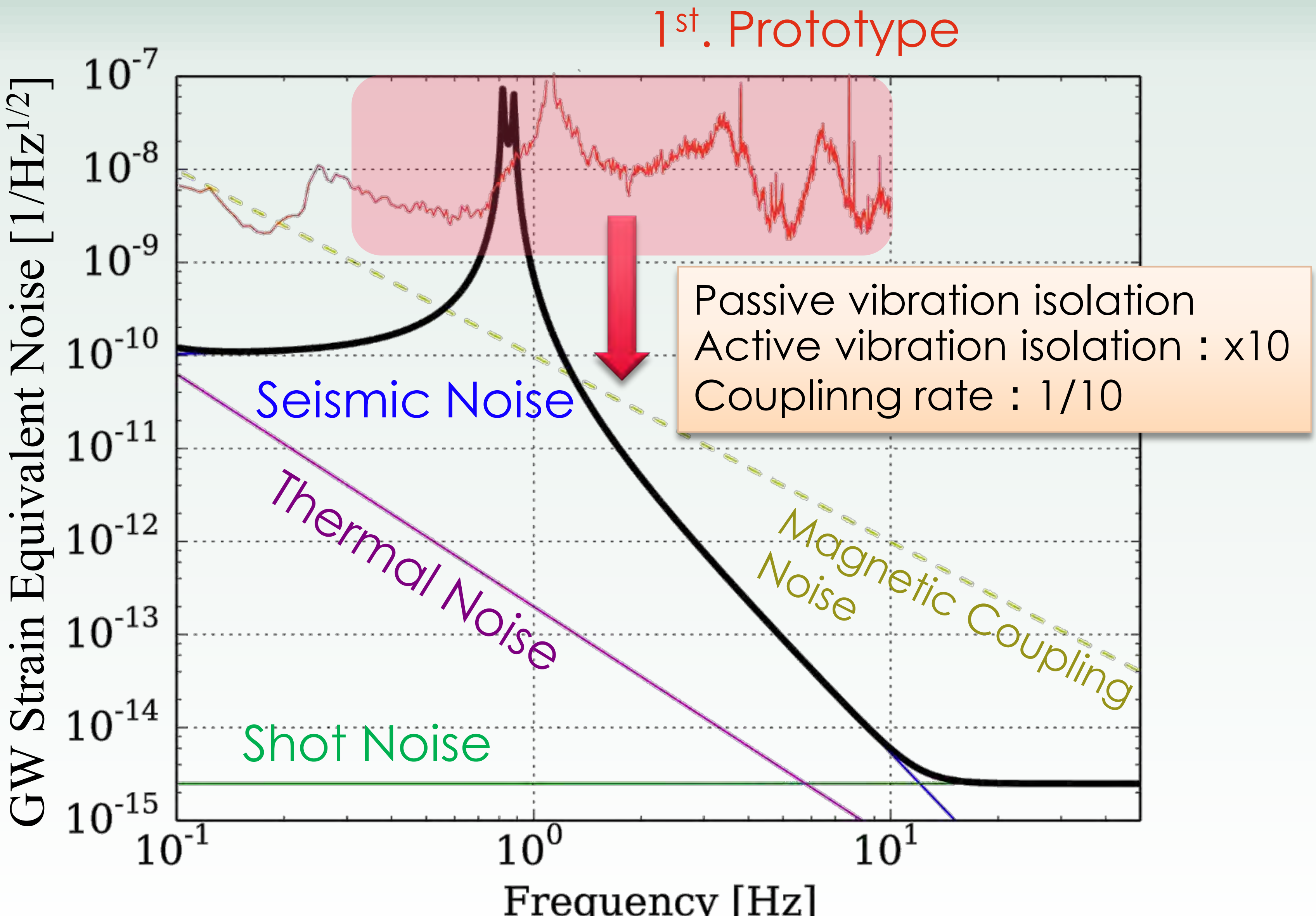
horizontal



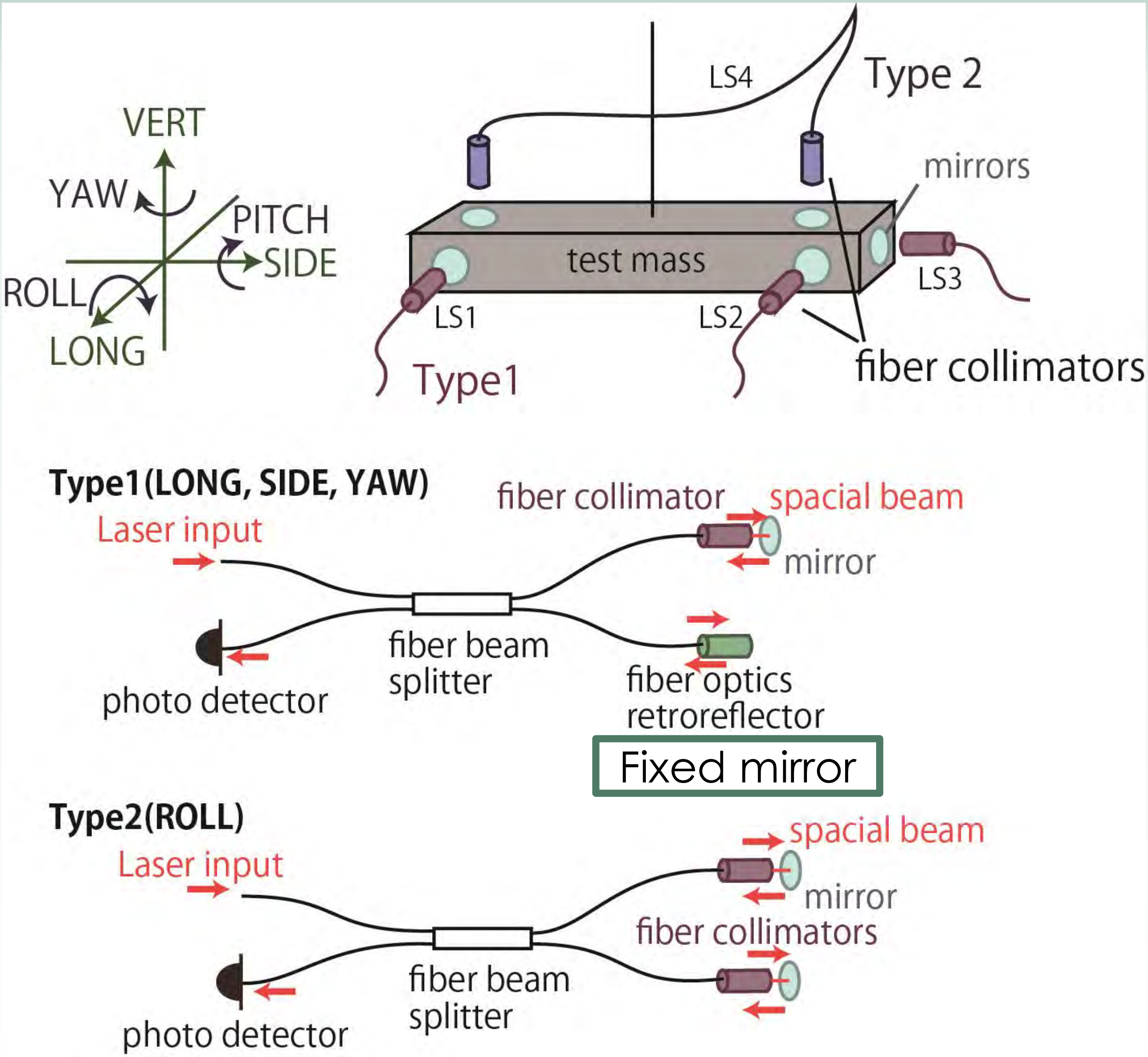
rotational



Fundamental Sensitivity

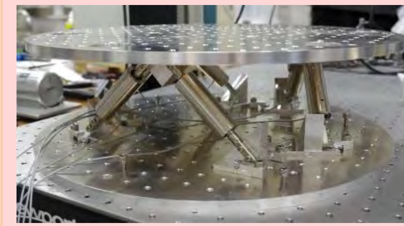


Sensor



VERT
YAW
PITCH
SIDE
ROLL
LONG
LS4
Type 2
mirrors
test mass
LS3
LS1
LS2
Type1
fiber collimators
Type1(LONG, SIDE, YAW)
fiber collimator
spacial beam
Laser input
mirror
fiber beam splitter
photo detector
fiber optics retroreflector
Fixed mirror
Type2(ROLL)
Laser input
spacial beam
mirror
fiber collimators
fiber beam splitter
photo detector

Comparison

	TAMA system (α2)	Hydraulic External Pre Isolator (HEPI)	Two Stage Isolator (TSI)	AVIT
				
System	Active	Active + Feedforward	Active + Passive	Active
Actuator	Air pressu			Piezoelectric material
Vacuum	In			Vacuum
Freq band	1 – 20 H		0 Hz)	0.3 – 10 Hz
Size	25cm × 4U	~ 4m	180 cm	45 cm
Max. load weight	1500 kg	4500 kg	950 kg	90 kg

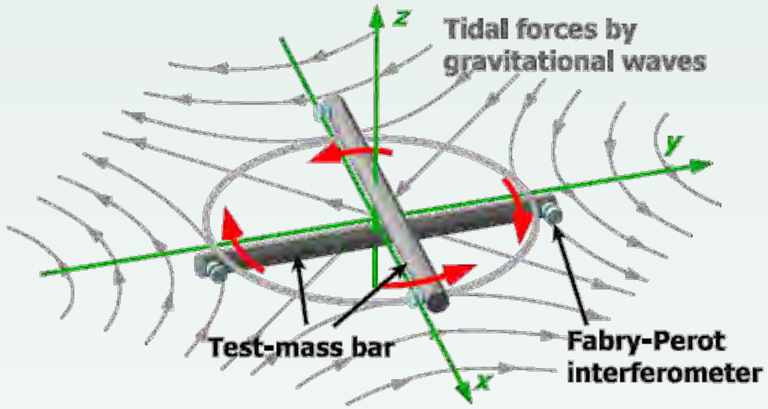
- ✓ Insensitive to balance
- ✓ Suppress vibrations from the outside (ex. Cryogenic system)

Multi-Output System

Get 3 signals from a single detector

Only we need: additional sensors

3 signals with different pattern functions



Merit 1.

Improve event rate

Merit 2.

Determine the sky position of the sources with less detectors