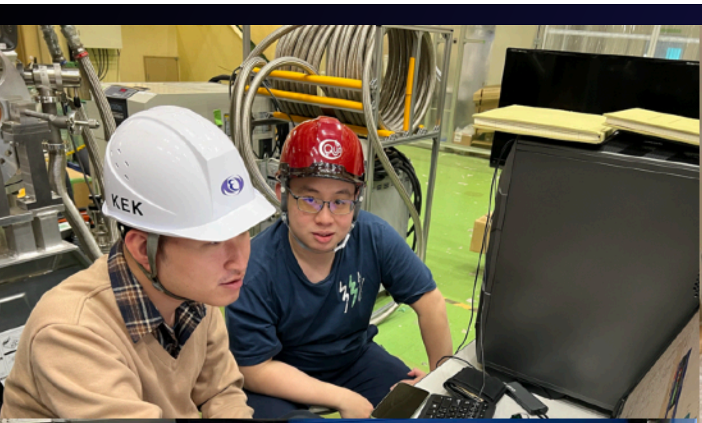
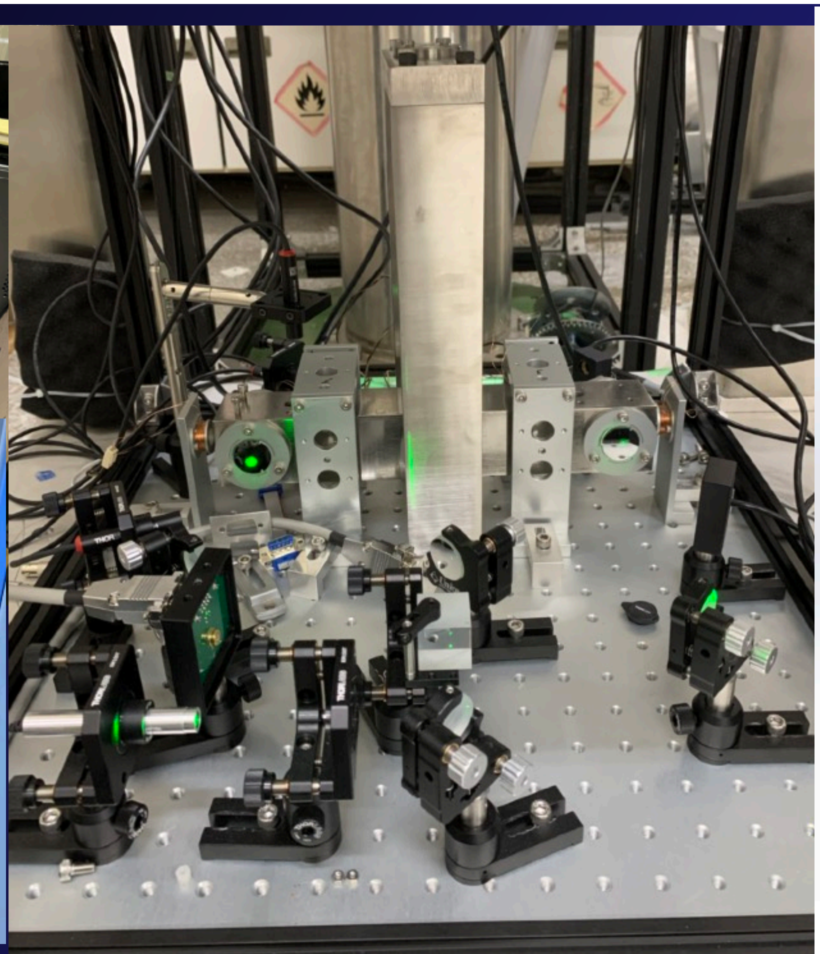
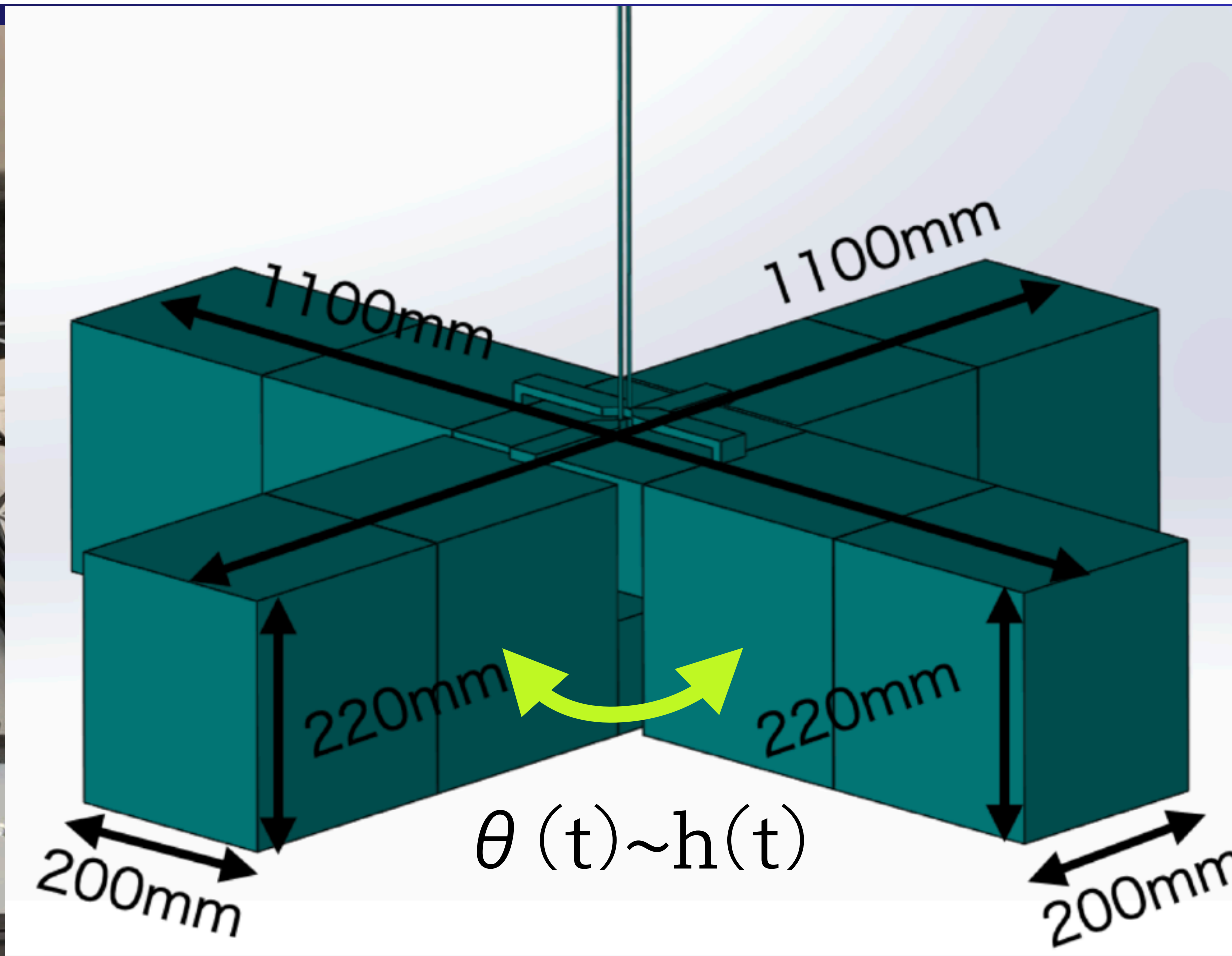






Quantum non-demolition measurement with CHRONOS gravitational wave detector

National Central University and Academia Sinica
Yuki Inoue

Introduce myself

Yuki Inoue

Associate professor in National Central University

Adjunct Associate research fellow in Academia Sinica

- Research history:
  - 2011-2016: POLARBEAR/Simons Array (Cosmic Microwave Background)
  - 2016-2021: KAGRA (Gravitational Wave experiment in Japan)
    - Calibration and Reconstruction
  - 2021-Now: LIGO (Gravitational Wave experiment in US)
  - 2025-Now: CHRONOS

Taiwan-LIGO instrumentation group

National Central University

Yuki Inoue (PI)
Miftahul Ma’arif
Ta-Hun Yu
Hsiang-Yu Huang
Avani Patel
Kun-Yao Chang

Academia Sinica

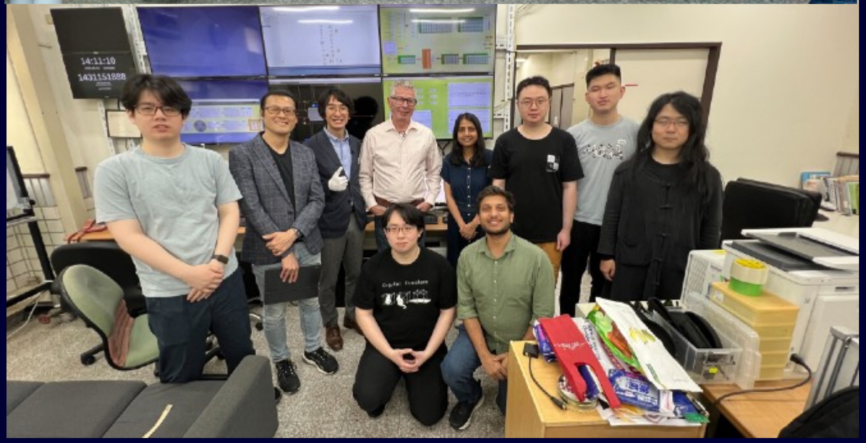
Tsz-King Wong
Feng-Kai Lin
Daiki Tanabe
Vivek Kumar
Ting-Yi Liang

Philippine

Mario Organo

Senior Member

Chao Shiuh



NCU-CMB group (from 2025 April)

National Central University

Yuki Inoue
Masashi Hazumi

Calibration Analysis

Data analysis and pipeline development for Ongoing Observation

Core-Optics R&D

R&D for the new technology of GW with Taiwan semiconductor technology

Experimental Cosmology

Landscape of Gravitational wave stochastic background study with GW and CMB data

17 staffs and students join our group

GW-CMB 2025 (Nov.6-7)

New Frontiers in Observational Cosmology with Gravitational Waves and Cosmic Microwave Background (GW-CMB 2025)

6–7 Nov 2025
National Central University
Asia/Taipei timezone

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- Overview
- Timetable
- Contribution List
- My Conference
  - My Contributions
- Registration

Overview

We live in an era striving to uncover the origin of the Universe through observation. A century after Hubble's discovery of cosmic expansion, our instruments have advanced dramatically. Through diverse probes—the cosmic microwave background (CMB), galaxy surveys, supernovae, and gravitational waves—the Universe's history has become a subject of direct measurement rather than theory.

Cosmology has entered a stage where **precision observations open new physics**, and at its frontier lies the search for the **stochastic gravitational-wave background (SGWB)**.

Within the next five years, two landmark discoveries may be within reach:
(1) **primordial gravitational waves** from inflation or cosmological phase transitions; and
(2) an **astrophysical SGWB** from compact binary mergers across cosmic time.

These goals unite cosmology and gravitational-wave astronomy, driving international efforts such as **LIGO–Virgo–KAGRA** and the **Simons Observatory** toward the next breakthrough.
In this mini-workshop, we explore the combined impact of **GW and CMB observations** on the emerging **Gravitational-Wave Landscape**, the cosmology and astrophysics they enable, and new ideas for **cross-correlations** with other probes.

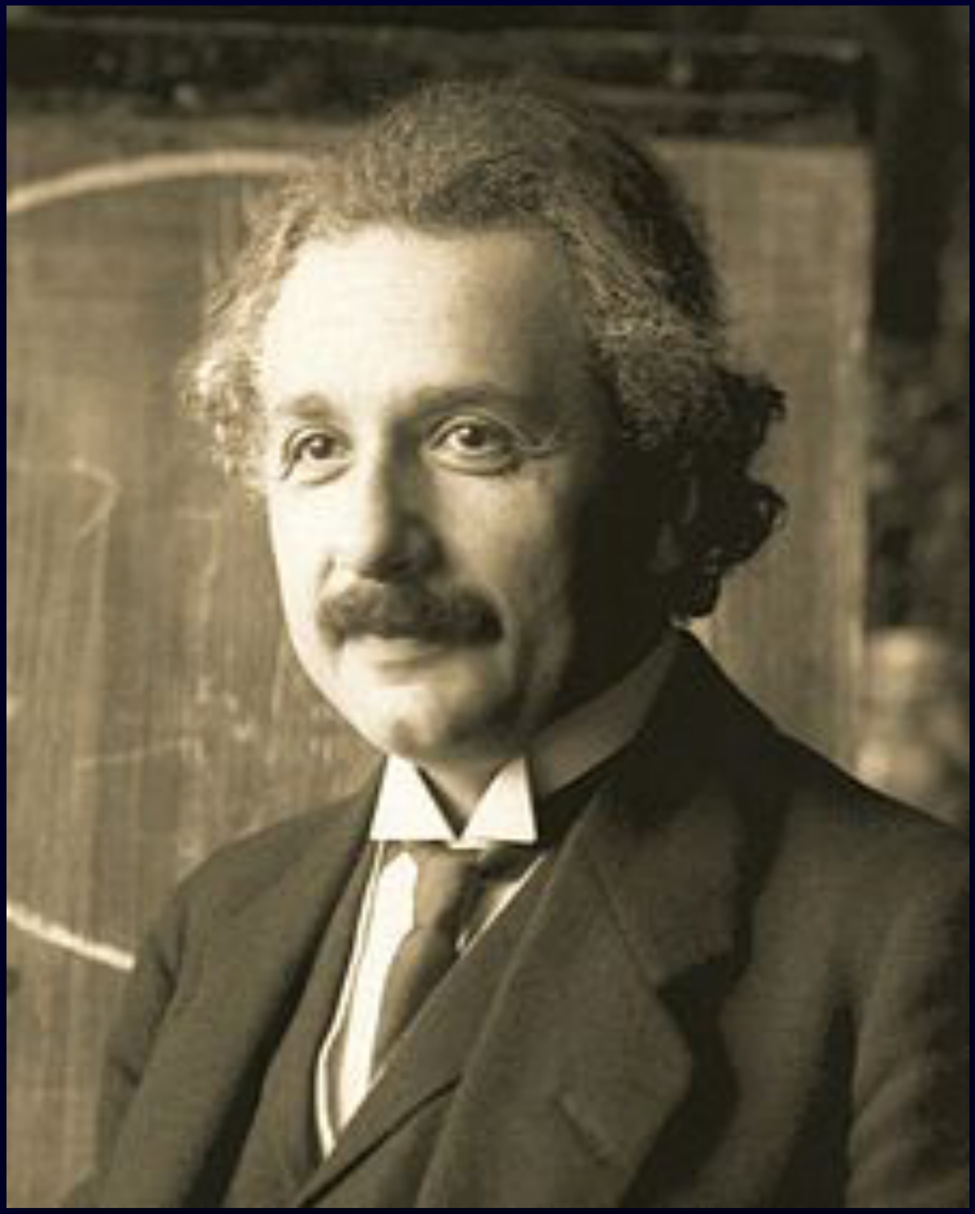
The program mainly consists of invited talks, but we can accept poster presentations and a few short oral presentations.

Outline

- Introduction
- CHRONOS project
- Principle
- Science
- Summary

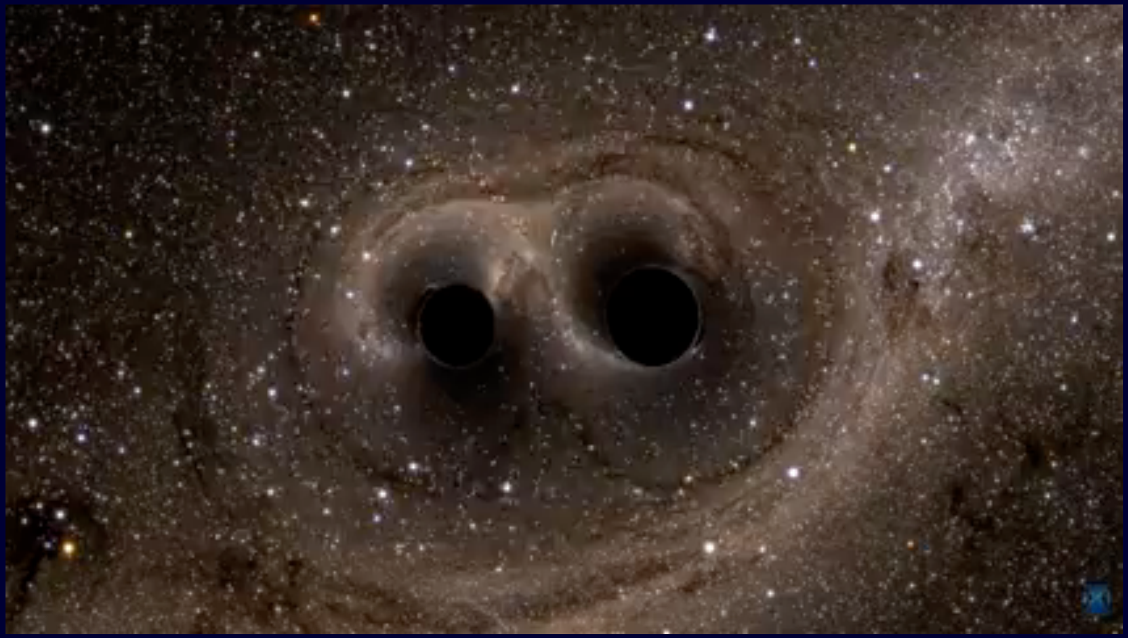
Introduction

Introduction



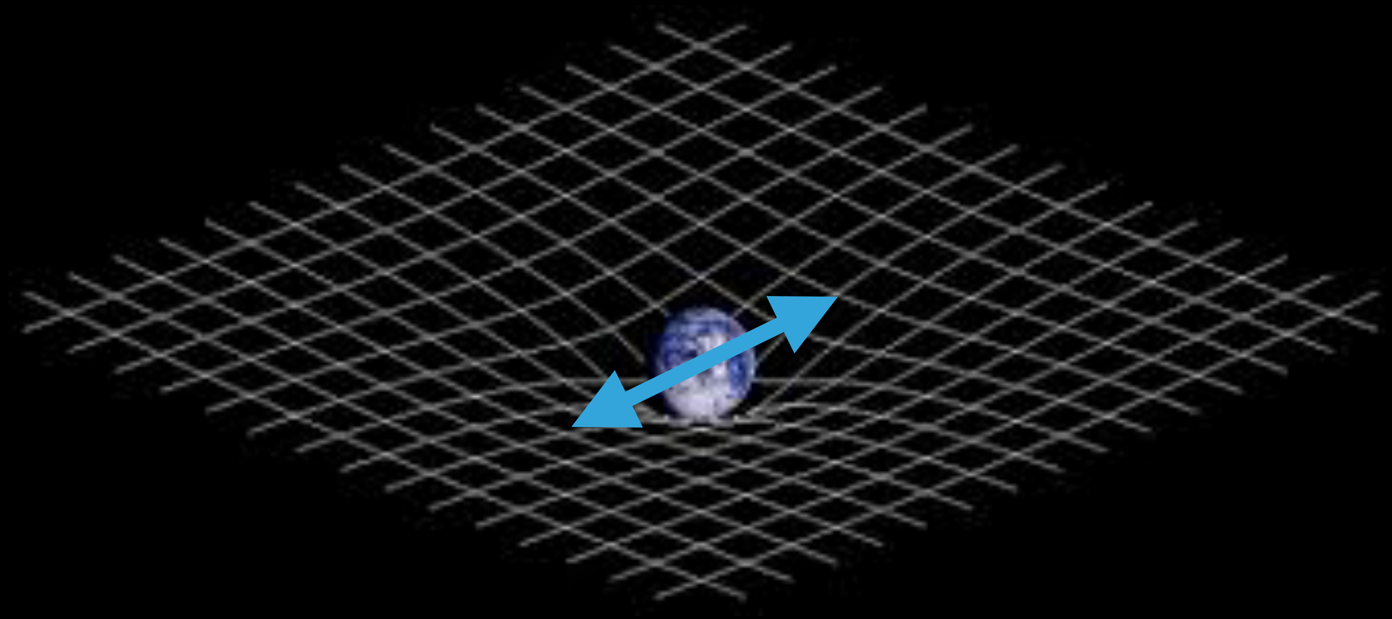
- Albert Einstein
- 1916 General Relativity
  - 'Distortion of Space and Time'
- One of the most important predictions:

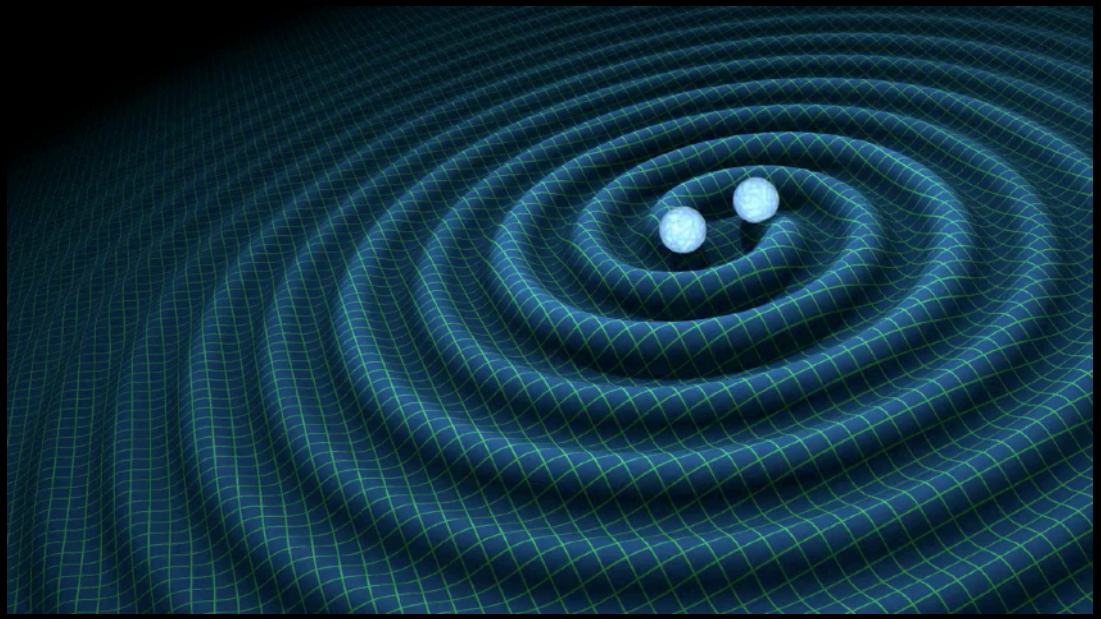
Gravitational Wave!



Nowadays, GW is observable target to know the astronomical phenomena.

How to generate Gravitational Waves





- Science target is observation of gravitational waves.
- GW is generated by the oscillation of the massive object.

Metric

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$$

Metric

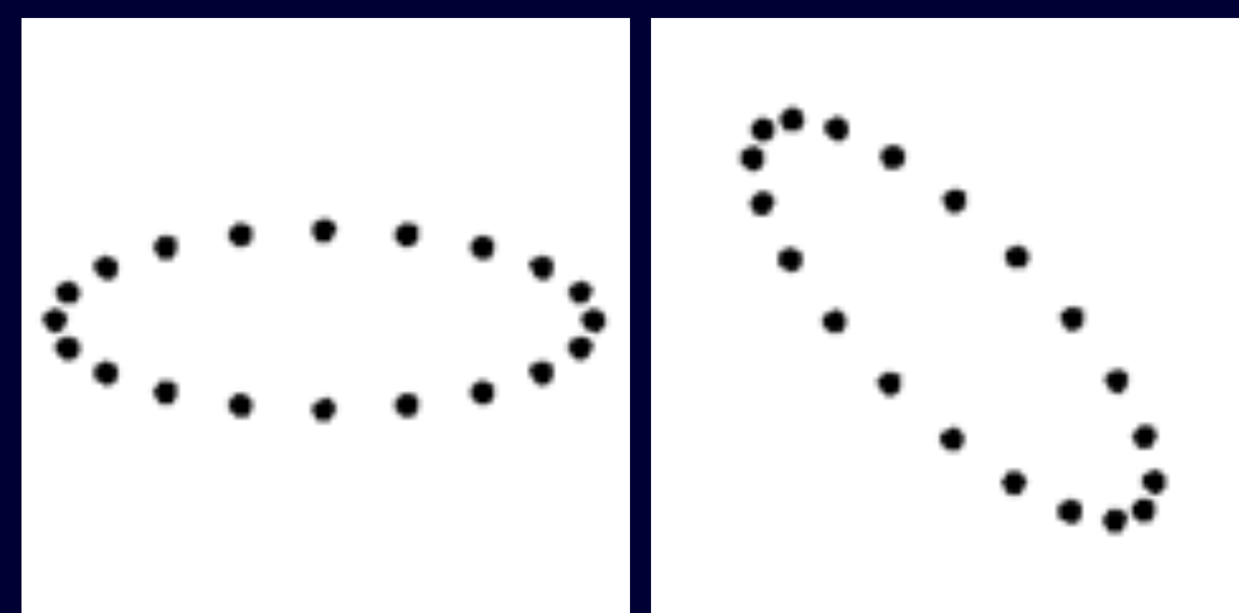
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Perturbation

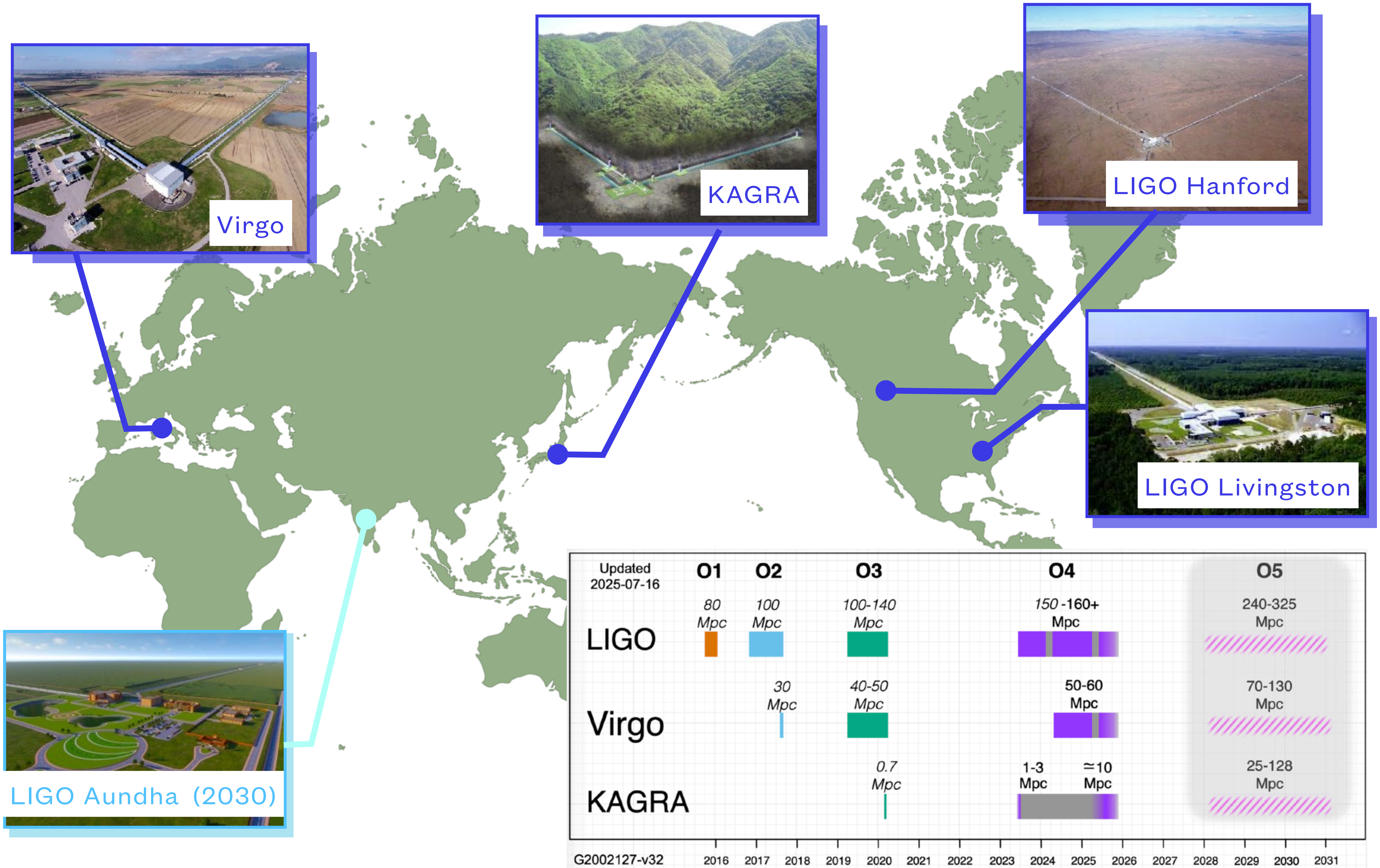
$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h = 0$$

$$h_{ij} = A_{ij} \times \exp\left[\mathrm{i}(\omega t - kz)\right]$$

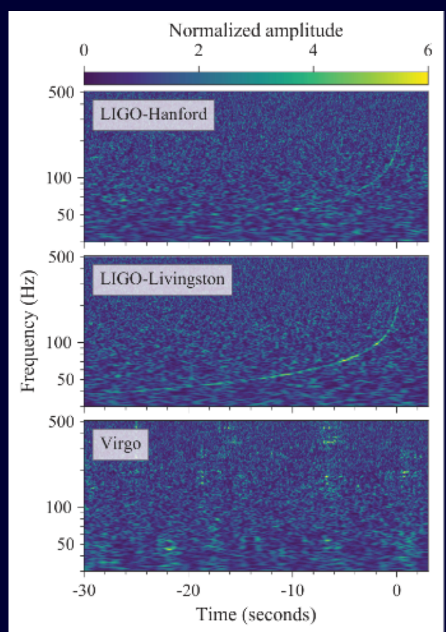
$$A_{ij} = \begin{bmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

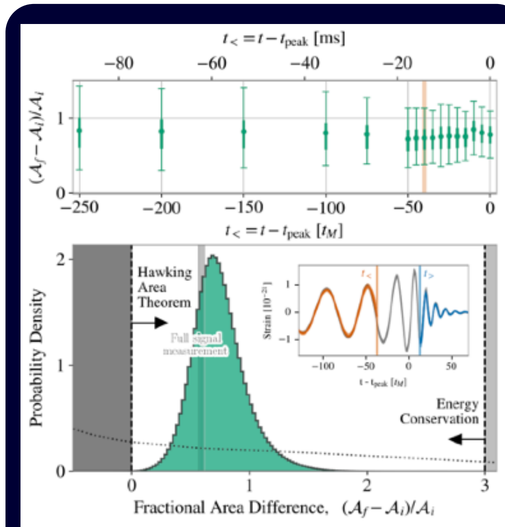


Gravitational wave observation network



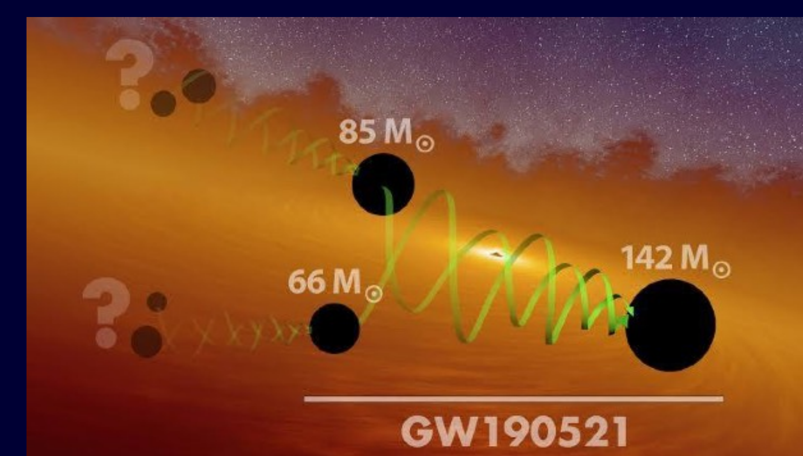
10 years anniversary



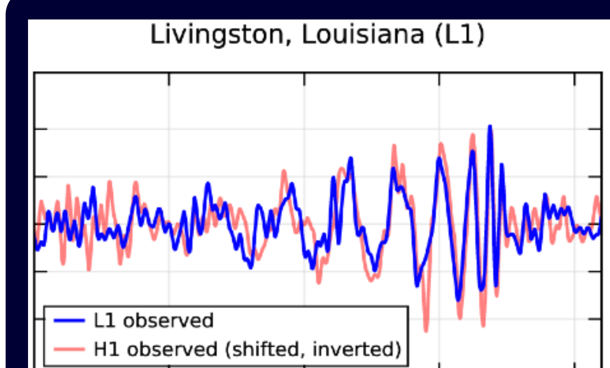


2025 Jan.14 Hawking's area law

2023 Nov.23 The largest Kerr black hole



2019 May. 21 IMBH



2017 Aug. 17 BNS

2015 Sep.14 The first detection

Before the great history of LIGO, there are discussion of quantum principle.

Quantum Non-demolition

Quantum Nondemolition Measurements

VLADIMIR B. BRAGINSKY, YURI I. VORONTSOV, AND KIP S. THORNE Authors Info & Affiliations

SCIENCE • 1 Aug 1980 • Vol 209, Issue 4456 • pp. 547-557 • DOI: 10.1126/science.209.4456.547

C.M. Caves, K.S. Thorne, R.W.P. Drever, V.D. Sandberg, M. Zimmermann, Rev. Mod. Phys. 52, 341 (1980)

GW detector can improve the sensitivity more than standard quantum limit.

One of the historically important questions for the quantum measurement.

1927 Heisenberg Uncertainty principle

$$\epsilon(x)\eta(p) \geq \frac{\hbar}{2}$$

Challenge to Heisenberg Uncertainty principle!

Crosscheck of calculation

M.Ozawa mathematically proofs Kip. S. Thorne theory.

M. Ozawa, Phys. Rev. Lett. 60, 385 (1988), J. Maddox, Nature 331, 559 (1988)

1927 Heisenberg Uncertainty principle

$$\epsilon(x)\eta(p) \geq \frac{\hbar}{2}$$

→ ?

M.Ozawa modified Heisenberg Uncertainty principle (2003)!

$$\epsilon(A)\eta(B) + \underline{\sigma(A_{in})\eta(B) + \epsilon(A)\sigma(B_{in})} \geq \frac{1}{2}\left|\langle\psi|[\hat{A}_{in}, \hat{B}_{in}]|\psi\rangle\right|$$

Additional term

J. Erhart et al. Nature Physics (2012) doi:10.1038/nphys2194.

Experimentally confirm the formula on neutron spin system.

Crosscheck of calculation

M.Ozawa mathematically proofs Kip. S. Thorne theory.

M. Ozawa, Phys. Rev. Lett. 60, 385 (1988), J. Maddox, Nature 331, 559 (1988)

1927 H

‘quantum non-demolition (QND) system’

is

keyword of today’s talk! We would like to discuss beyond the Heisenberg principle based on Taiwanese Gravitational wave detector project.

Definition: [H,A] = 0 ⇨ quantity A meet QND

M.Oza

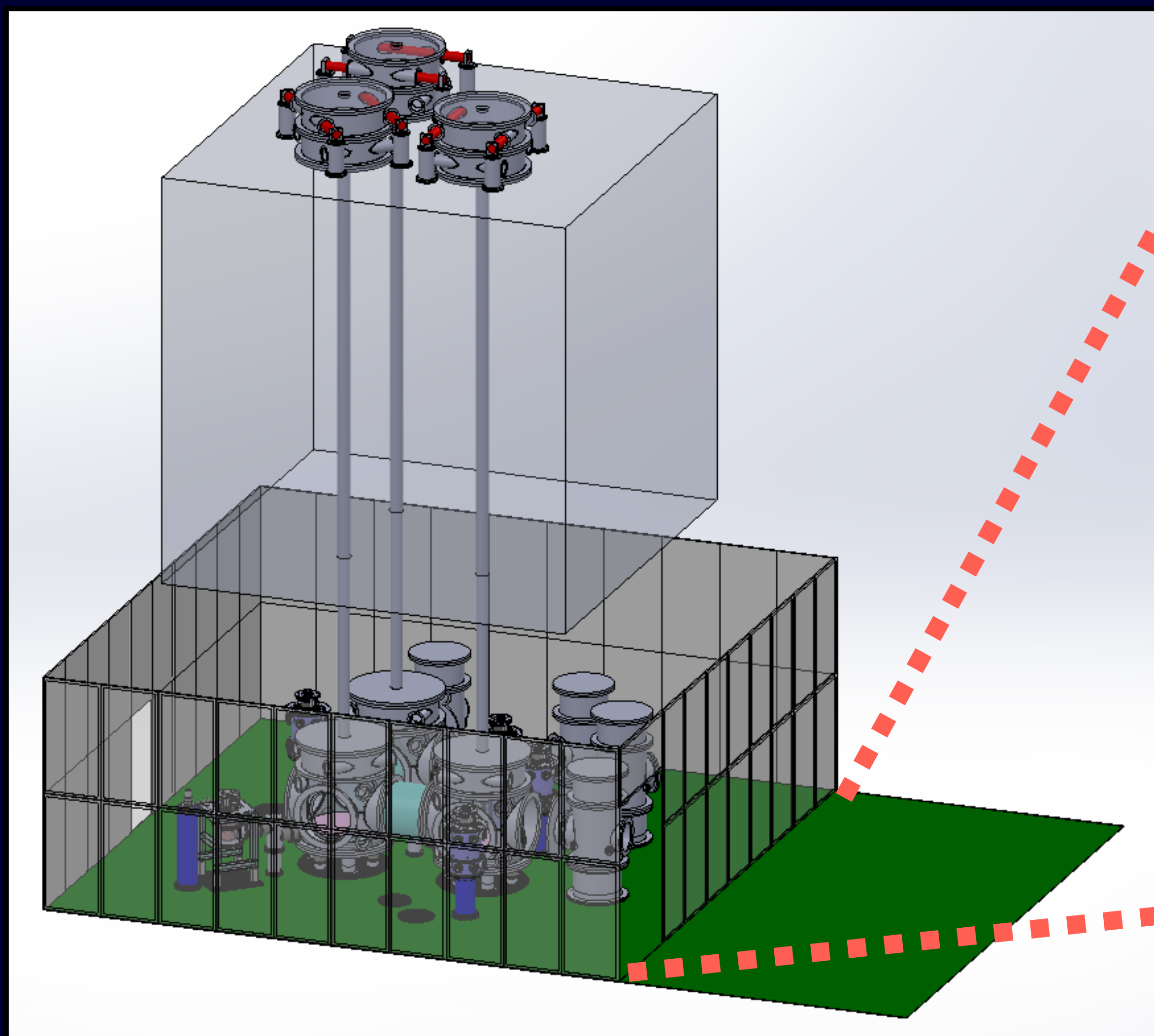
$\epsilon(A)\eta($

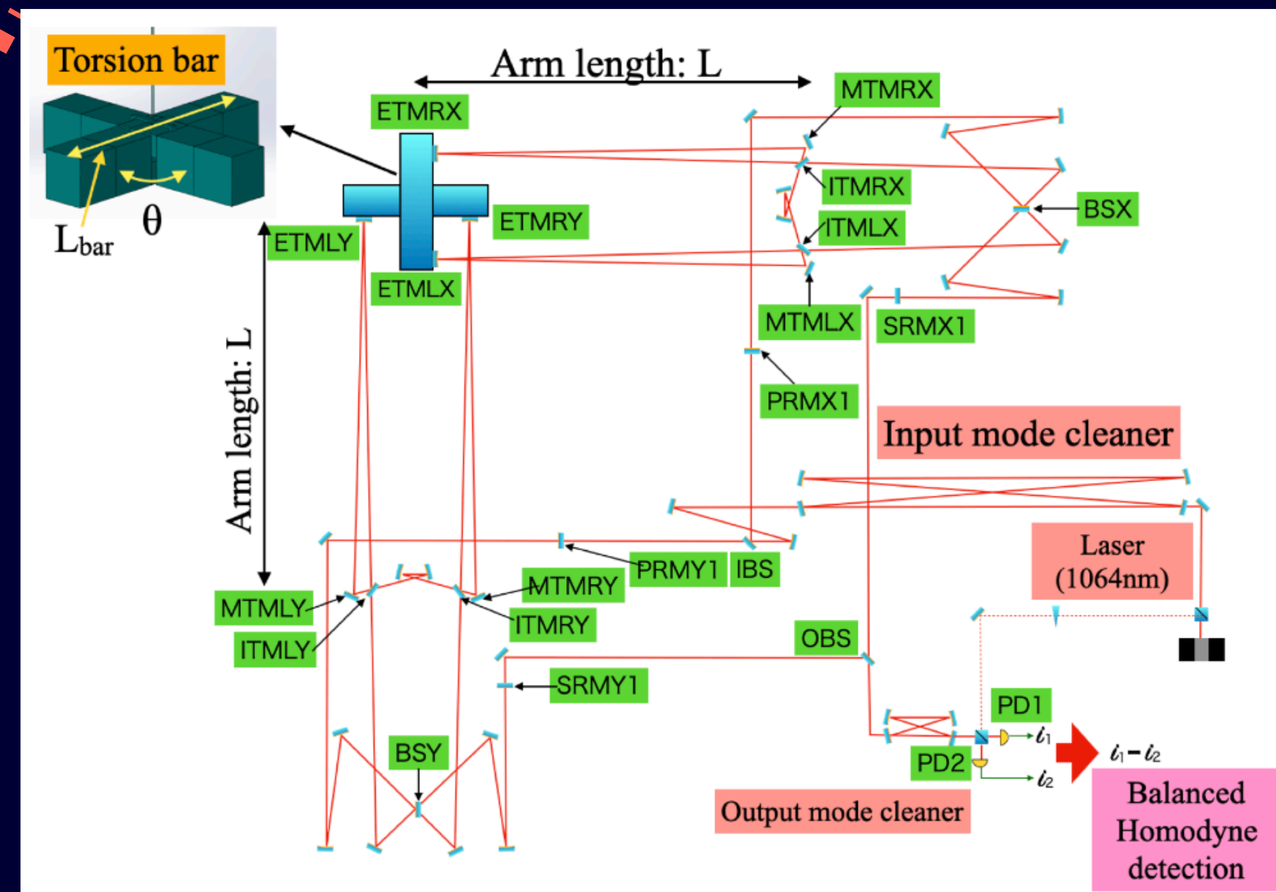
J. Erhart et al. Nature Physics (2012) doi:10.1038/nphys2194.

Experimentally confirm the formula on neutron spin system.

CHRONOS project

CHRONOS Overview





Cryogenic sub-**H**z c**RO**ss torsion bar detector with quantum **NO**n-demolition **S**peed meter

CHRONOS

CHRONOS Overview

- Mission: Search for Intermediate black hole on Sub-Hz range
- Method: Interferometorical Speed meter
- Full success: First detection of Intermediate Black hole merger on $O(10^4 M_\odot)$ range
- Unique point: 10m x 10m Observatory

SPEED METER

Key technologies

CRYOGENIC **TORSION BAR**

CHRONOS Overview

- Location: Underground site in Taiwan
- R&D is ongoing
  - Phase 1: R&D for Key technologies (2020-2025)
  - Phase 2: Integration test (2025-2033)
  - Phase 3: Construction of CHRONOS in Underground lab (2030-2035)

CHRONOS's target observation year = 2035

Recent paper

CHRONOS: Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter

Yuki Inoue,[1,2,3,4,*] Hsiang-Chieh Hsu,[3] Hsiang-Yu Huang,[1,2] M.Afif Ismail,[1,2,3] Vvek Kumar,[3,5] Miftahul Ma'arif,[1,2] Avani Patel,[1,2] Daiki Tanabe,[3,2,4] Henry Tsz-King Wong,[3,2] and Ta-Chun Yu[1,2]
[1]*Department of Physics,National Central University, Taoyuan, Taiwan*
[2]*Center for High Energy and High Field (CHiP), National Central University, Taoyuan, Taiwan*
[3]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[4]*Institute of Particle and Nuclear Studies, High Energy Acceleration Research Organization (KEK), Tsukuba, Japan*
[5]*Department of Physics, Institute of Applied Sciences and Humanities, GLA University, Mathura 281406, India.*
(Dated: October 25, 2025)

Optical design and sensitivity optimization of Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter (CHRONOS)

Yuki Inoue,[1,2,3,4,*] Daiki Tanabe,[3,2,4] M.Afif Ismail,[1,2,3] Vivek Kumar,[3,5] Mario Juvenal S Onglao III,[6,2] and Ta-Chun Yu[1,2]
[1]*Department of Physics,National Central University, Taoyuan, Taiwan*
[2]*Center for High Energy and High Field (CHiP), National Central University, Taoyuan, Taiwan*
[3]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[4]*Institute of Particle and Nuclear Studies, High Energy Acceleration Research Organization (KEK), Tsukuba, Japan*
[5]*Department of Physics, Institute of Applied Sciences and Humanities, GLA University, Mathura 281406, India.*
[6]*National Institute of Physics, University of the Philippines - Diliman, Quezon City 1101, Philippines*
(Dated: October 25, 2025)

Torque cancellation effect of Intensity noise for Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter (CHRONOS)

Daiki Tanabe[a,b,d†], Yuki Inoue[c,d,a,b‡], Vivek Kumar[e,a], Miftahul Ma'arif[c,d], Ta-Chun Yu[c,d]
[a]Institute of Physics, Academia Sinica, Nangang, Taipei, 015011, Taiwan
[b]Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[c]Physics Department, National Central University, Taoyuan 32001, Taiwan
[d]Center for High Energy and High Field Physics, National Central University, Taoyuan 32001, Taiwan
[e]Department of Physics, Institute of Applied Sciences and Humanities, GLA University, Mathura 281406, India

Main project paper

Y.Inoue et. al.

arXiv: 2509.23172

Submitted to PRL. Under reviewing.

Optical feasibility paper

Y.Inoue and D.Tanabe et. al.

arXiv: 2510.24780

Submit to PRD. 3 hours ago!

Intensity noise paper

D.Tanabe and Y.Inoue et. al.

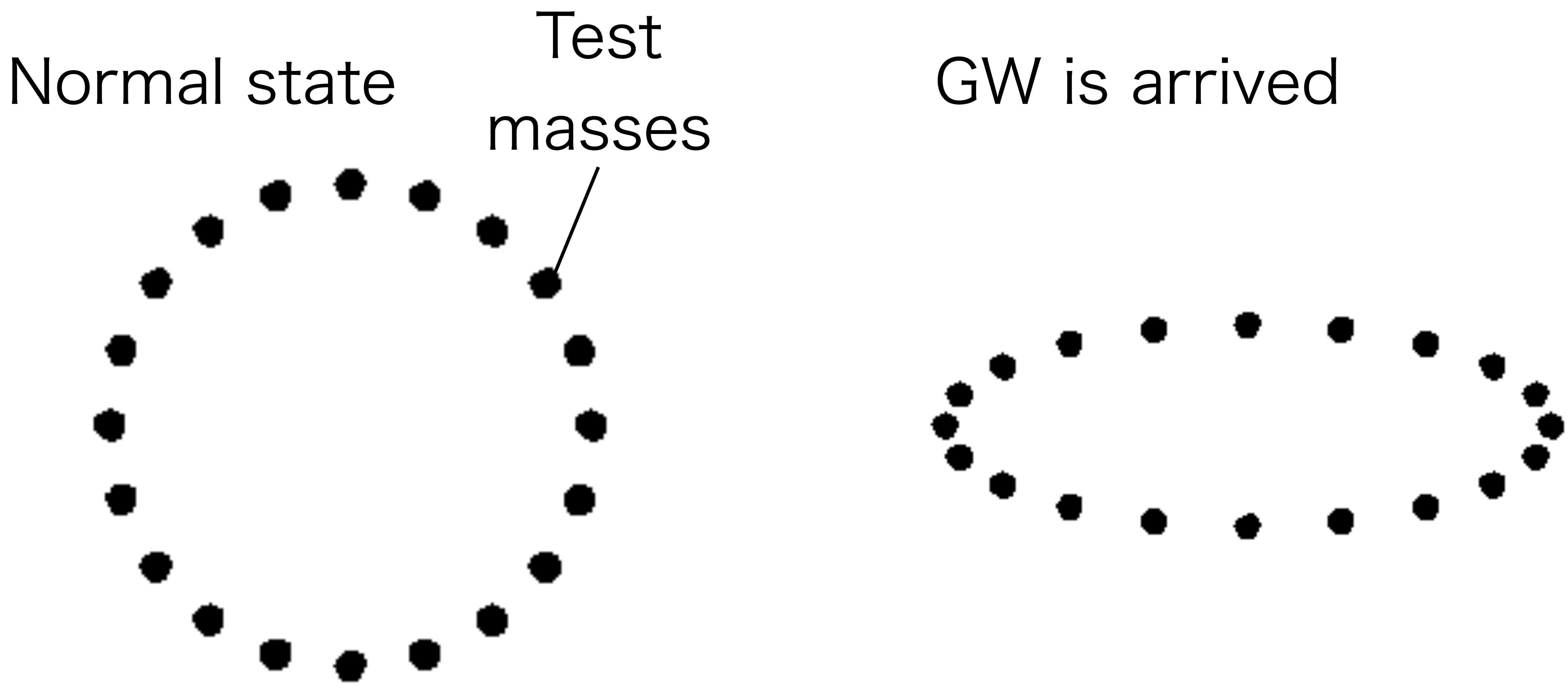
arXiv: 2510.24779

Submit to PRD. 3 hours ago!

Today's contents are based on these articles!

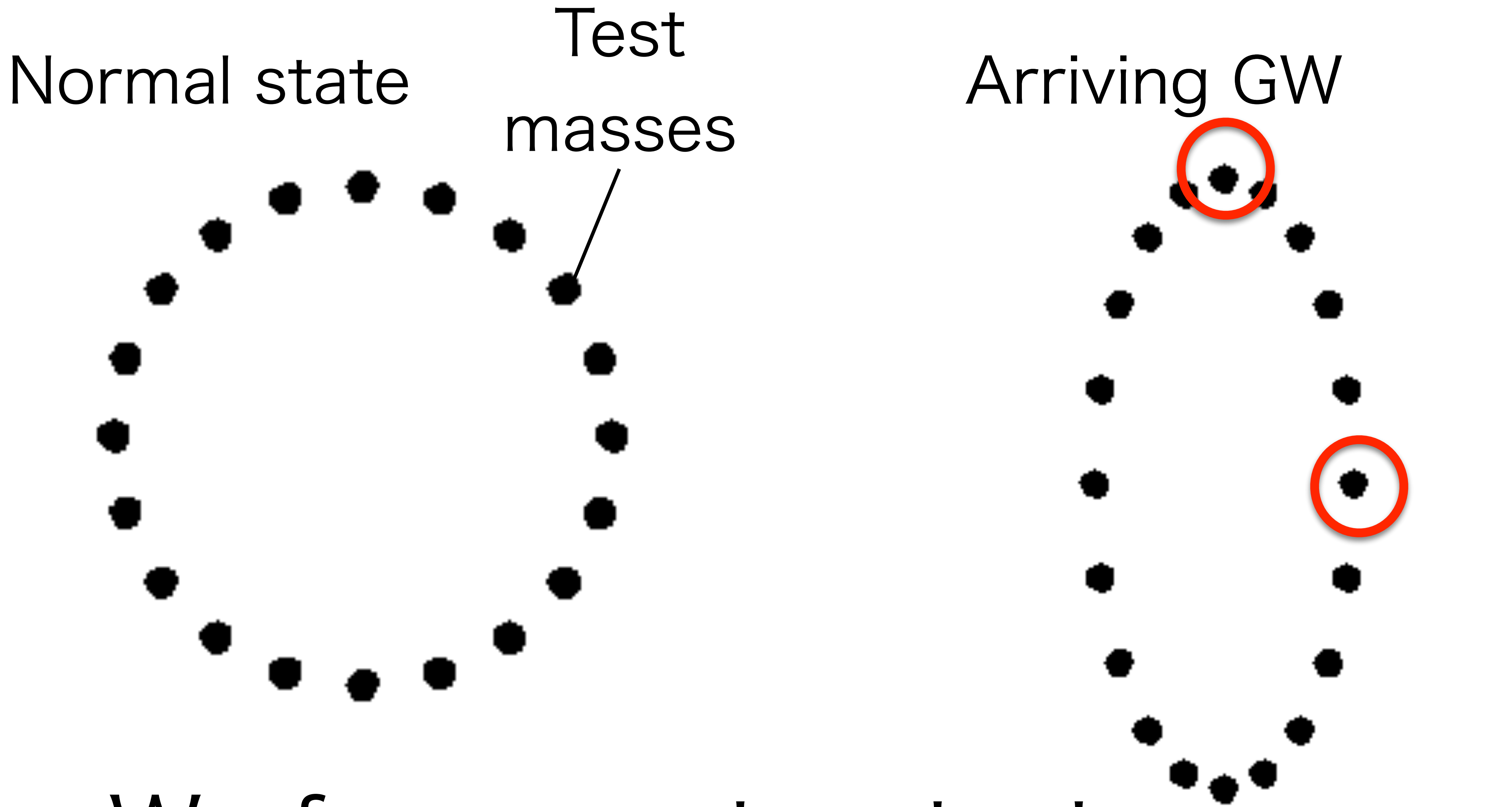
Principle

Principle of Observation



Test masses are moved by GWs.

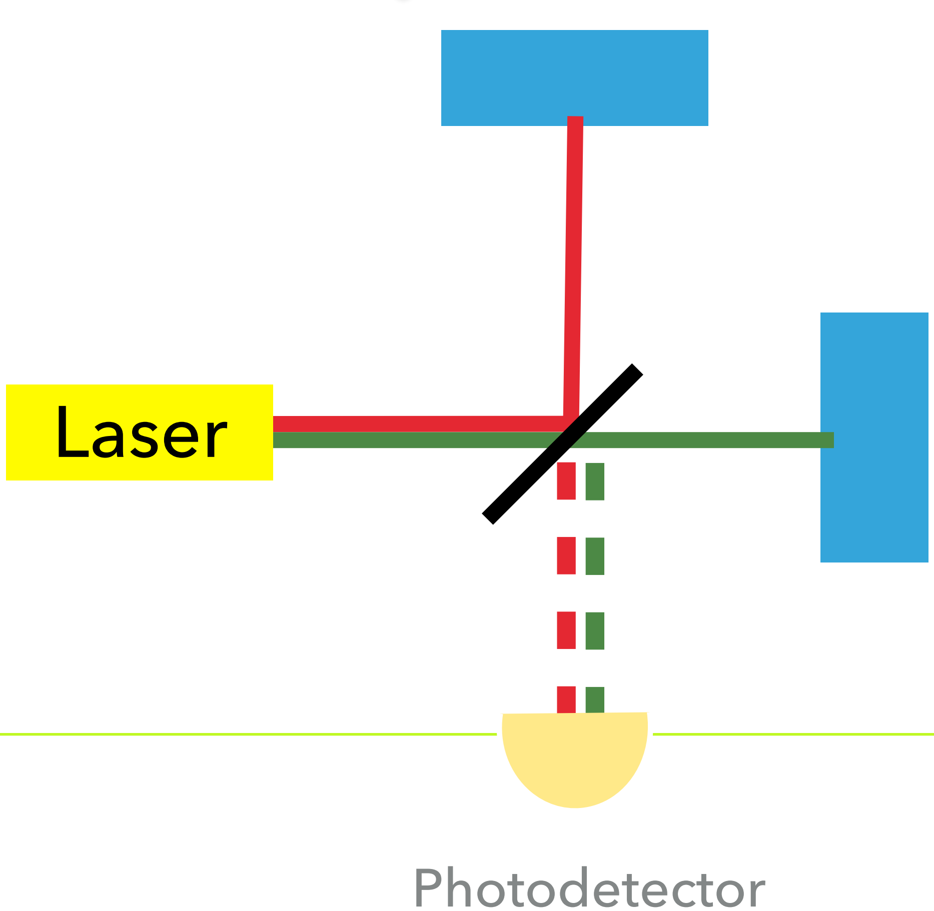
Principle of Observation

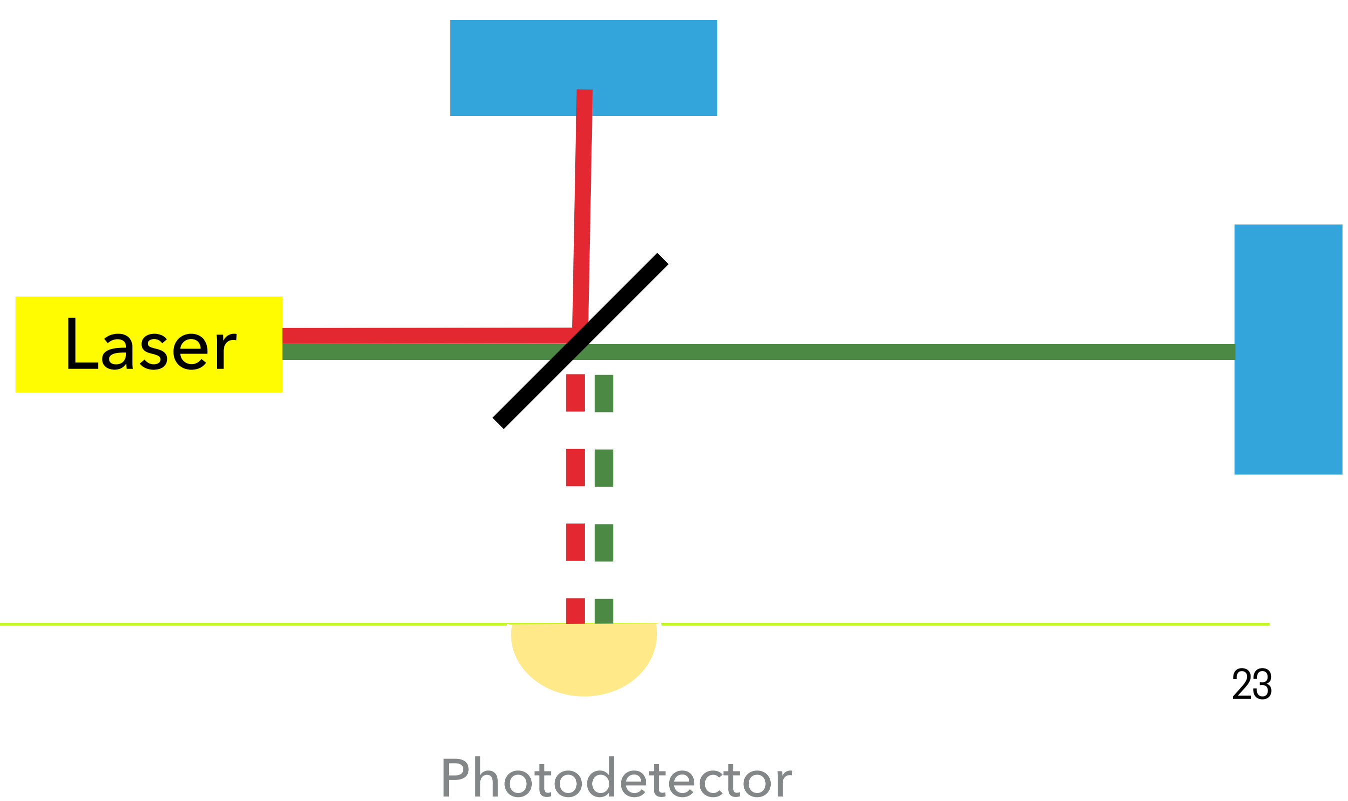


We focus on two test masses.

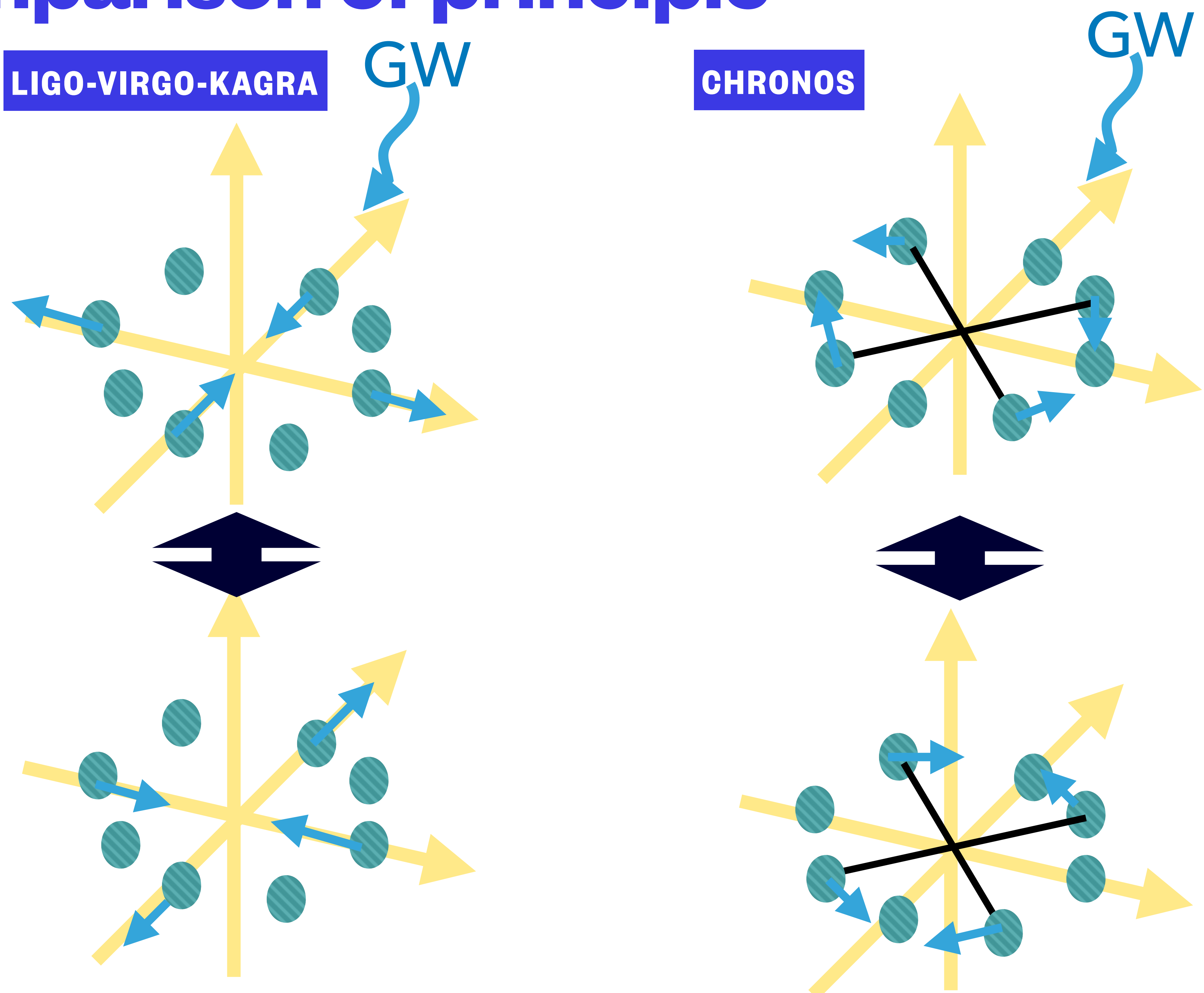
Principle of Observation

We replace the test masses to the mirror.



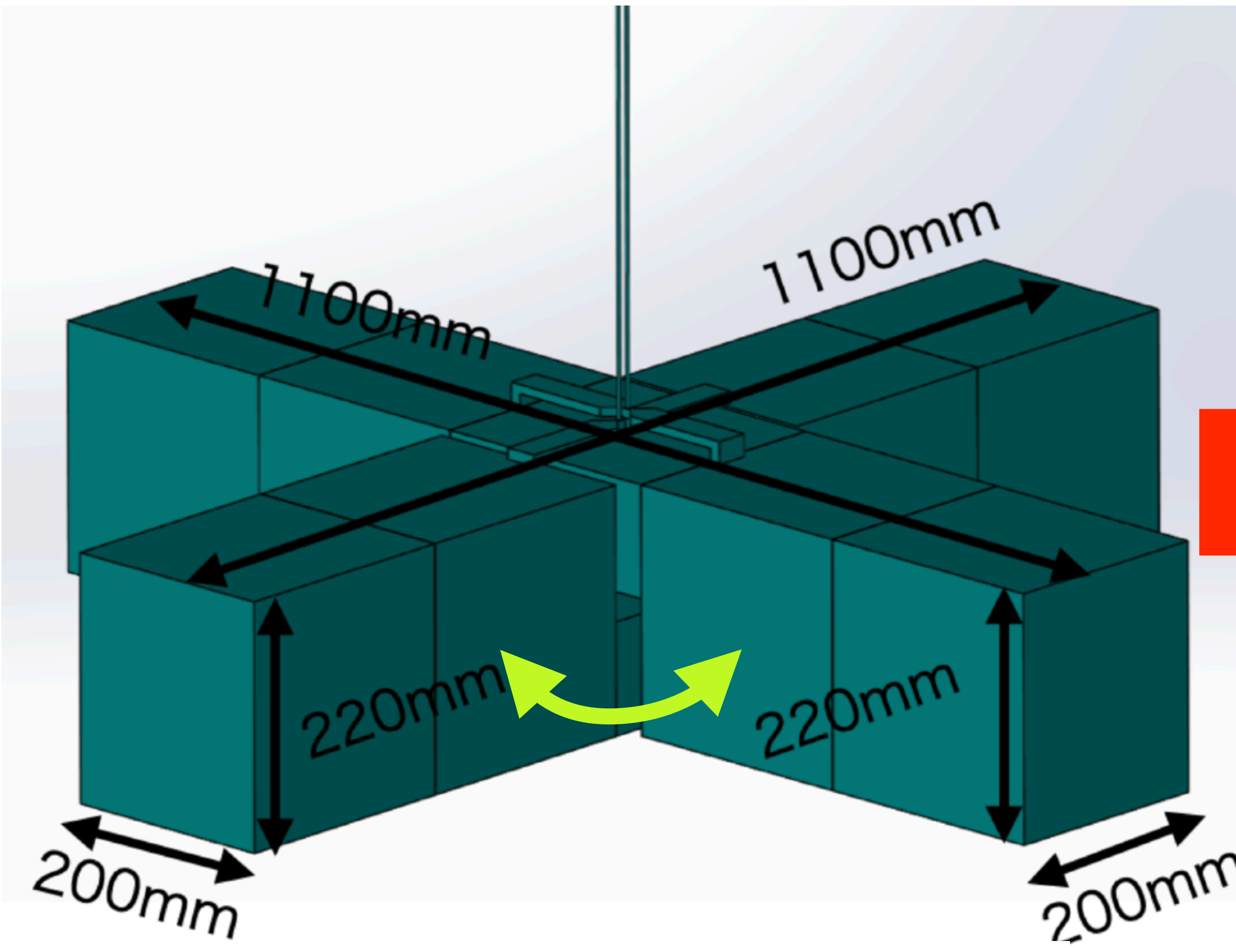


Comparison of principle



LIGO and CHRONOS have Independent detection method

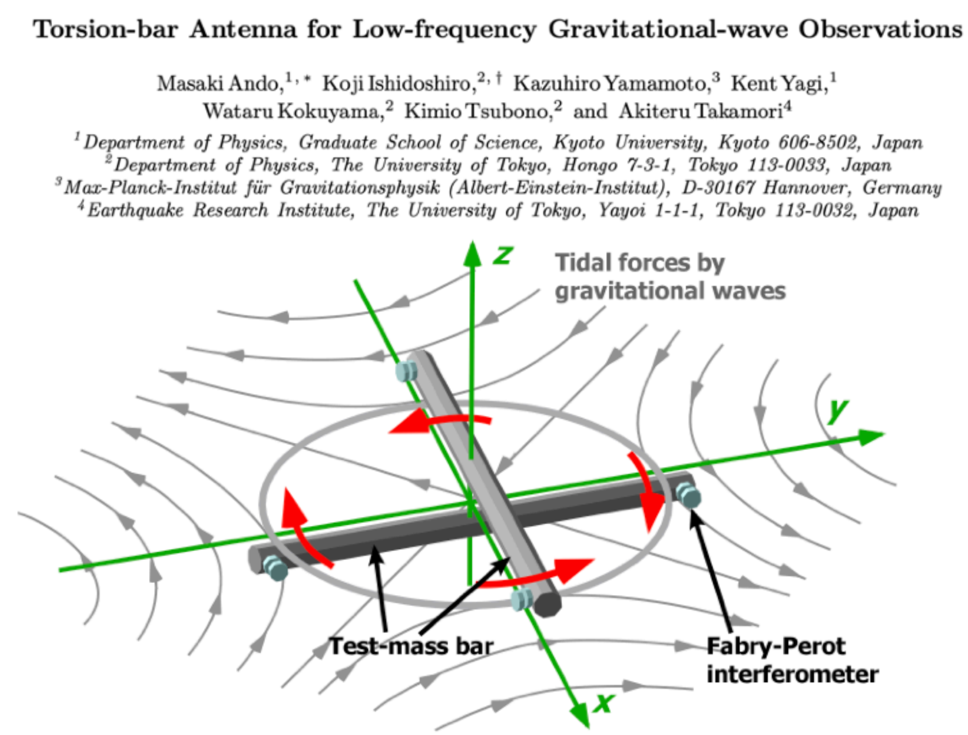
CHRONOS test mass



$$\theta(\Omega) \simeq \frac{I_{\rm eff}}{2I}\left(h_+F_+ + h_\times F_\times\right).$$

We need to monitor the angle by laser interferometer method.

ORIGINAL PAPER



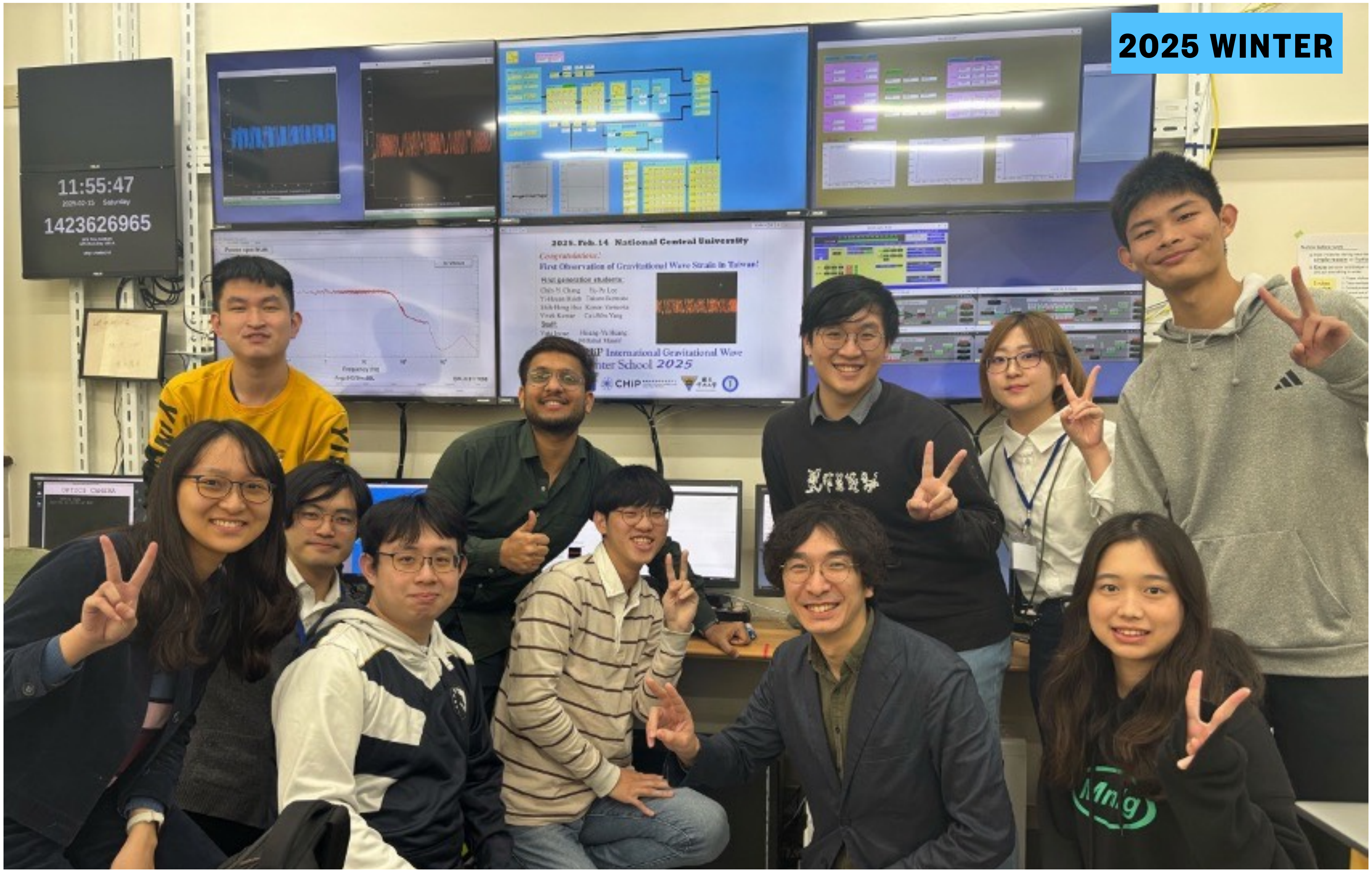
Torsion-bar Antenna for Low-frequency Gravitational-wave Observations

Masaki Ando,[1,*] Koji Ishidoshiro,[2,†] Kazuhiro Yamamoto,[3] Kent Yagi,[1]
Wataru Kokuyama,[2] Kimio Tsubono,[2] and Akiteru Takamori[4]

[1] *Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*
[2] *Department of Physics, The University of Tokyo, Hongo 7-3-1, Tokyo 113-0033, Japan*
[3] *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), D-30167 Hannover, Germany*
[4] *Earthquake Research Institute, The University of Tokyo, Yayoi 1-1-1, Tokyo 113-0032, Japan*

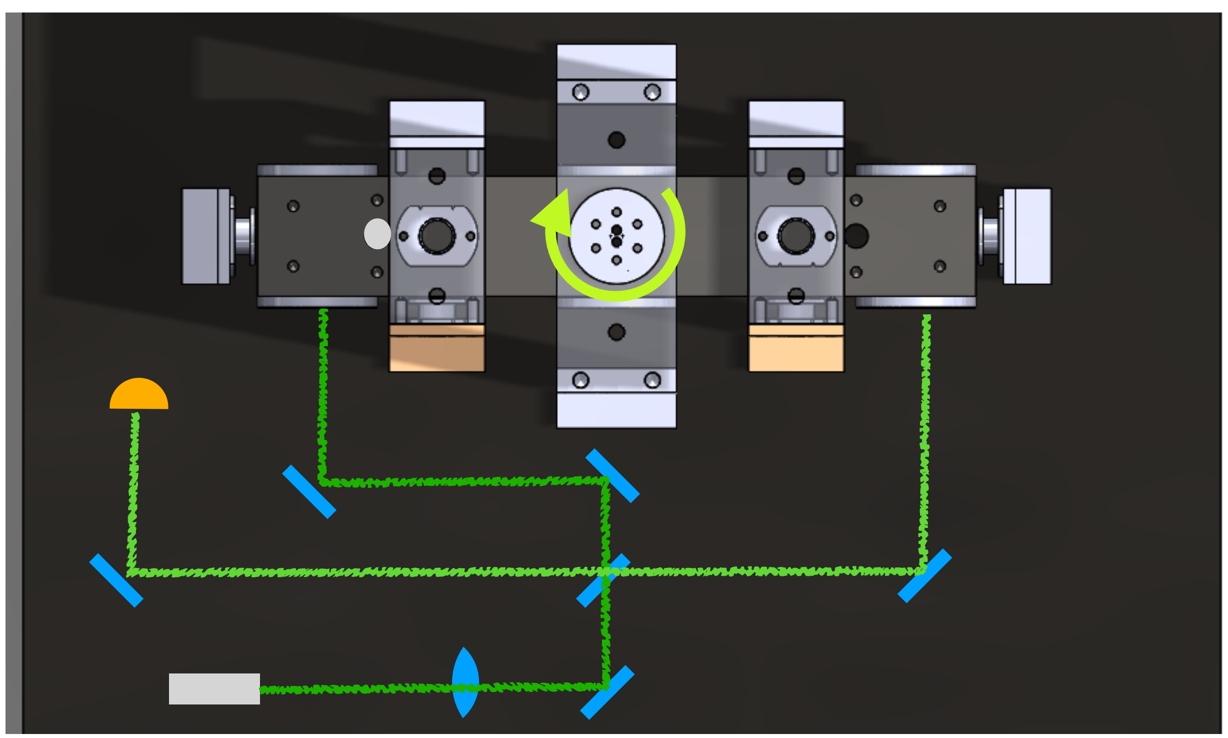
TOBA and TorPeDOR already demonstrate the principle of torsion bar detector.

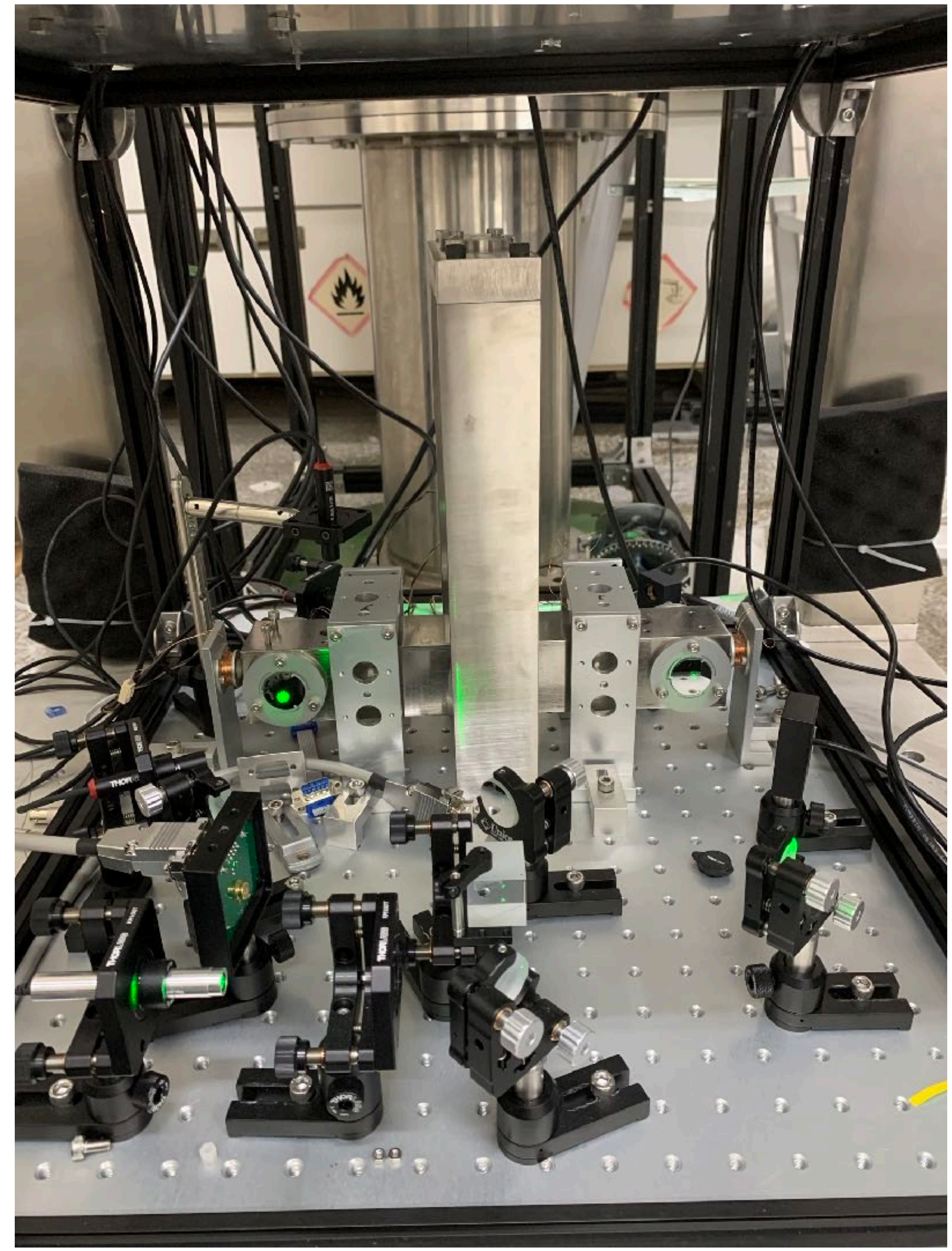
CHiP international GW Winter school



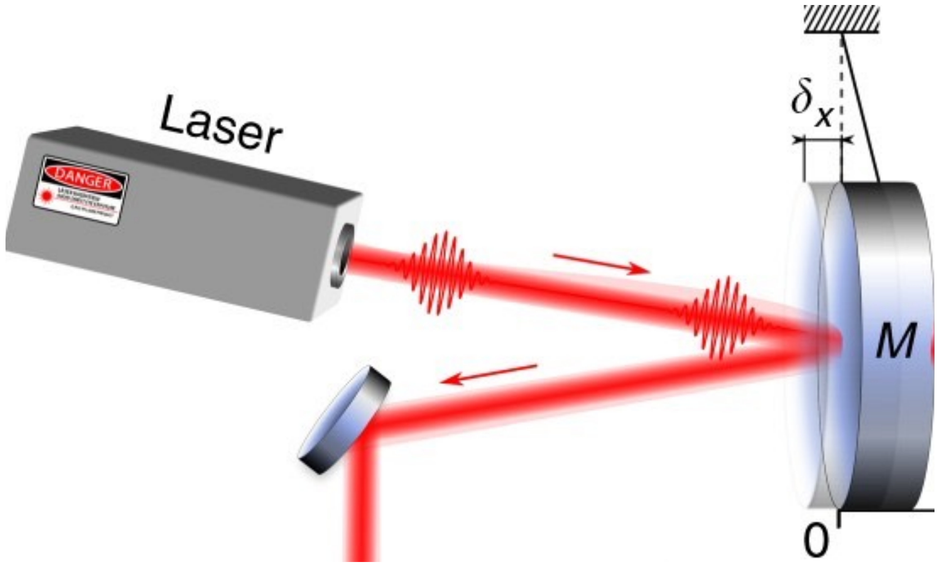
Demonstration with mini-CHRONOS

- 300mm torsion bar
- First Demonstration of technology
- Educational system
- Text book and lecture
- 10days program





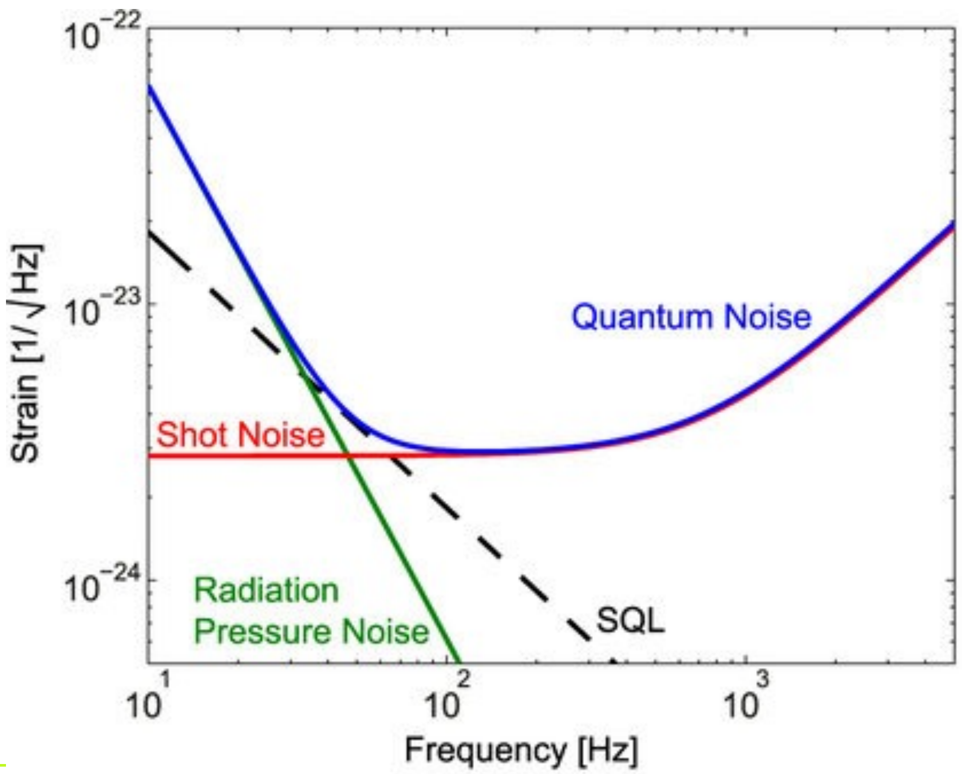
Gravitational Wave Experiment



$$\epsilon(x)\eta(p) \geq \frac{\hbar}{2}$$

Back action disturbance

Displacement Measurement



Injection of photon = Δx measurement

- If we increase the power, we can improve δx(t) measurement
- But, it causes back action and changes future δx(t+τ)

$$dx/dt = [H,x] \neq 0$$

Comparison of Technology

	Thermal noise	Bar thermal noise	Quantum noise
TorPeDO	Room temperature	SUS(Low-Q) High Optical availability	1m torsion bar
TOBA	Cryogenic technology	Silicon (High-Q)	10m torsion bar
CHRONOS	Cryogenic technology	Sapphire(High-Q)	1 meter torsion bar Speed meter

Termal noise

Radiation noise

Small size

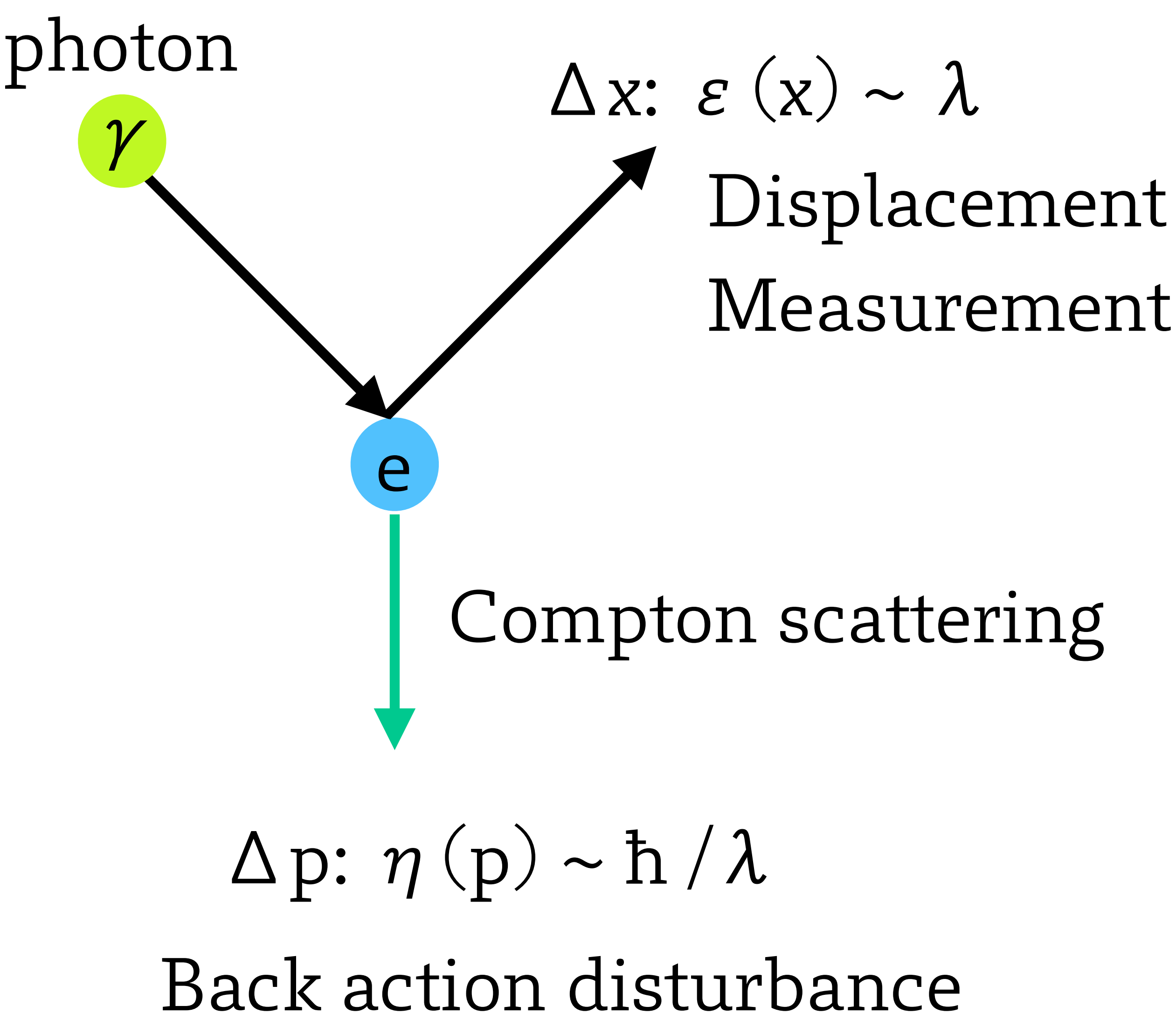
By unifying speed meter, we solved mirror size problem.

Sicence

Quantum approach

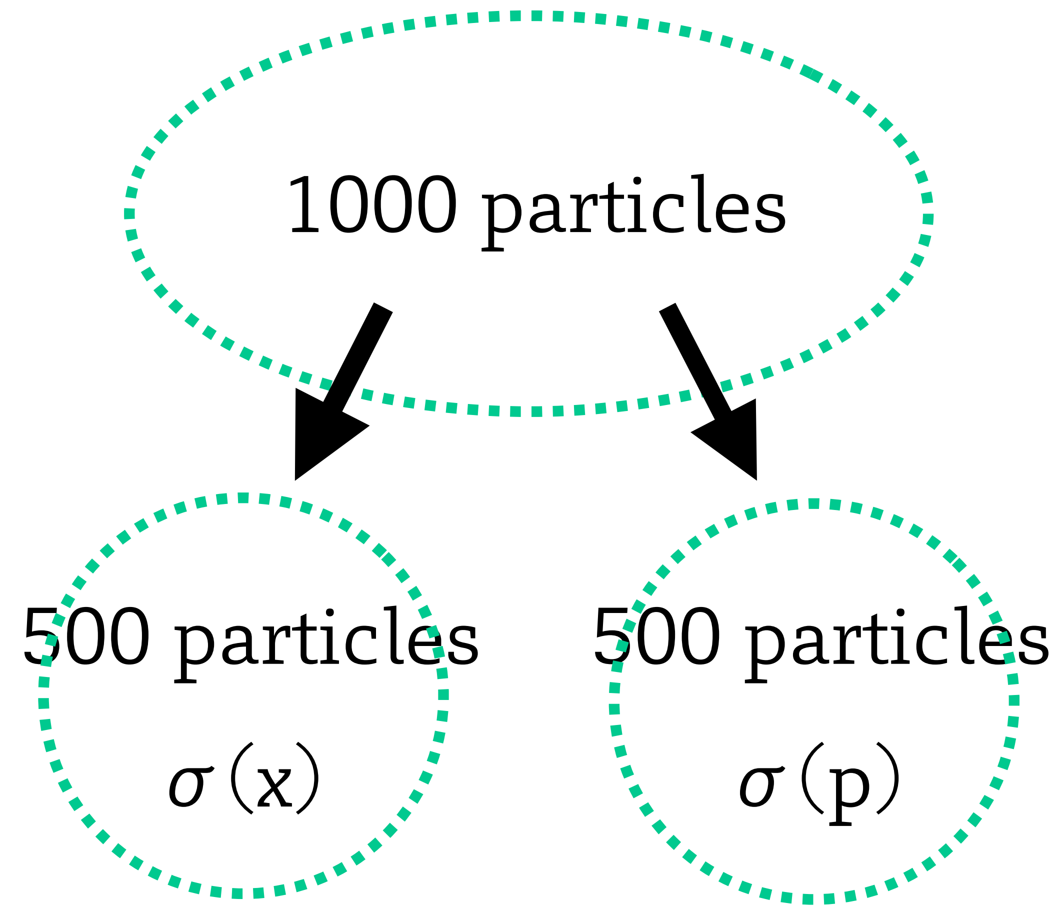
1927 Heisenberg Uncertainty principle

$$\epsilon(x)\eta(p) \geq \hbar$$



1929 Robertson relation

$$\sigma(A)\sigma(B) \geq \frac{1}{2}\left|\langle[\hat{A}, \hat{B}]\rangle\right|$$



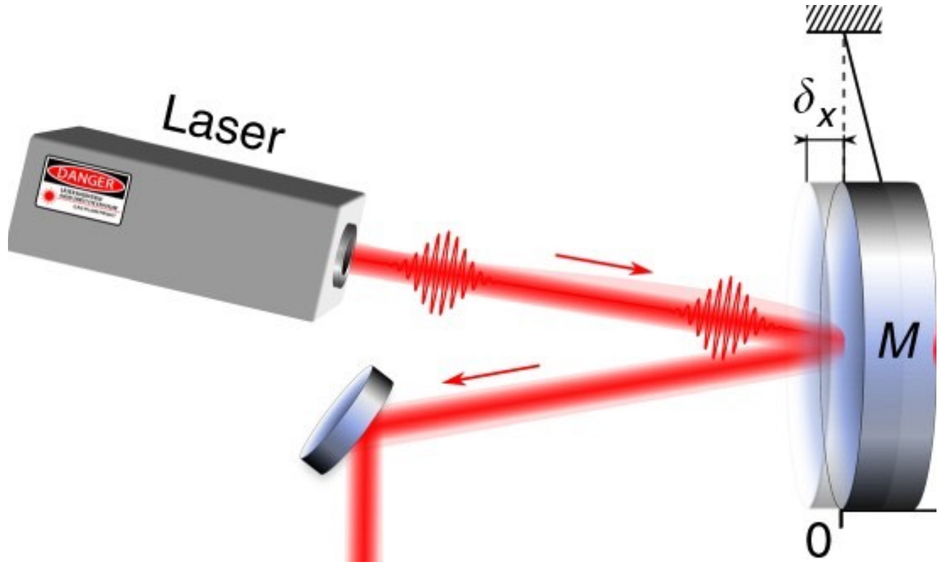
$$\sigma(x)\sigma(p) \geq \frac{\hbar}{2}$$

Ozawa's Inequality

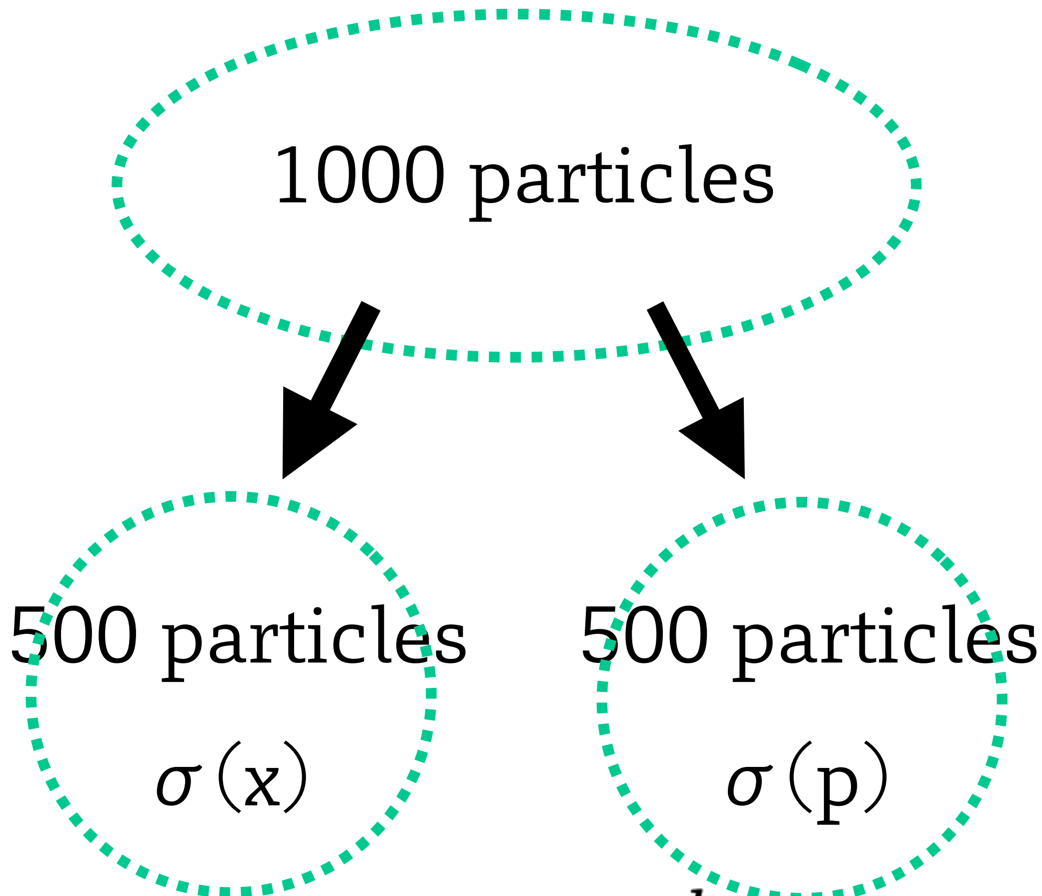
Prof. Ozawa modified Heisenberg Uncertainty principle (2003)!

$$\epsilon(A)\eta(B) + \sigma(A_{in})\eta(B) + \epsilon(A)\sigma(B_{in}) \geq \frac{1}{2}\left|\langle\psi|[\hat{A}_{in}, \hat{B}_{in}]|\psi\rangle\right|$$

Δp: η (p) ~ ħ / λ
Back action disturbance



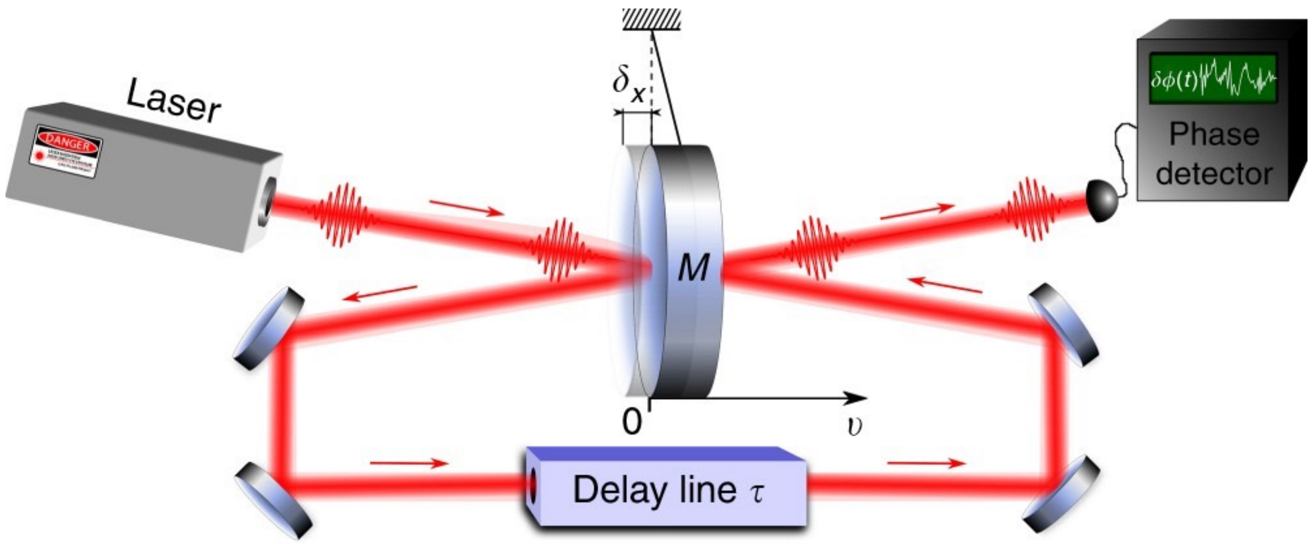
Δx: ε (x) ~ λ
Displacement Measurement



$$\sigma(x)\sigma(p) \geq \frac{\hbar}{2}$$

How to realize non-demolition system?

Speed meter!



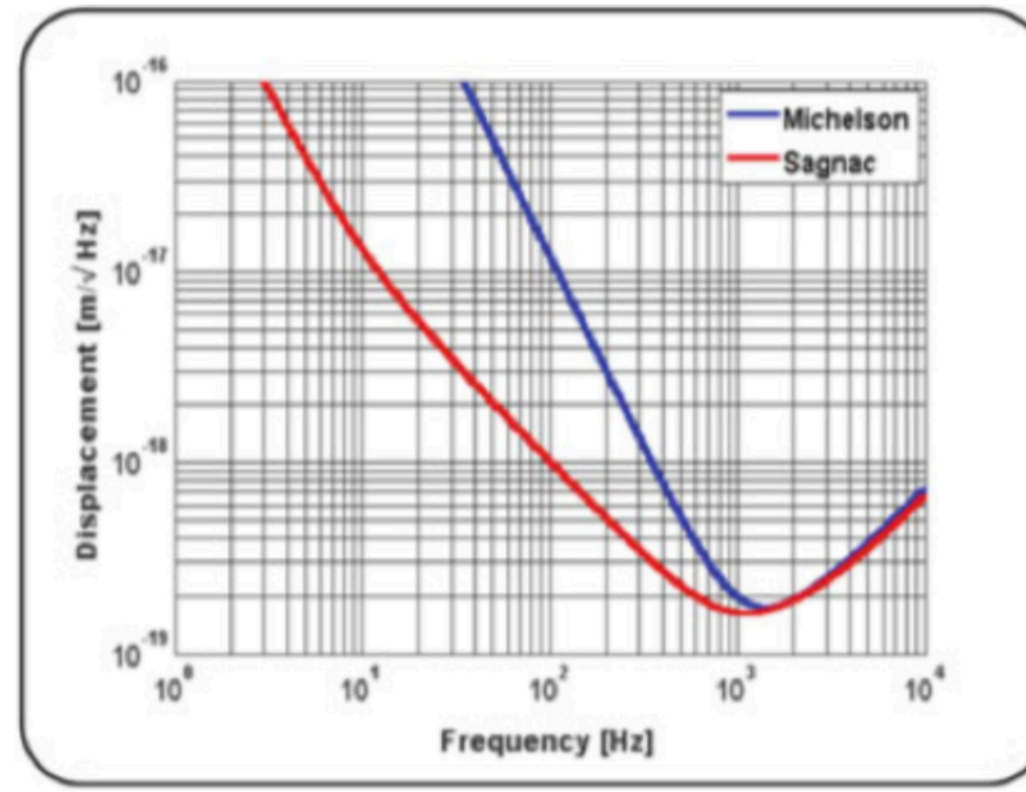


Photo detector = $\delta x(t+\tau)-\delta x(t) = v\tau$ measurement,

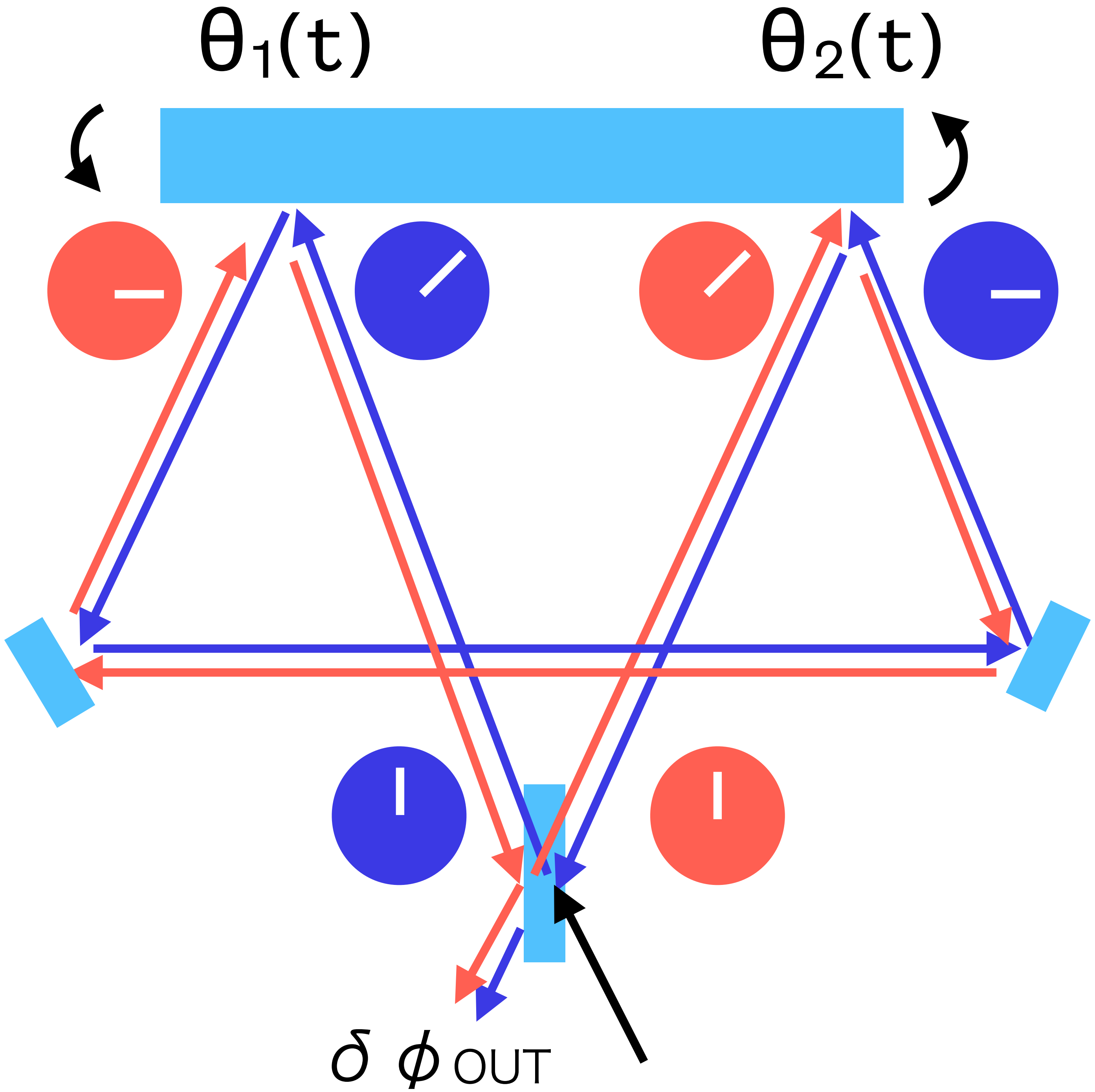
where τ is constant.

Probe is proportional to momentum!

$[\hat{H}, \hat{\boldsymbol{p}}] = 0$ → non-demolition!

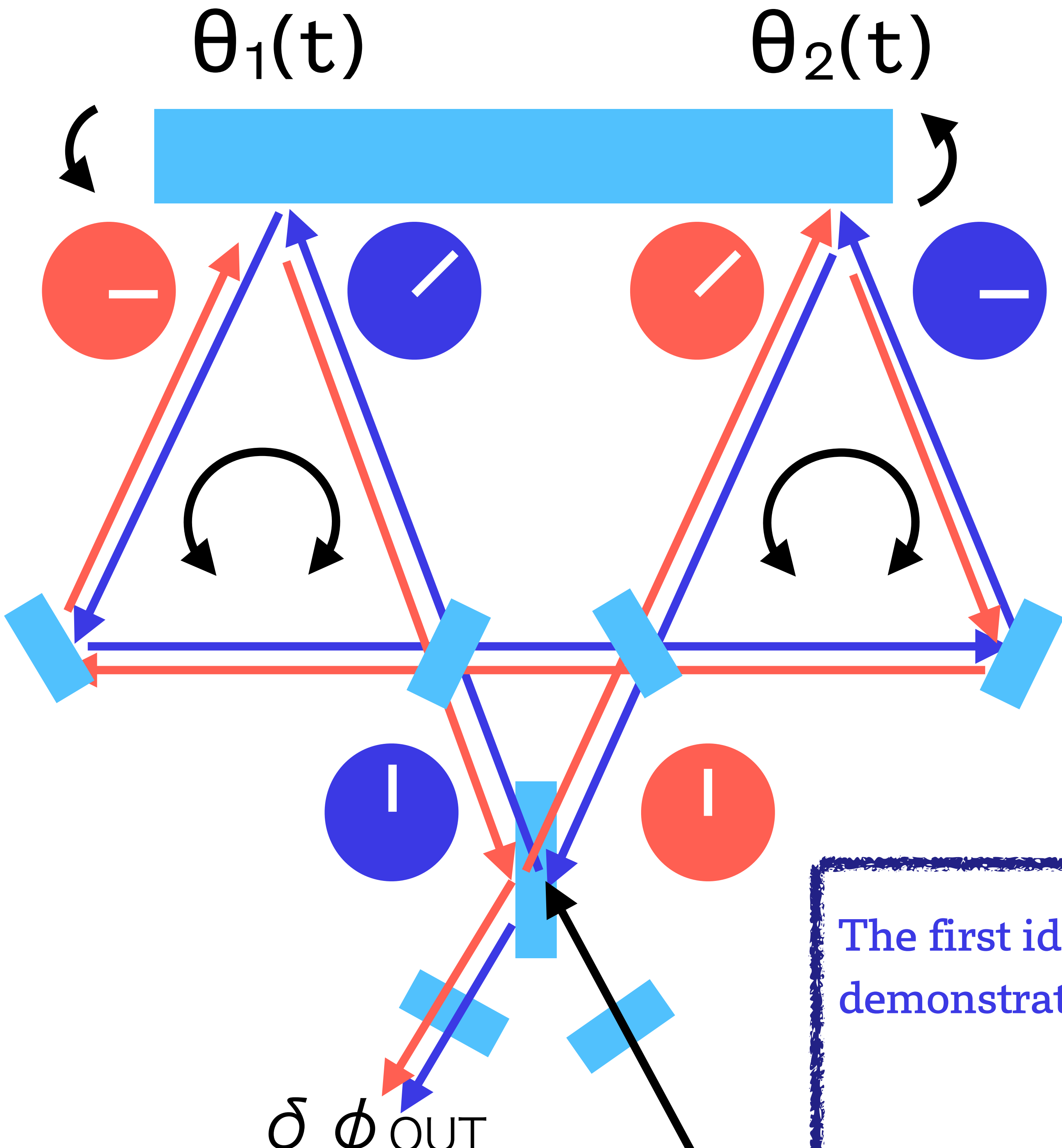
Demonstration of non-demolition system is also unique science

Speed meter for torsion bar



- $\delta\phi_{CW} \propto \theta_2(t)+\theta_1(t+\tau)$
- $\delta\phi_{CCW} \propto \theta_1(t)+\theta_2(t+\tau)$
- $\delta\phi_{OUT}=\tau(\omega_1-\omega_2)$
- We employ Sagnac interferometer.
- We measure the phase delay of CW and CCW beams.
- Time interval, τ, should be same because of common path.

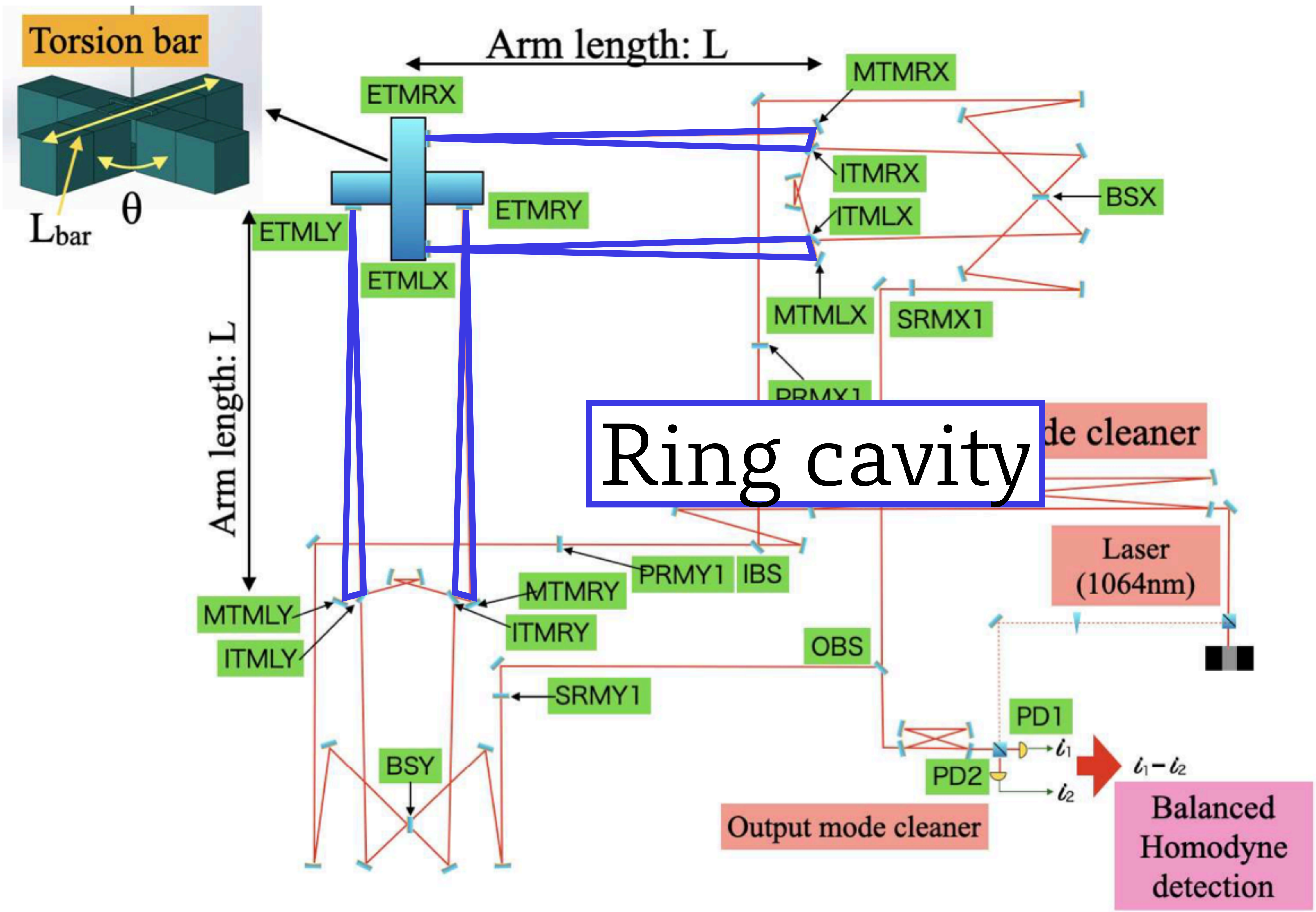
Speed meter technique

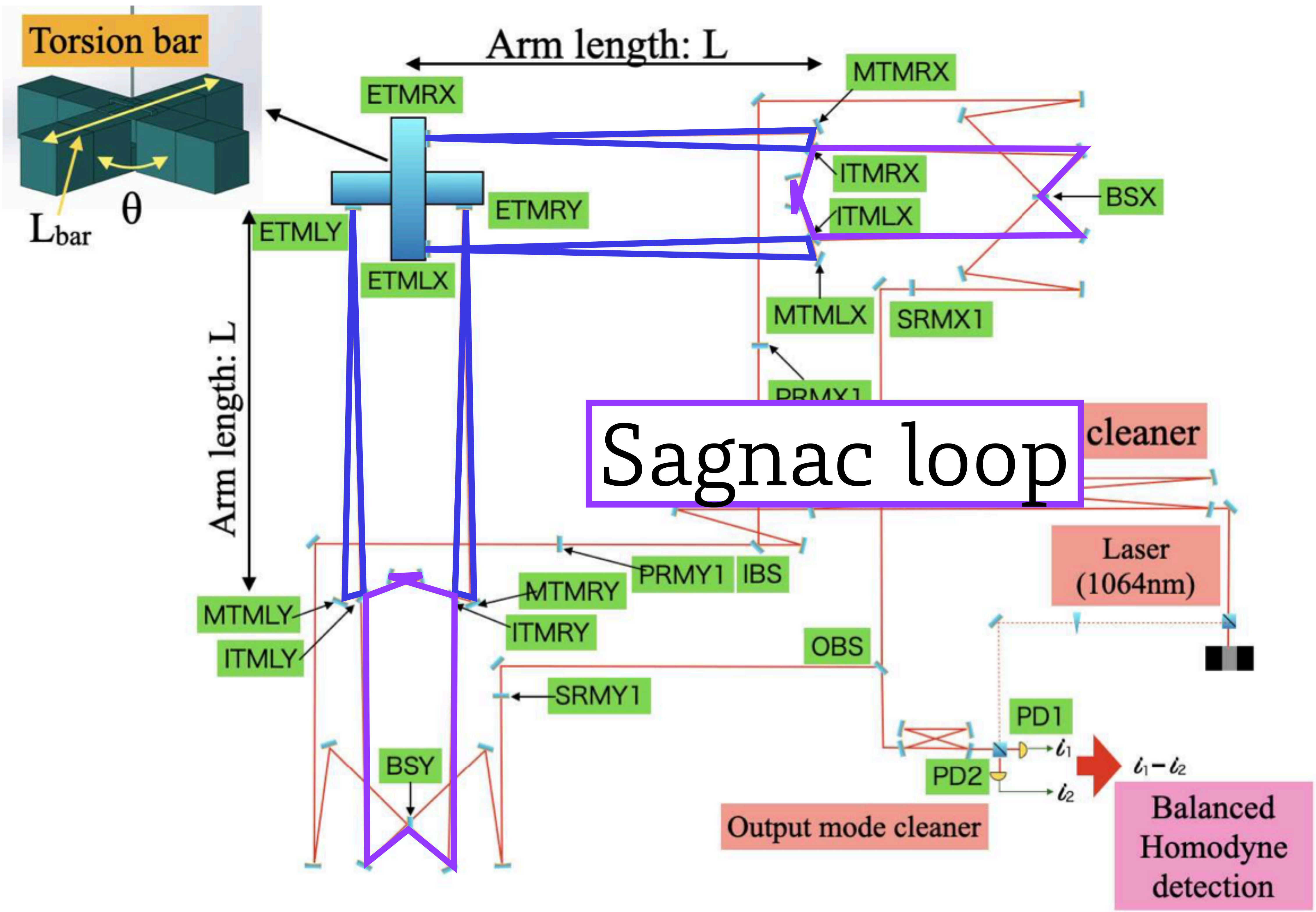


- $\delta\phi_{CW} \propto \theta_2(t)+\theta_1(t+\tau)$
- $\delta\phi_{CCW} \propto \theta_1(t)+\theta_2(t+\tau)$
- $\delta\phi_{OUT}=\tau_{eff}(\omega_1-\omega_2)$
- Install the ring cavity to amplify the signal.
- Power recycling cavity and Signal recycling cavity are also employed

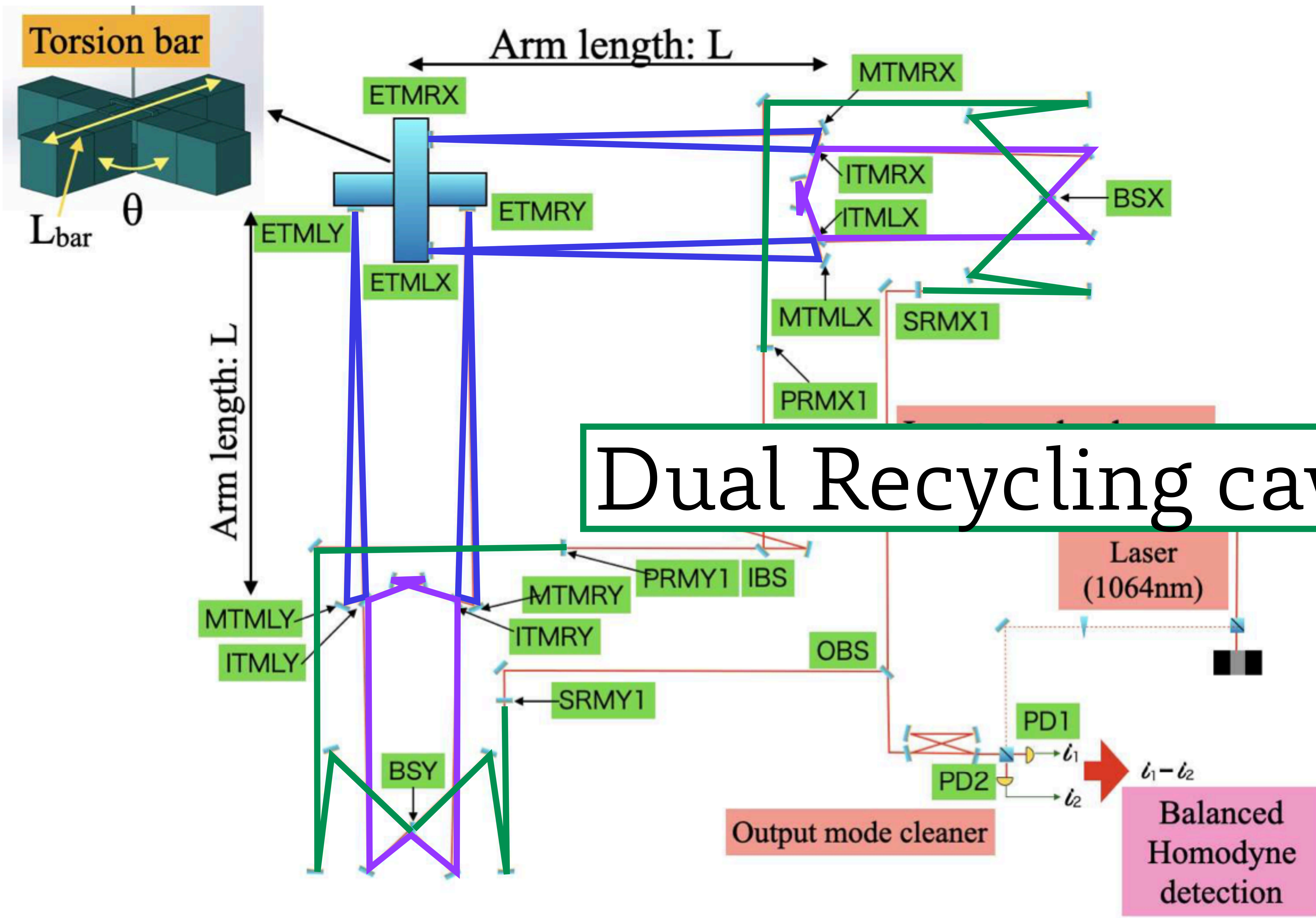
The first idea of Quantum non-demolition demonstration on angular momentum for GW detector:

$$\dot{L} = [\hat{H}, \hat{L}] = 0$$


Torsion bar
L_{bar}
θ
Arm length: L
ETMRX
MTMRX
ITMRX
ITMLX
BSX
ETMRY
ETMLY
ETMLX
MTMLX
SRMX1
Arm length: L
Ring cavity
Laser
(1064nm)
PRMY1
IBS
MTMRY
MTMLY
ITMLY
ITMRY
OBS
SRMY1
PD1
PD2
i_1
i_2
$i_1 - i_2$
BSY
Output mode cleaner
Balanced
Homodyne
detection


Torsion bar
L bar
θ
Arm length: L
ETMRX
MTMRX
ITMRX
ITMLX
BSX
ETMRY
ETMLY
ETMLX
MTMLX
SRMX1
Arm length: L
Sagnac loop
cleaner
Laser (1064nm)
PRMY1
IBS
MTMRY
MTMLY
ITMRY
ITMLY
OBS
SRMY1
PD1
PD2
i1
i2
i1 − i2
BSY
Output mode cleaner
Balanced Homodyne detection

Dual Recycling cavity



Comparison

Ozawa's inequality

$$\underbrace{\epsilon(A)\eta(B)}_{\text{SQL}} + \underbrace{\sigma(A_{in})\eta(B)}_{\text{Radiation noise}} + \underbrace{\epsilon(A)\sigma(B_{in})}_{\text{Shot noise}} \geq \frac{1}{2}\left|\langle\psi|[\hat{A}_{in}, \hat{B}_{in}]|\psi\rangle\right|$$

(i) aLIGO: $A=\hat{x}$, $B=\hat{p}$

$d\hat{x}/dt = [\hat{H},\hat{x}] \neq 0$ ⇨ tradeoff b/w $\eta(\hat{p})$ and $\varepsilon(\hat{x})$

(ii) aLIGO+speed meter: $A=\hat{p}$, $B=\hat{x}$

$d\hat{p}/dt = [\hat{H},\hat{p}] = 0$ ⇨ minimize $\eta(\hat{x})$ by keeping shot noise $\varepsilon(\hat{p})$

(iii) TOBA: $A=\hat{\theta}$, $B=\hat{L}$

$d\hat{\theta}/dt = [\hat{H},\hat{\theta}] \neq 0$ ⇨ tradeoff b/w $\eta(\hat{L})$ and $\varepsilon(\hat{\theta})$

(iv) CHRONOS (This work): $A=\hat{L}$, $B=\hat{\theta}$

$d\hat{L}/dt = [\hat{H},\hat{L}] = 0$ ⇨ minimize $\eta(\hat{\theta})$ by keeping shot noise $\varepsilon(\hat{L})$

※Squeezing is corresponding to σ term.

Comparison

Ozawa's inequality

$$\epsilon(A)\eta(B) + \sigma(A_{in})\eta(B) + \epsilon(A)\sigma(B_{in}) \geq \frac{1}{2}|\langle\psi|[\hat{A}_{in}, \hat{B}_{in}]|\psi\rangle|$$

SQL

(i) aLIGO:

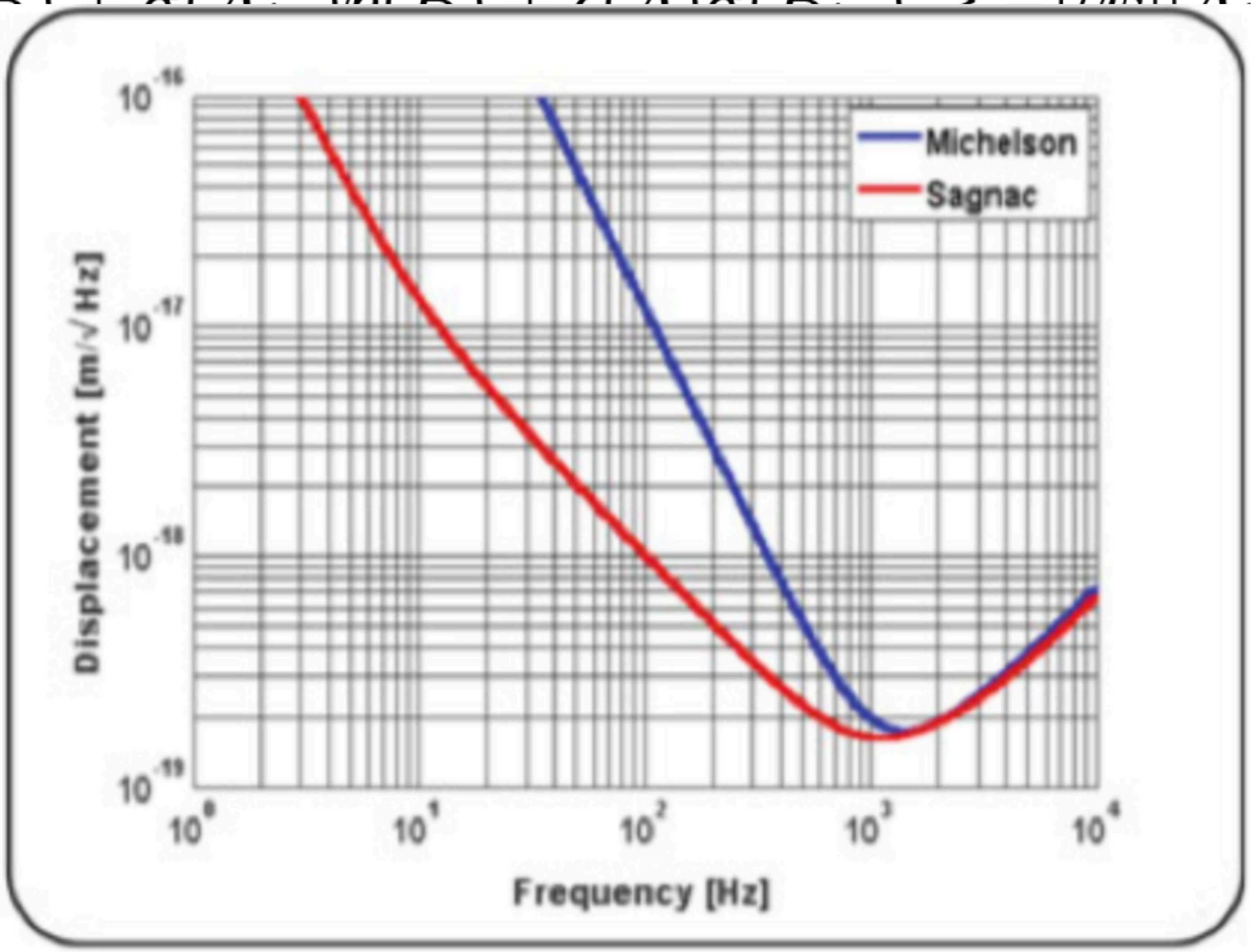
dx/dt = [H

(ii) aLIGO+s

[H,p] = 0 … e $\varepsilon(\hat{p})$

(iii) TOBA:

d θ /dt = [… $\hat{\theta}$)

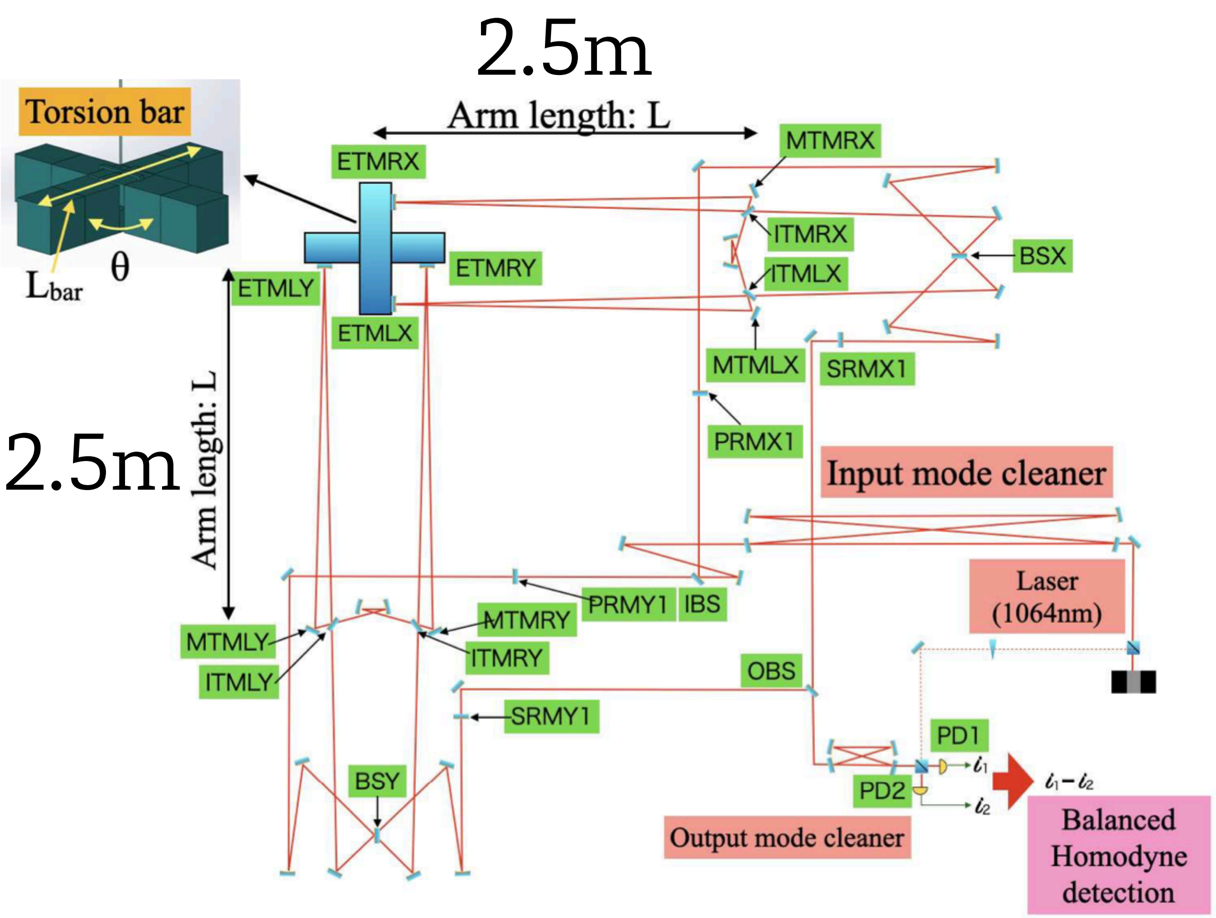


(iv) CHRON

[H,$\hat{L}$] = 0 ⇨ minimize $\eta(\hat{\theta})$ by keeping shot noise $\varepsilon(\hat{L})$

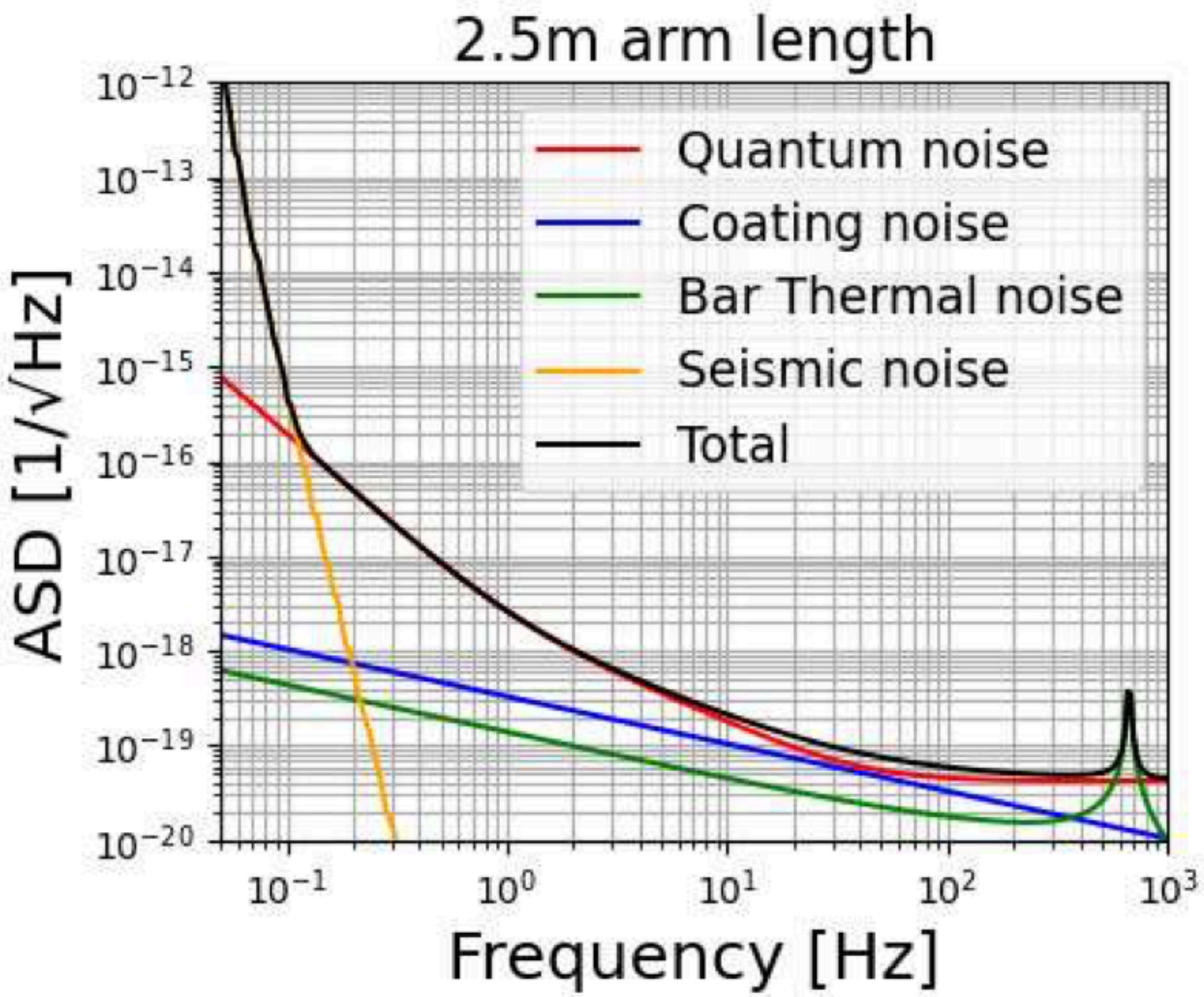
※Squeezing is corresponding to σ term.

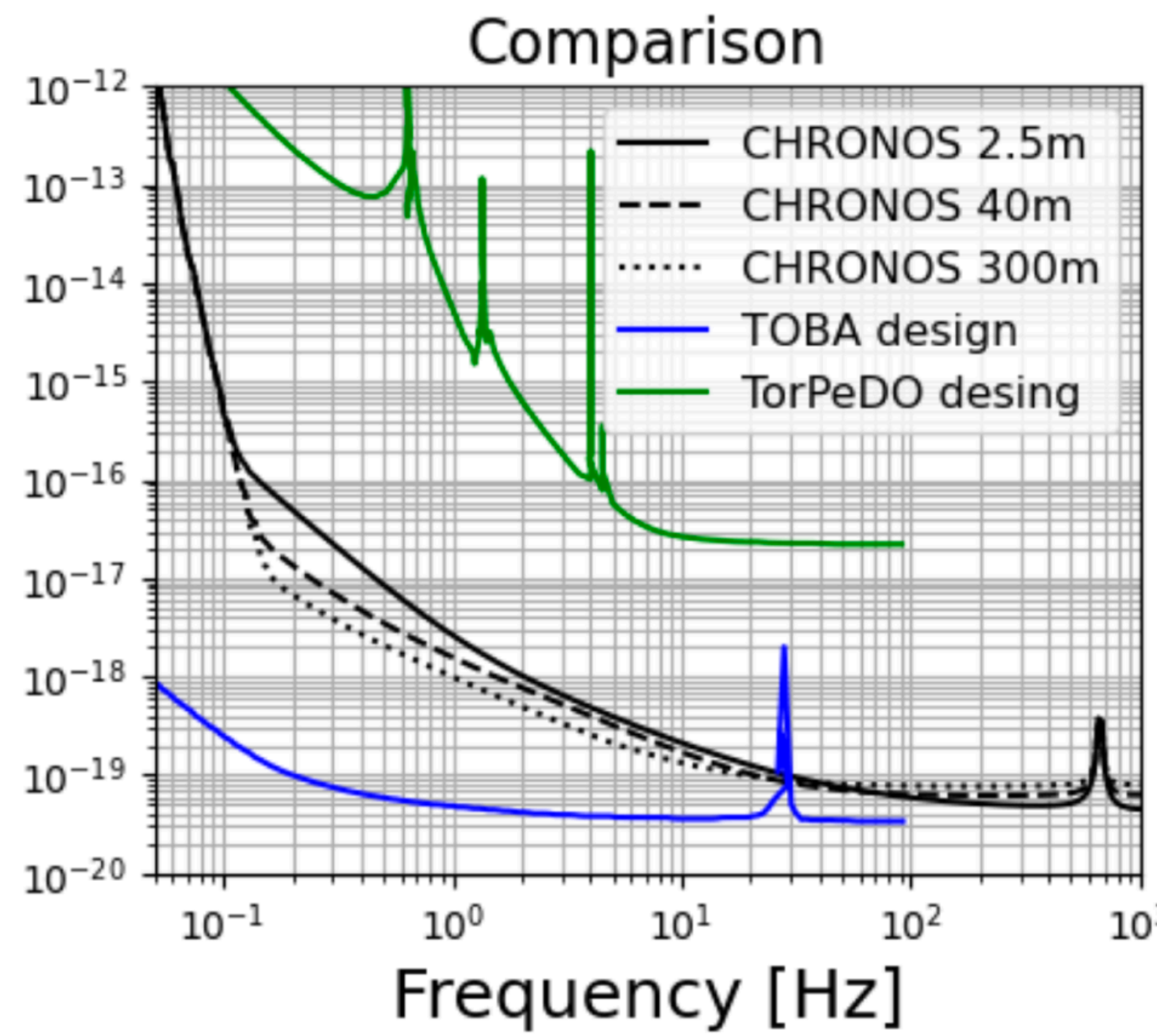
Specification



Definition	Symbol	Value
Signal-recycling mirror reflectivity	R_s	0.5
Power-recycling mirror reflectivity	R_p	0.9
Input test-mass reflectivity	R_i	0.9999
Input laser power	$P_{\rm in}$	1 W
Circulating power in arm cavity	$P_{\rm arm}$	444 W
PRC detuning phase	ϕ_p	$-85°$
SRC detuning phase	ϕ_s	$0°$
Homodyne detection angle	ζ	$46°$
Ring-cavity finesse	$F_{\rm ring}$	3.14×10^4
Beam radius on ETM	w	2.6 mm
ETM mass	$M_{\rm ETM}$	171 kg
ETM moment of inertia	$I_{\rm ETM}$	19.9 kg m^2
Torsion-bar length	$L_{\rm bar}$	1 m
Geometrical coupling factor	η	0.936

Sensitivity

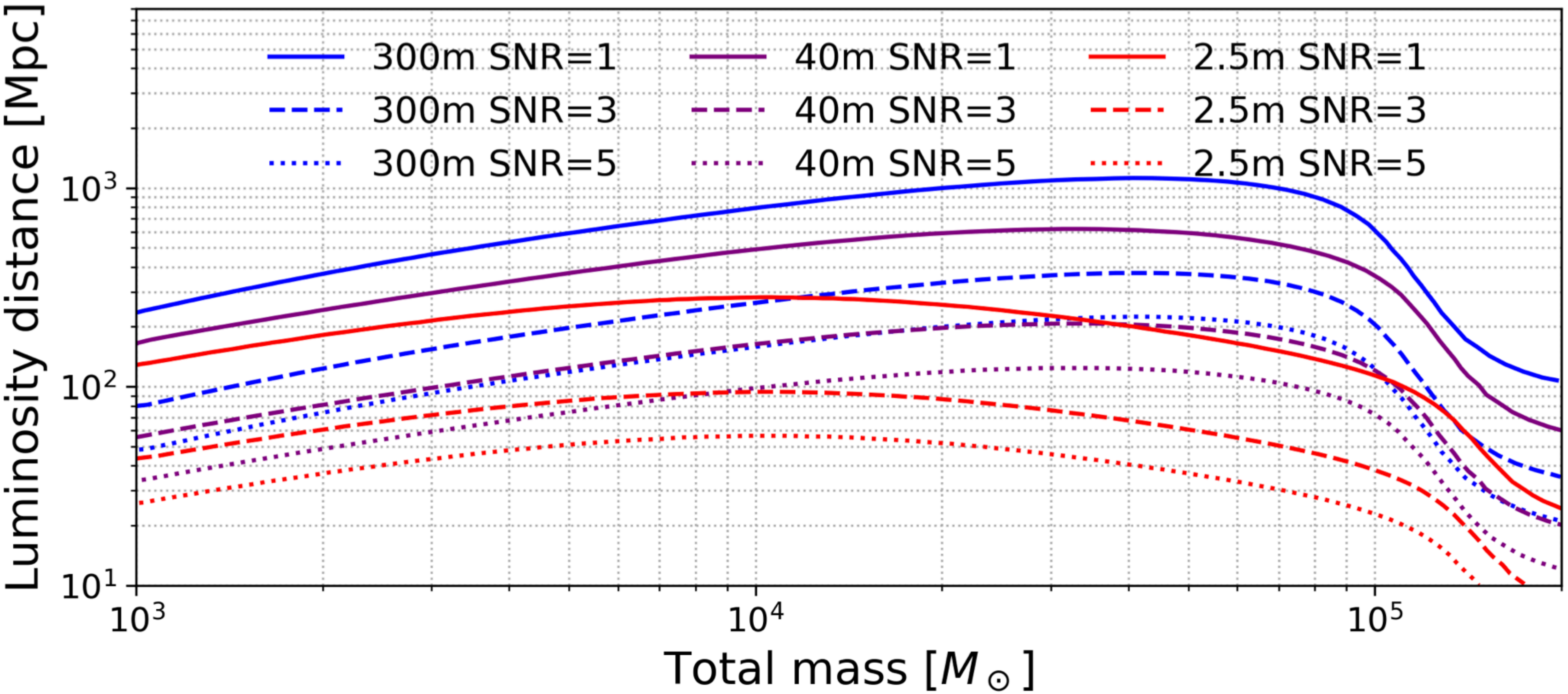




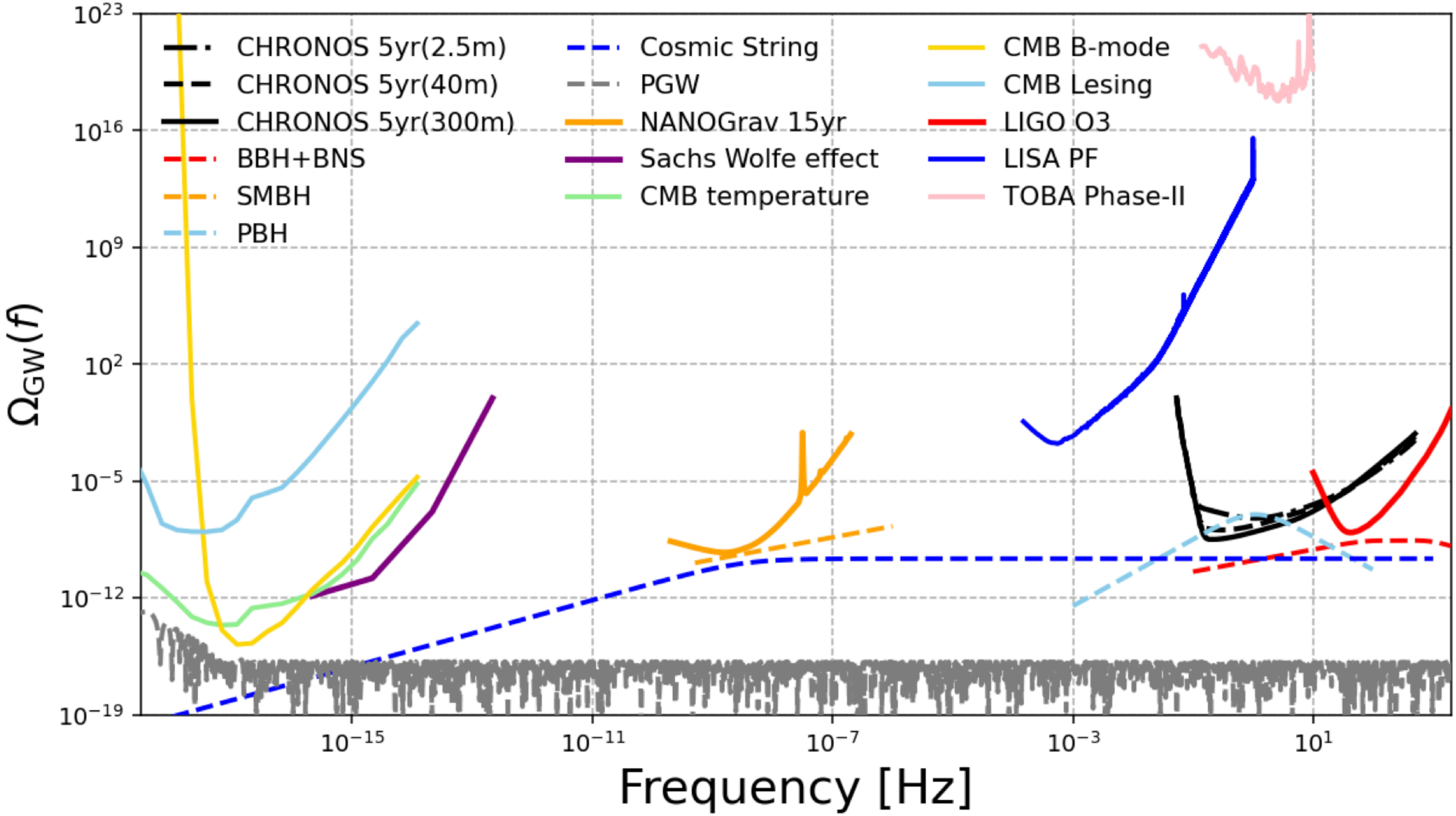
$$\theta = \frac{\theta_{\rm SQL}}{\sqrt{2\,\Gamma(\phi_s,\zeta)\,\kappa_{\rm sag}}}\sqrt{1+\left(\cot\zeta_{\rm eff}-\kappa_{\rm eff}\right)^2},$$

$3\times10^{-18}\ [1/\sqrt{\rm Hz}]$ at $1\,{\rm Hz}$

Inter mediate black hole

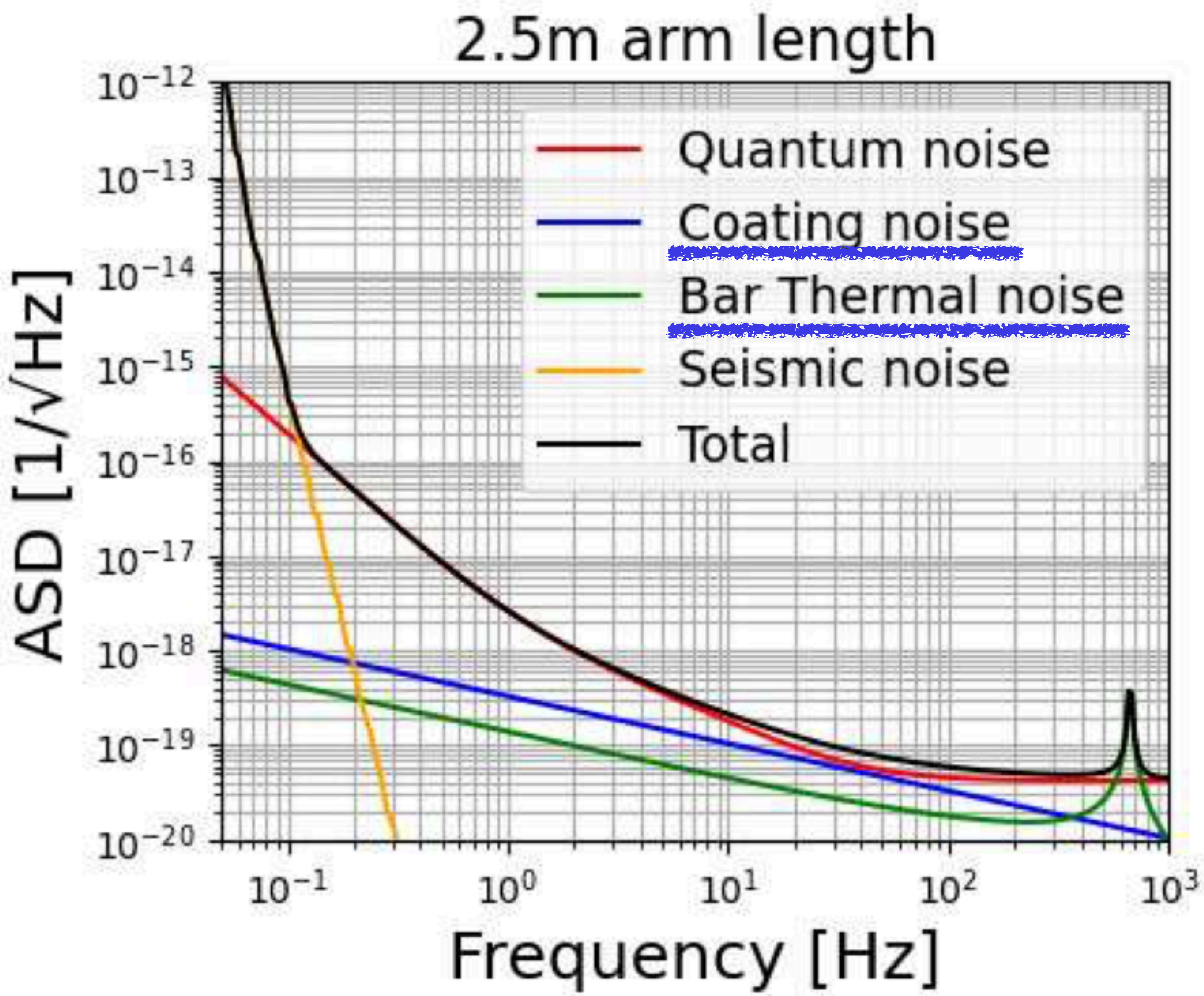


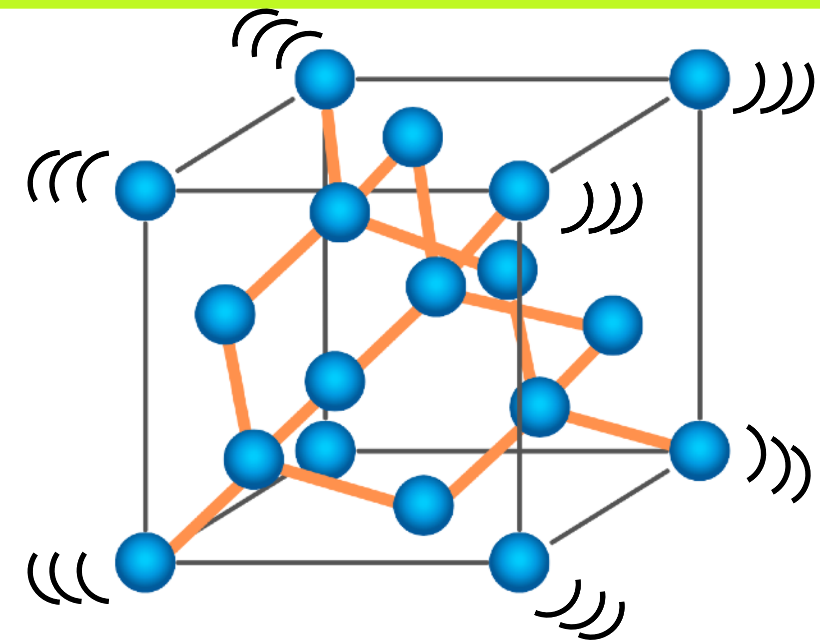
Stochastic background



Instrumental Noise

1. Cryogenic





Noise = **source** × **TF**

TF = Transfer function

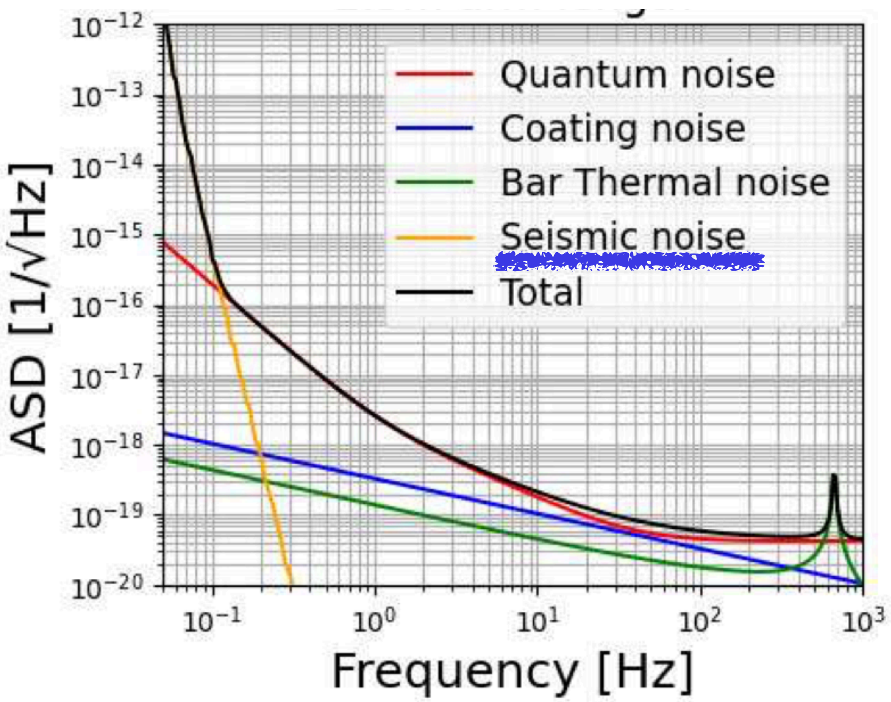
Brownian morion of crystal causes vibration source

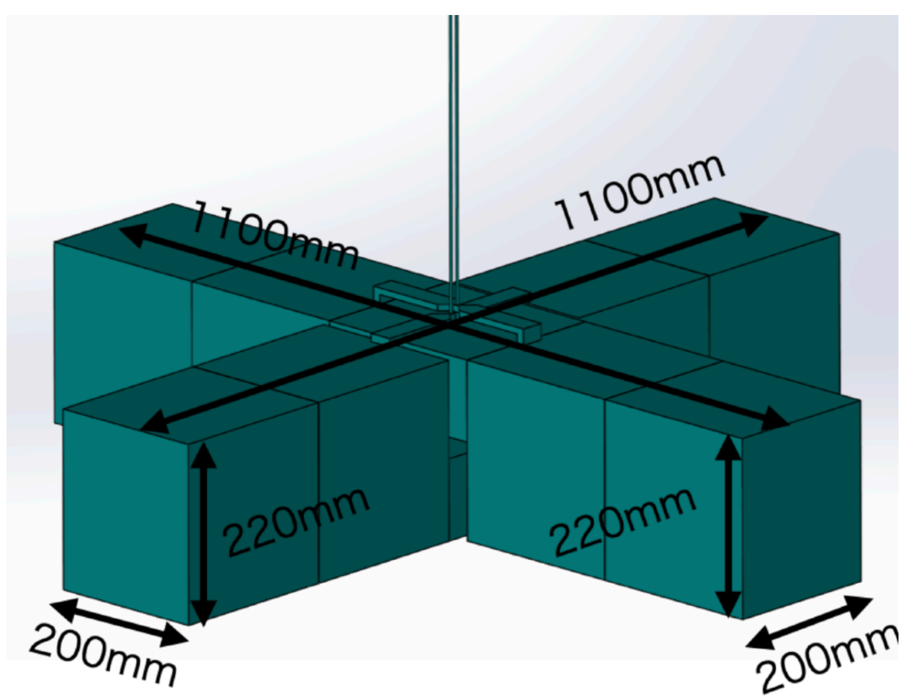
Temperature

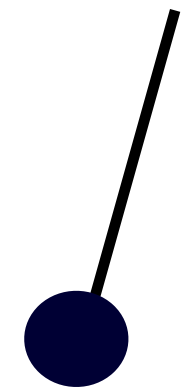
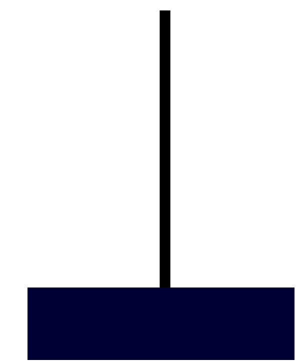
Resonant peak and its tail amplify the source signal

Q factor

2.Torsion bar system



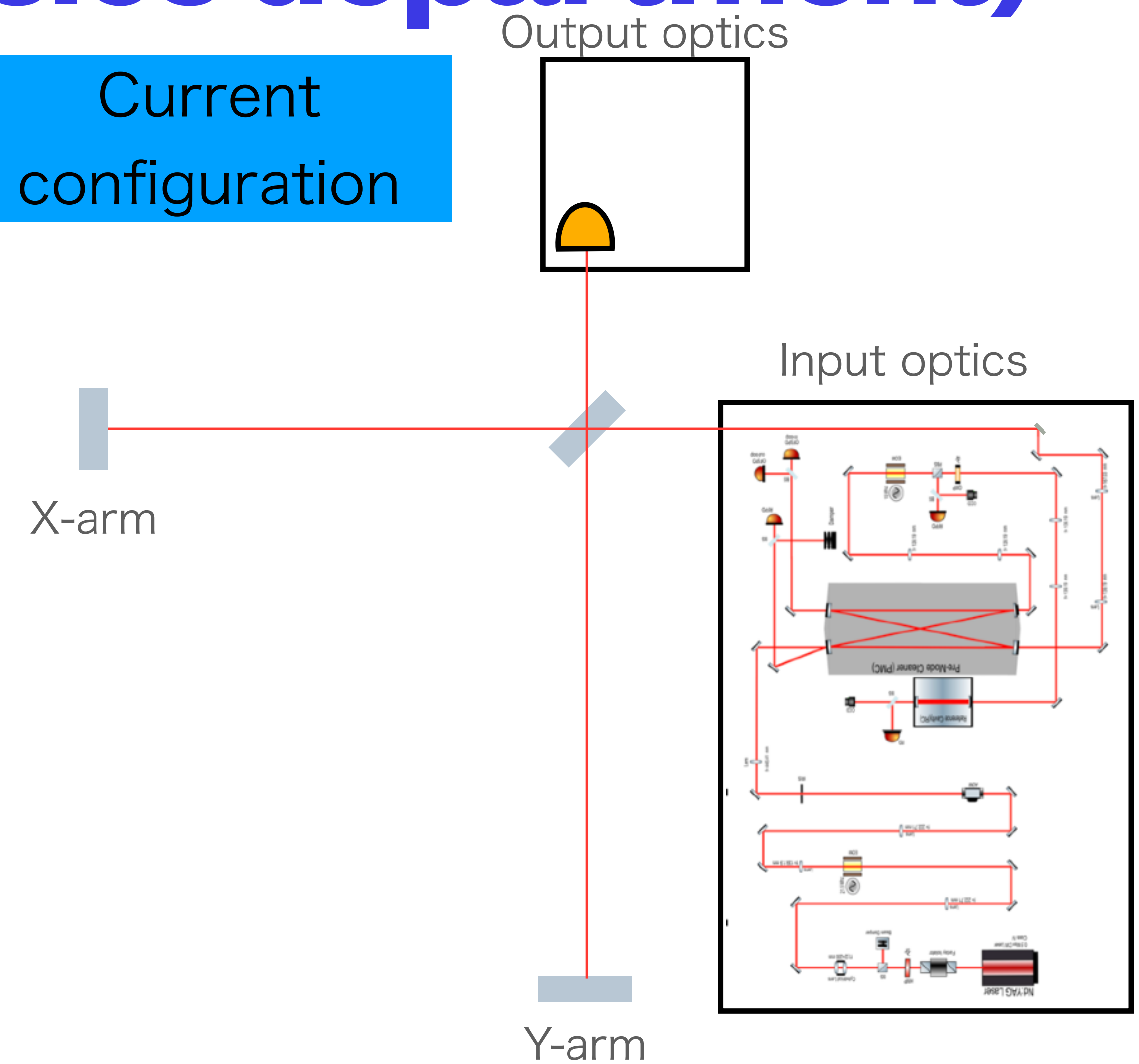


	LVK	CHRONOS
type	 Pendulum	 Torsion bar
EOM	$m\ddot{x} + c\dot{x} + kx = F$	$I\ddot{\theta} + \Gamma\dot{\theta} + \mu\theta = \tau$
Resonant Freq.	$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$	$f = \frac{1}{2\pi}\sqrt{\frac{\mu}{I}}$ $\mu = \frac{\pi G r^4}{2l}$ $G = \frac{E}{2(1+\nu)}$
Typical value (l=10m, d=1mm)	0.15Hz	0.004Hz

Project Status

NCU observatory (Physics department)

Current configuration



Michelson type interferometer

We demonstrate the interferometer operation with real suspension system

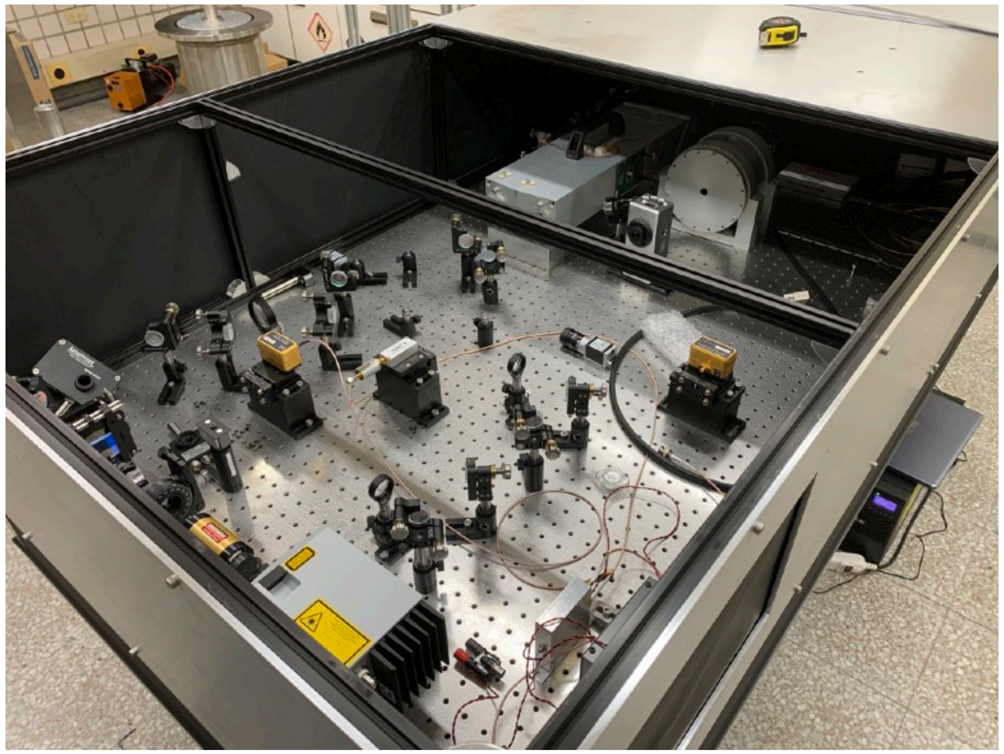
Input optical system

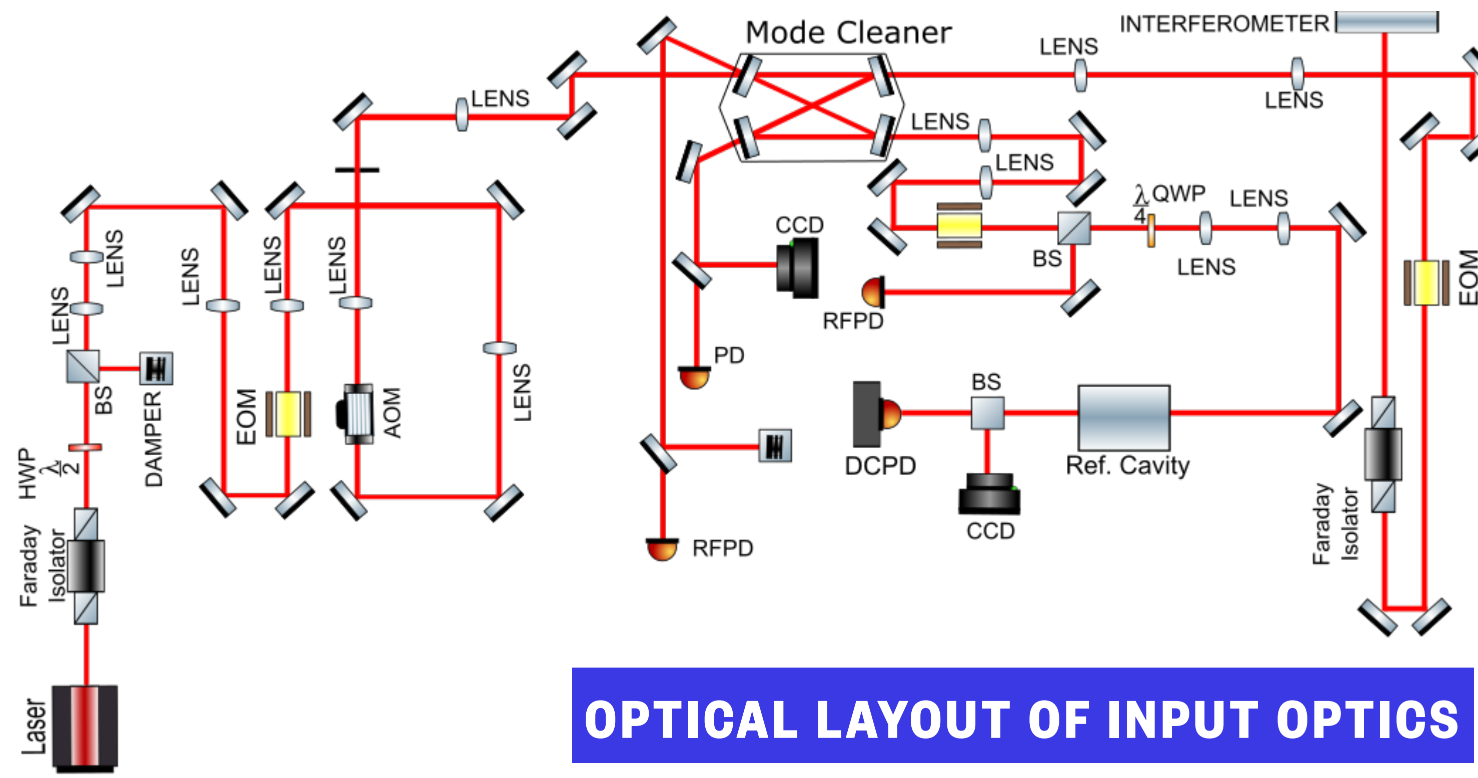
$$E(x,y)=A\exp(i\omega t)$$

Beam → Mode cleaner

Intensity → Intensity Stabilization

Phase → Frequency Stabilization



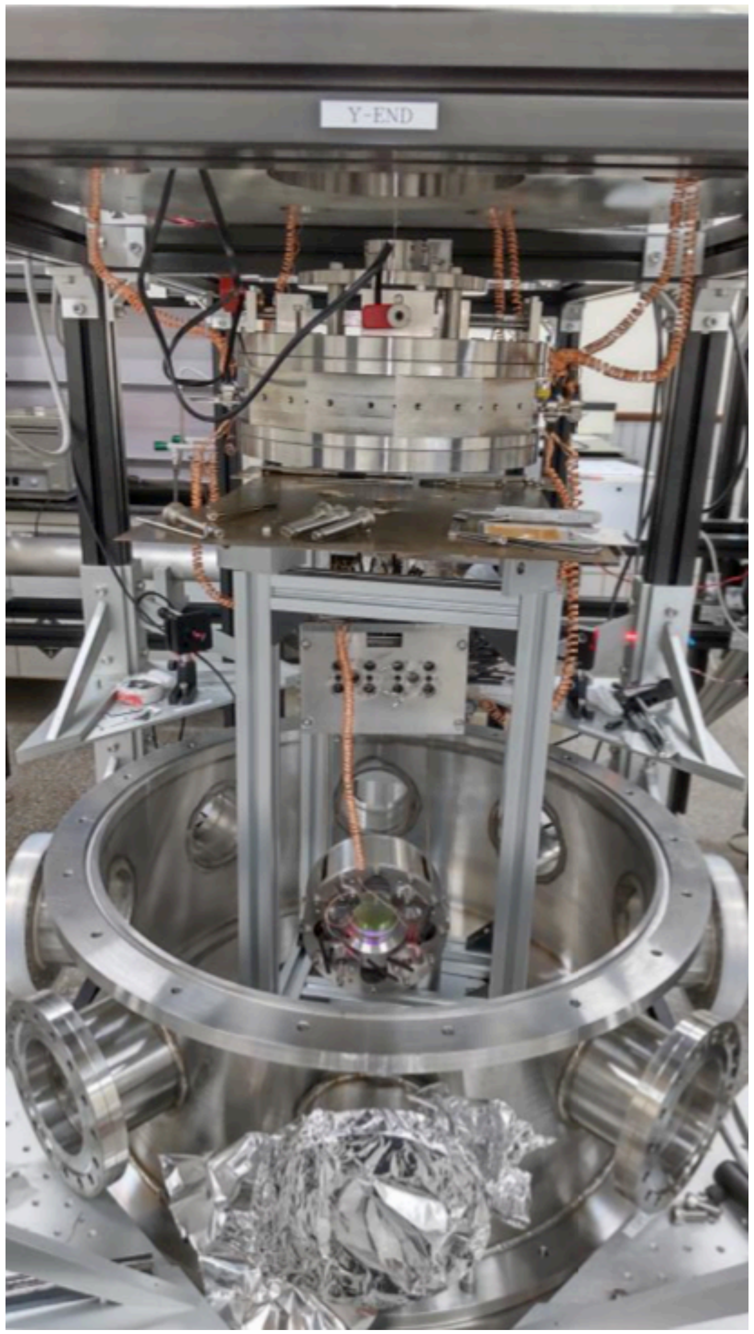


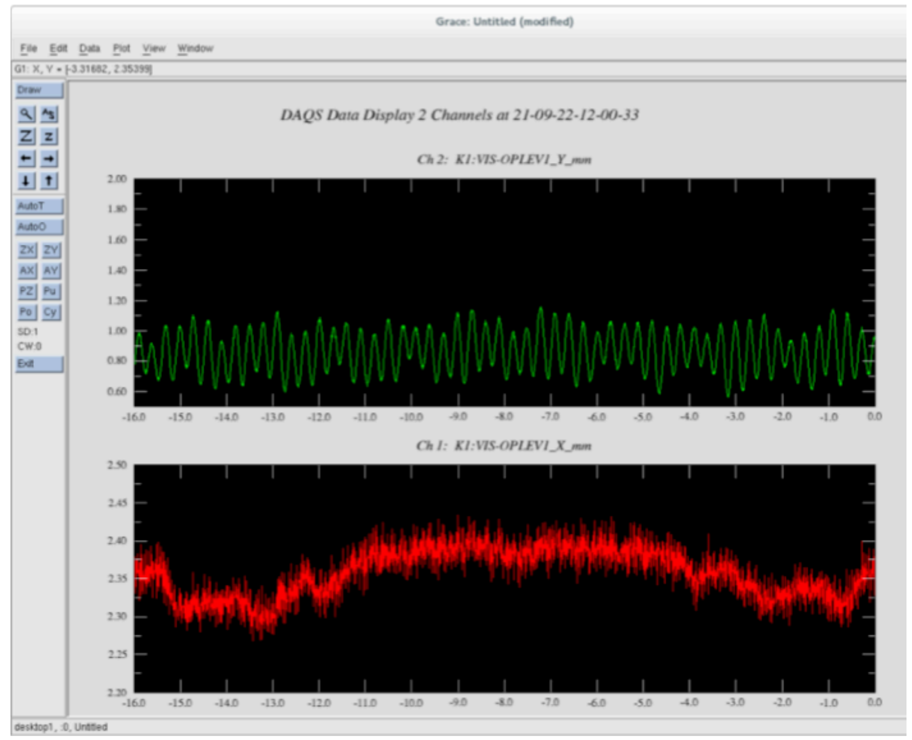
OPTICAL LAYOUT OF INPUT OPTICS

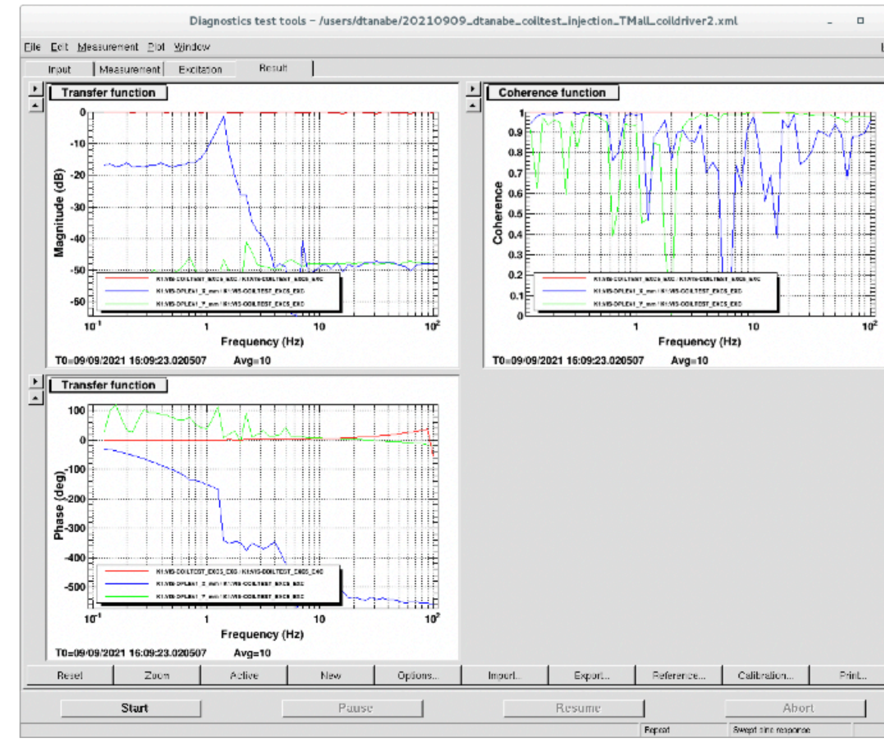
- To keep the lock acquisition state constantly, we need to provide high quality laser beam
- By using feedback control system, we stabilize the laser beam.

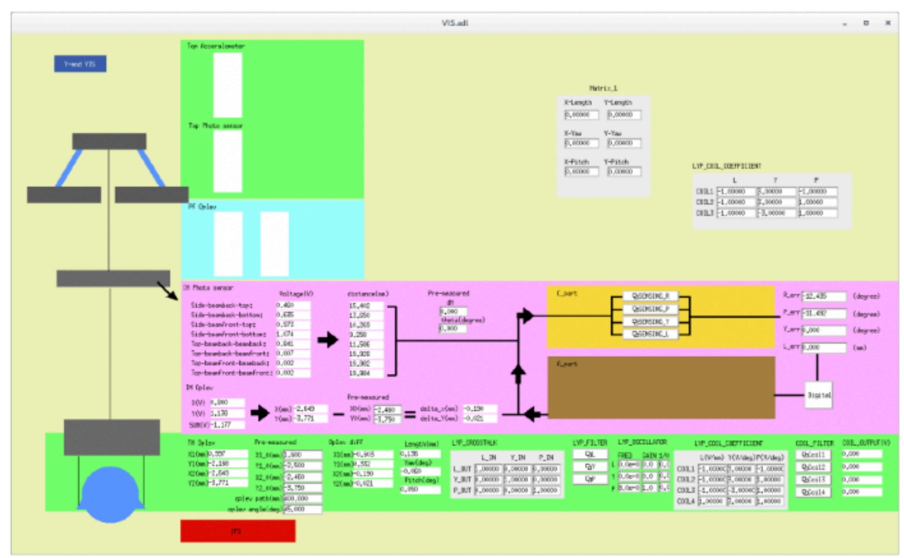
CHRONOS

Vibration Isolation system



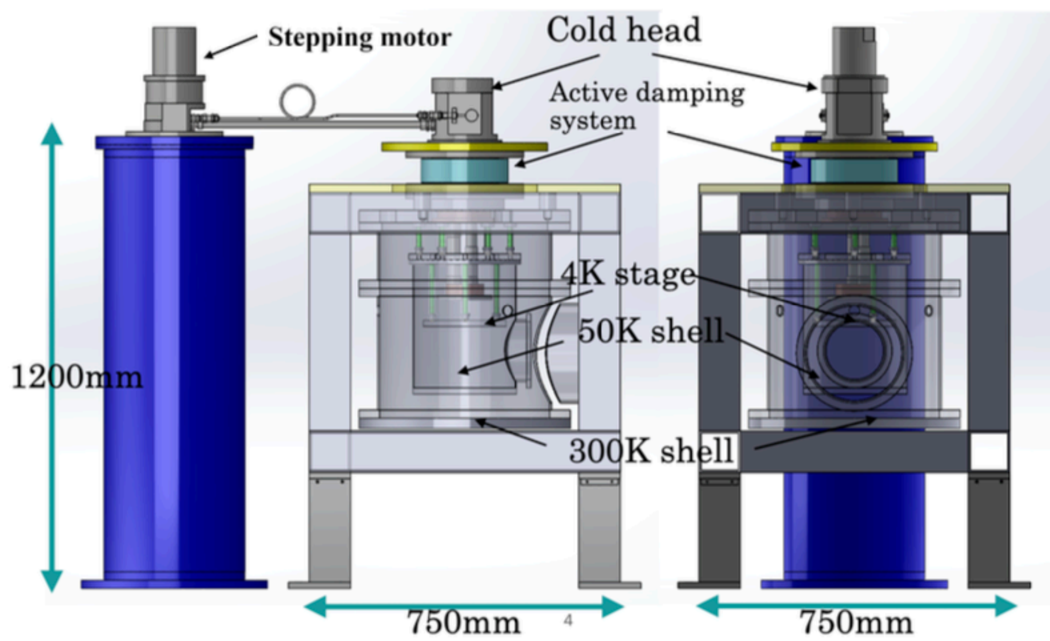




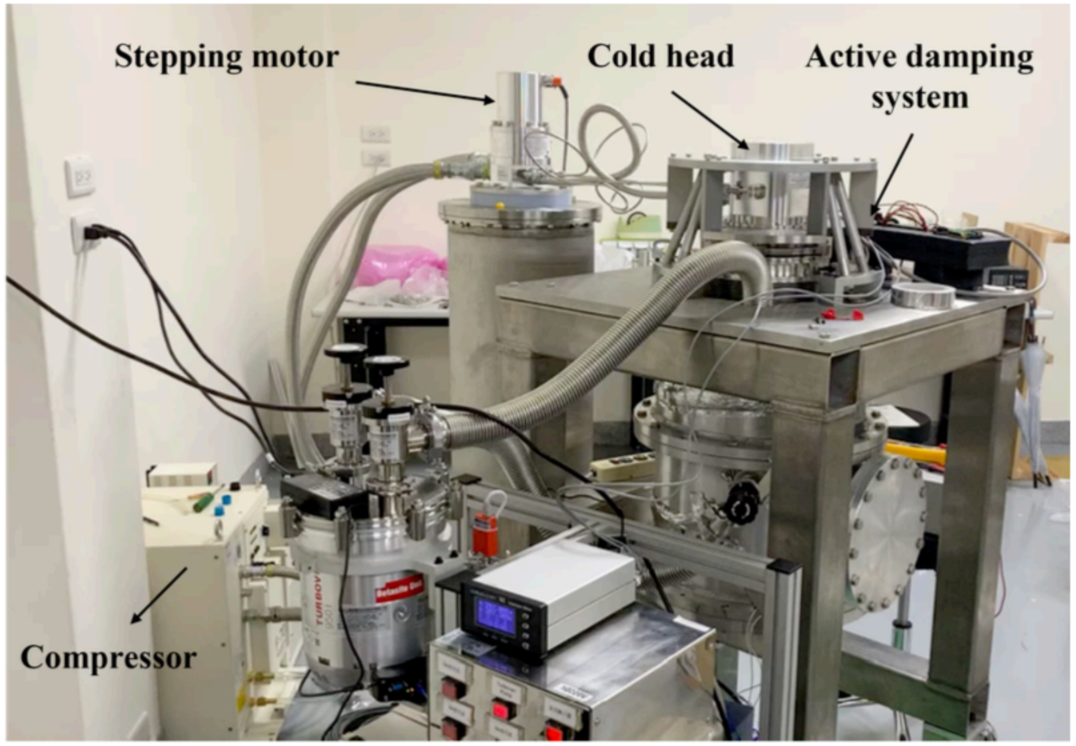


- Isolation from ground motion with feedback control system
- Small suspension test is ongoing.

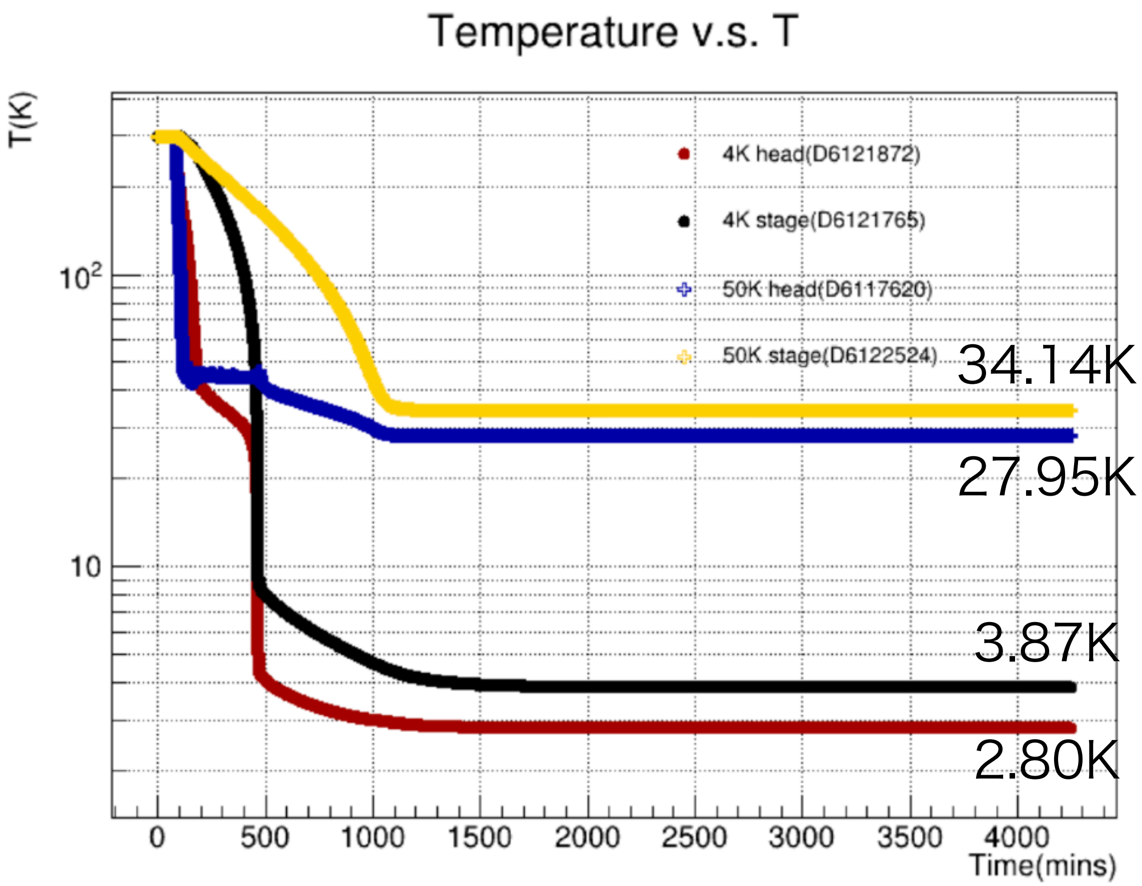
Cryogenic performance

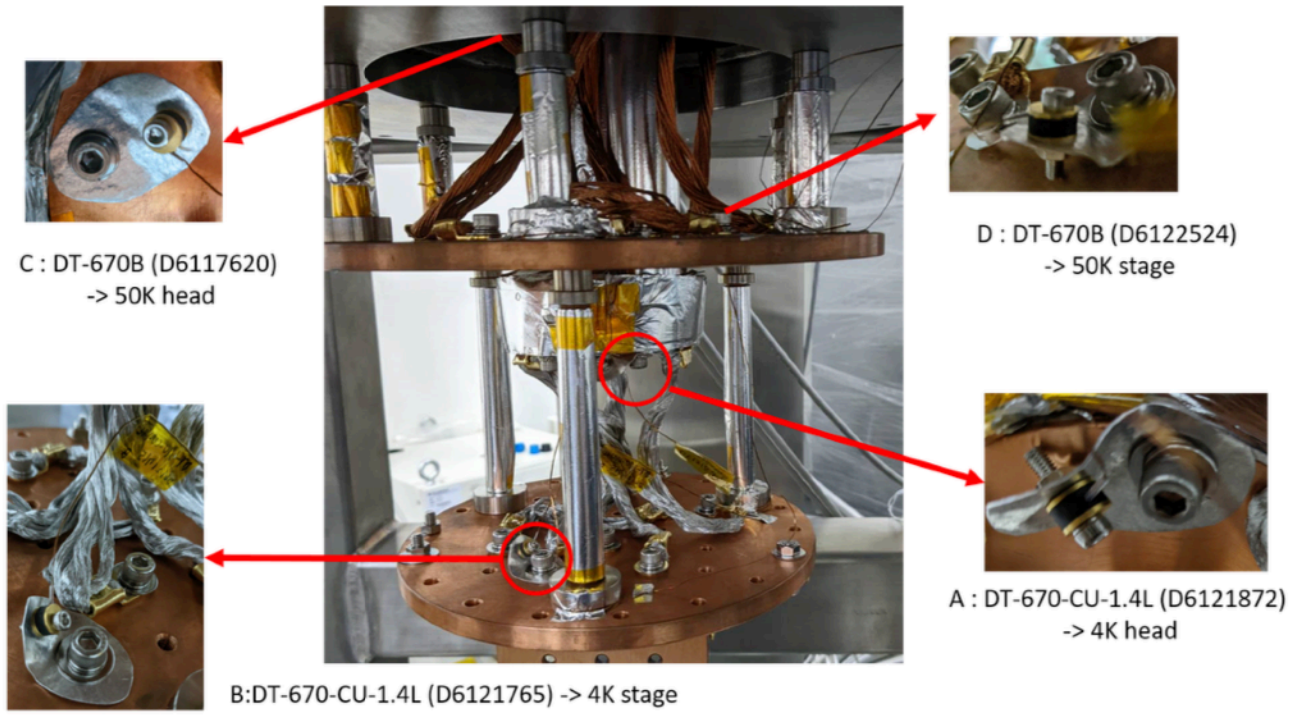


(a) The CAD rendering of the cryogenic



(b) The picture of the cryogenic chamber.





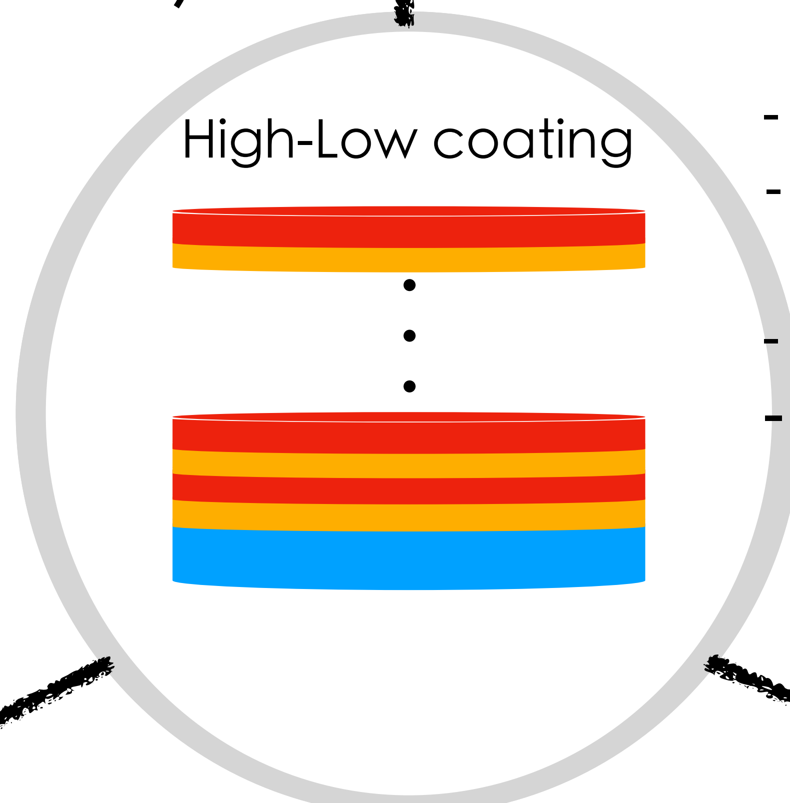
Low Pressure CVD Coating

a-Si coating (n =~3.95)

-Fabrication: Done

-Optical absorption: Ongoing

- Mechanical loss: Ongoing



SiNO coating (n =~1.62)

- Fabrication: Done
- Optical absorption:2.8e-6@1550nm (Preliminary)
- Mechanical loss: Ongoing
- Taiwan demonstrated with PECVD

$$SiH_2Cl_{2(g)} + N_2O_{(g)} + NH_{3(g)} \longrightarrow SiO_xN_yH_{z\ (s)} + \text{residual gas}$$

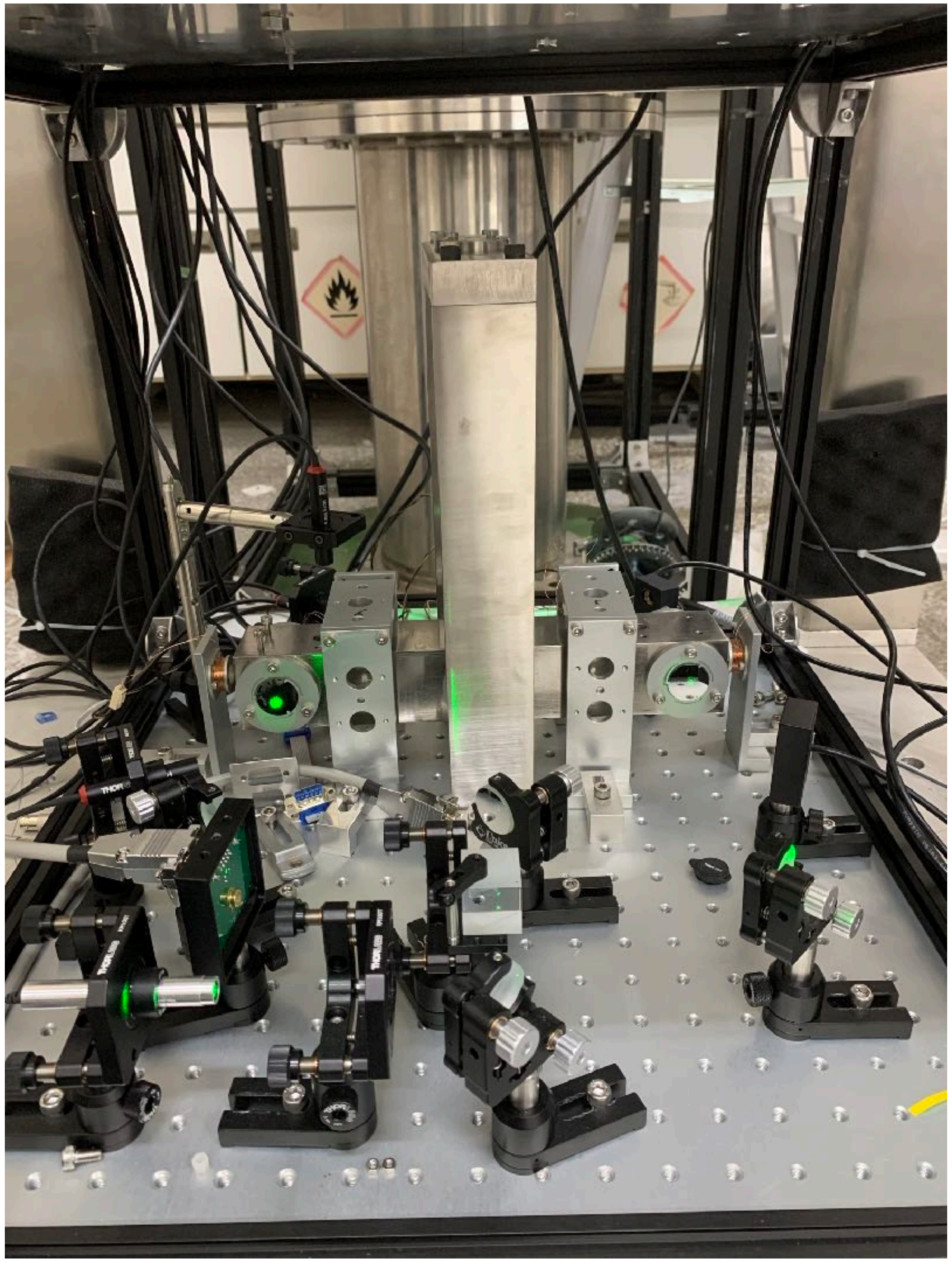
SiN coating (n =~2.68)

- Fabrication: Done
- Optical absorption:5.8e-6@1550nm
- Mechanical loss: Ongoing

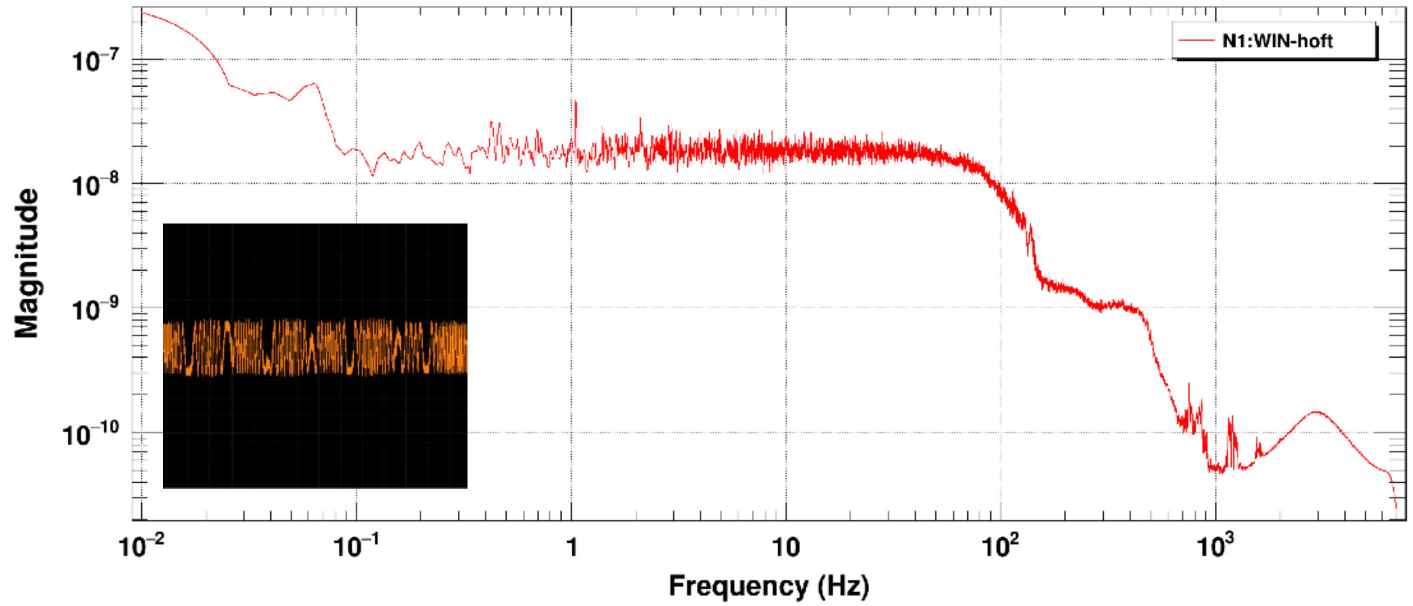
$$SiH_2Cl_2 + NH_3 \xrightarrow{Heat} Si_XN_Y + residual\ gas(HCl + H_2)$$

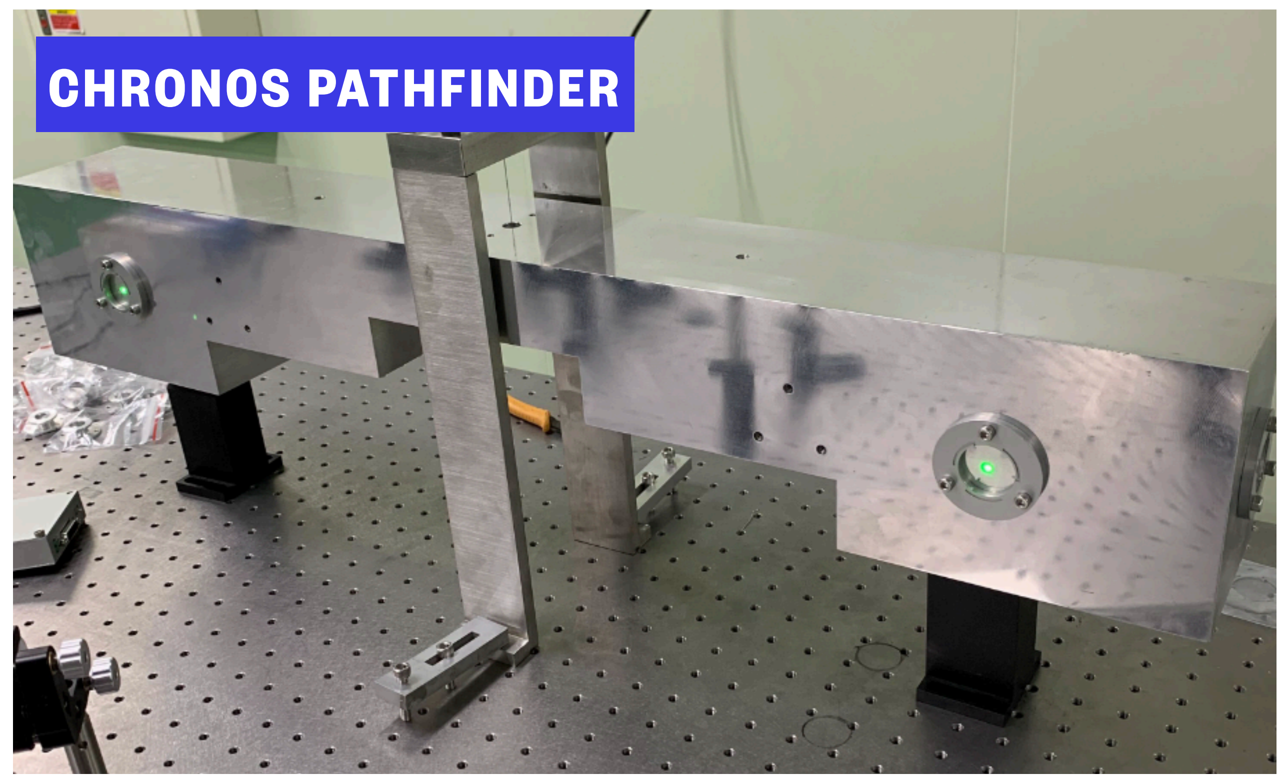
Nobody have tried three combinations! Candidate of LIGO voyager.

Demonstration with mini-CHRONOS and CHRONOS Pathfinder



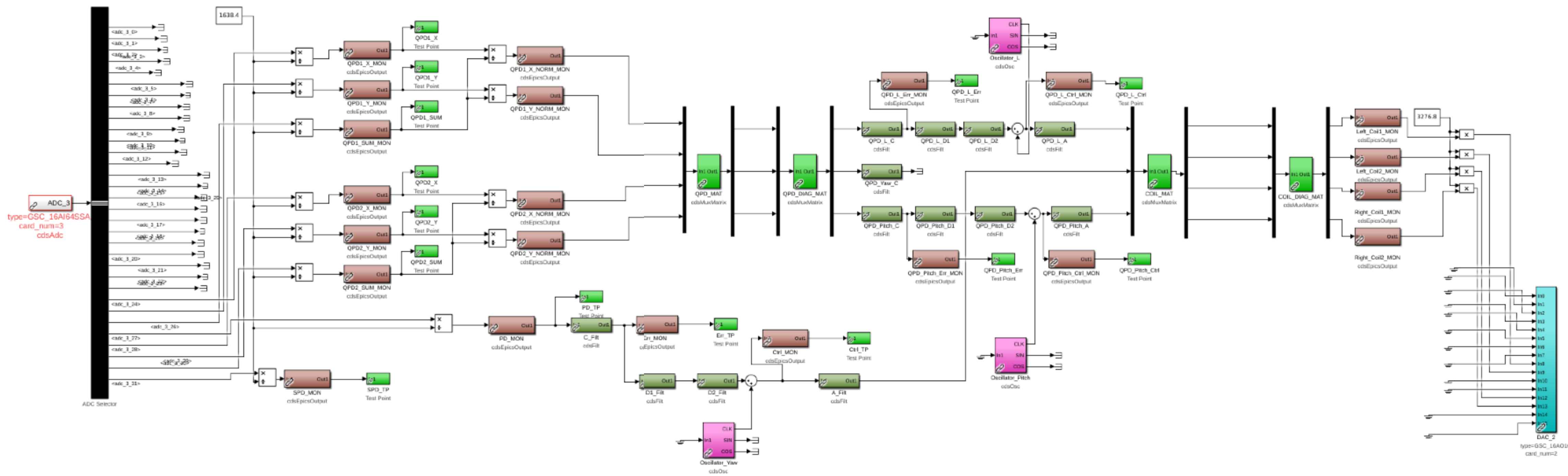
300mm bar length

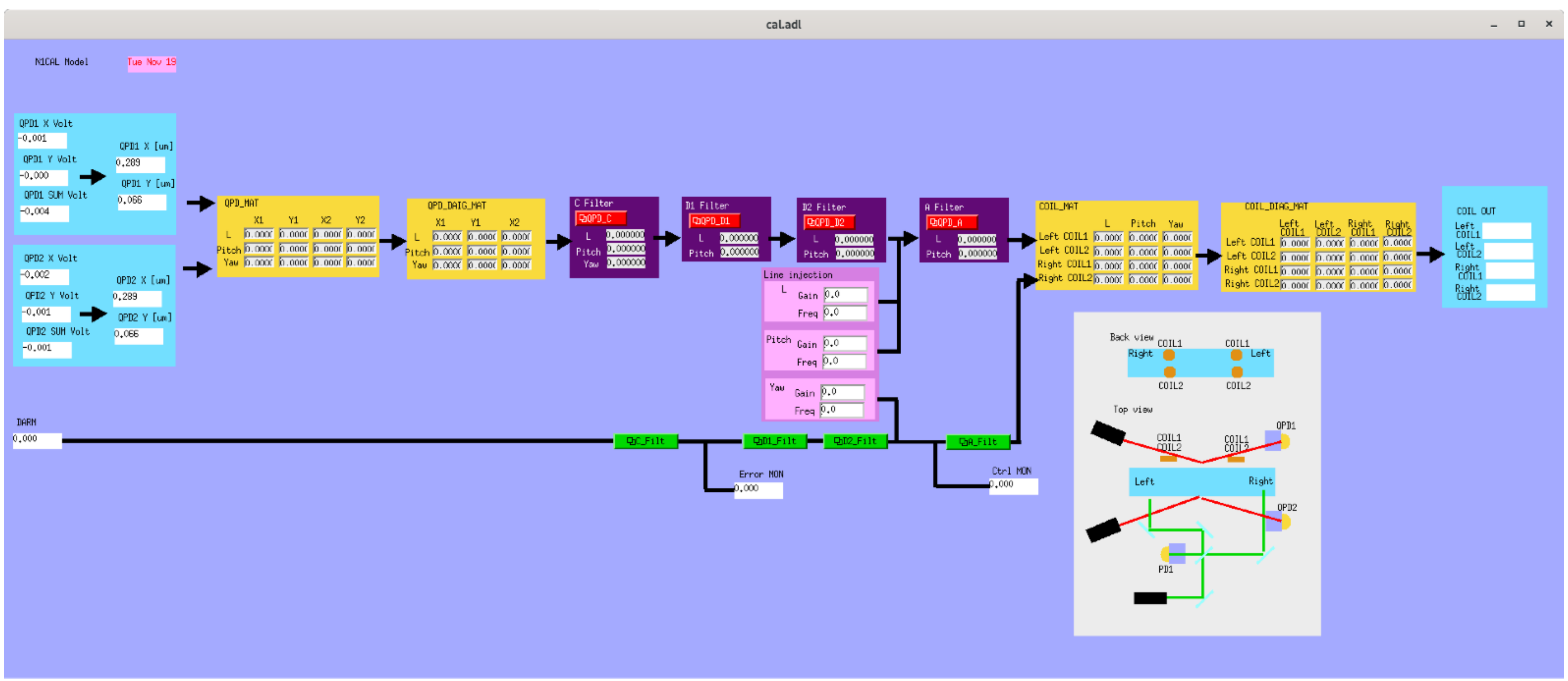




800mm bar length

Digital Control System



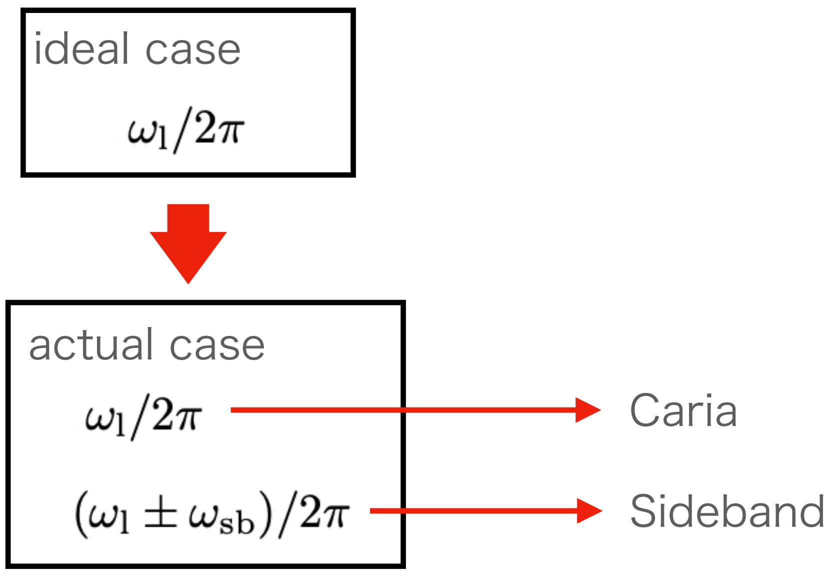


Summary

- CHRONOS is an idea of Taiwanese GW experiment.
- By using Speed meter, Cryogenic, and Torsion bar system, we will improve the low frequency noise for Sub-Hz region.
- CHRONOS is corresponding to the demonstration of non-demolition measurement system for angular momentum.
- By assuming realistic parameter of CHRONOS instruments, we can reach $3 \times 10^{-18}/\sqrt{\mathrm{Hz}}$ Strain sensitivity.
- Instrumental demonstration is ongoing.

two-photon mode

Single freq. + Noise



Operator of sideband

$$\hat{a}_\pm \equiv \hat{a}_{\omega_1 \pm \omega}, \quad \hat{a}^\dagger_\pm \equiv \hat{a}^\dagger_{\omega_1 \pm \omega}$$

Operator meats following relation:

$$[\hat{a}_+, \hat{a}_{+'}] = 0, \quad [\hat{a}_-, \hat{a}_{-'}] = 0, \quad [\hat{a}_+, \hat{a}_{-'}] = 0,$$

$$[\hat{a}_+, \hat{a}^\dagger_{+'}] = 2\pi\delta(\omega - \omega'), \quad [\hat{a}_-, \hat{a}^\dagger_{-'}] = 2\pi\delta(\omega - \omega')$$

Define:

Creation and Annihilation operator

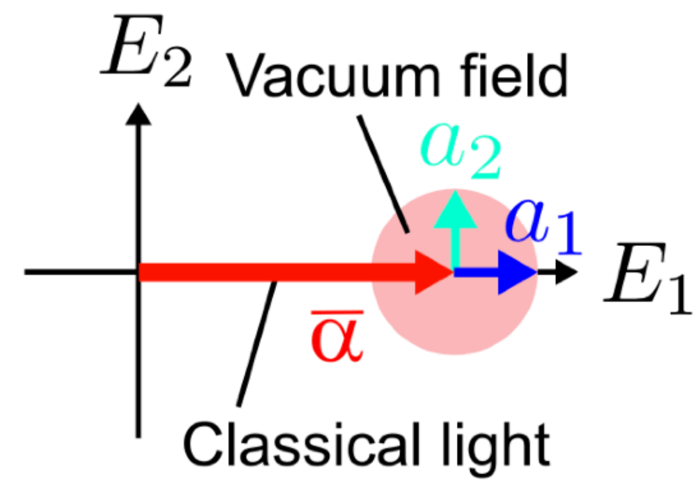
Define

Amplitude quadrature

$$\hat{a}_1 \equiv \frac{\hat{a}_+ + \hat{a}^\dagger_-}{\sqrt{2}}$$

Phase quadrature

$$\hat{a}_2 \equiv \frac{\hat{a}_+ - \hat{a}^\dagger_-}{i\sqrt{2}}$$



$$[\hat{a}_1, \hat{a}_{1'}] = 0, \quad [\hat{a}_2, \hat{a}_{2'}] = 0, \quad [\hat{a}_1, \hat{a}_{2'}] = 0,$$

$$[\hat{a}_1, \hat{a}^\dagger_{2'}] = 2i\pi\delta(\omega - \omega'), \quad [\hat{a}_2, \hat{a}^\dagger_{1'}] = -2i\pi\delta(\omega - \omega')$$

Finally, we can describe the photo-electro field as

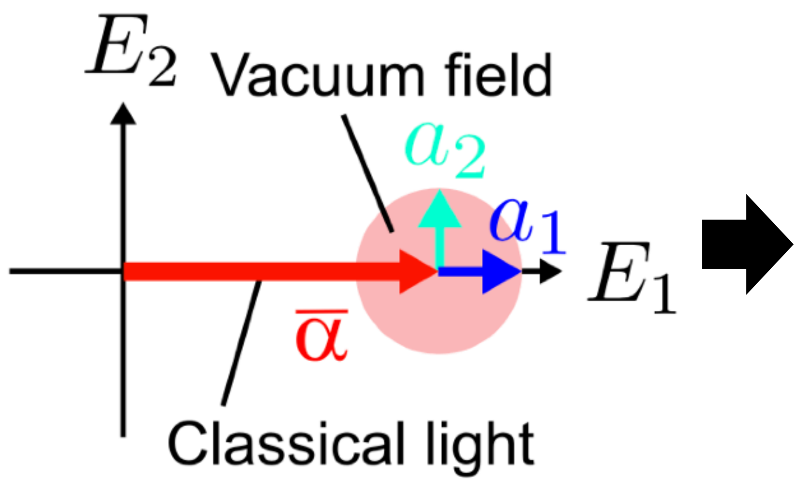
$$\hat{E}(\boldsymbol{r}, t) = u(\boldsymbol{r})\sqrt{\frac{4\pi\hbar\omega_1}{\mathcal{A}c}}[\hat{a}_1(z,t)\cos\omega_1 t + \hat{a}_2(z,t)\sin\omega_1 t]$$

$$\hat{a}_j(z,t) \equiv \int_0^\infty \left[\hat{a}_j e^{-i(\omega t - kz)} + \hat{a}^\dagger_j e^{i(\omega t - kz)}\right]\frac{d\omega}{2\pi} \quad (j = 1, 2)$$

We will neglect the following factor in this discussion

$$\hat{E}(\boldsymbol{r}, t) = u(\boldsymbol{r})\sqrt{\frac{4\pi\hbar\omega_1}{\mathcal{A}c}} \quad e^{\pm ikz}$$

Squeezed state



No correlation for AQ and PQ fluctuation.
However, we can make a correlation state with non-lender optical system

We call is as ‘Squeezed state’

Squeezed state: $|\chi\rangle$

$$|r,\phi\rangle \equiv \exp\left[r\left(\hat{a}_+\hat{a}_-e^{-2i\phi} - \hat{a}_+^\dagger\hat{a}_-^\dagger e^{2i\phi}\right)\right]|0\rangle \equiv \underline{\hat{S}[r,\phi]}\,|0\rangle$$

squeezed state operator

Action for operator:

$$\hat{S}^\dagger[r,\phi]\hat{a}_1\hat{S}[r,\phi] = \hat{a}_1(\cosh r + \sinh r\cos 2\phi) - \hat{a}_2\sinh r\sin 2\phi$$

$$\hat{S}^\dagger[r,\phi]\hat{a}_2\hat{S}[r,\phi] = \hat{a}_2(\cosh r - \sinh r\cos 2\phi) - \hat{a}_1\sinh r\sin 2\phi$$

(i) $\phi = 0$

$$\hat{S}^\dagger[r,0]\hat{a}_1\hat{S}[r,0] = e^r\hat{a}_1$$

$$\hat{S}^\dagger[r,0]\hat{a}_2\hat{S}[r,0] = e^{-r}\hat{a}_2$$

Squeezed to AQ direction!

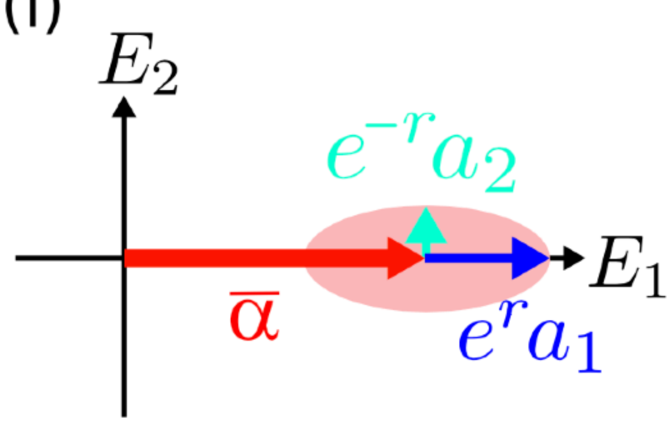
(ii) $\phi = \pi/2$

$$\hat{S}^\dagger[r,\pi/2]\hat{a}_1\hat{S}[r,\pi/2] = e^{-r}\hat{a}_1$$

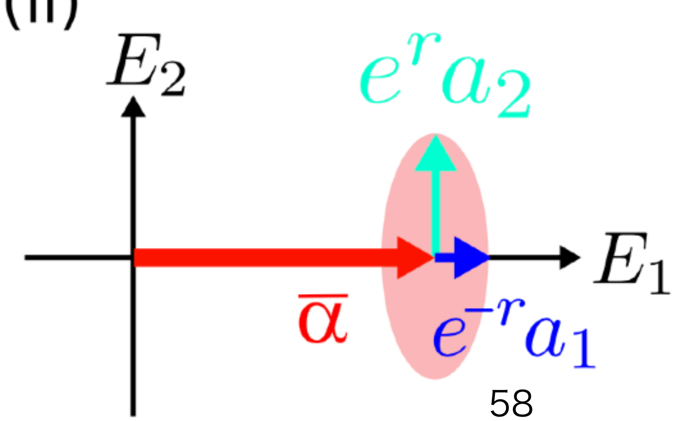
$$\hat{S}^\dagger[r,\pi/2]\hat{a}_2\hat{S}[r,\pi/2] = e^{r}\hat{a}_2$$

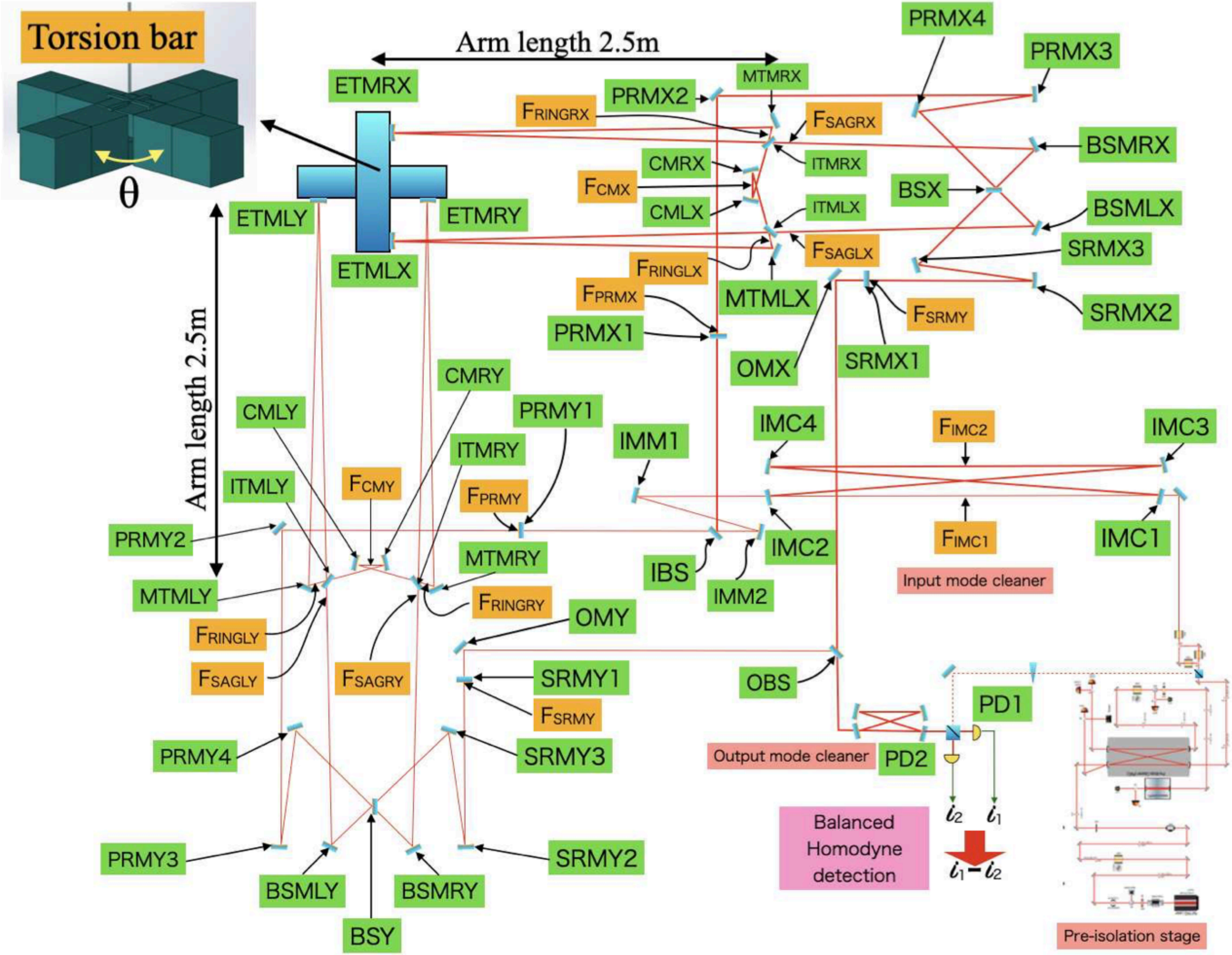
Squeezed to PQ direction!

(i)



(ii)




Torsion bar
θ
Arm length 2.5m
Arm length 2.5m
ETMRX
ETMLY
ETMRY
ETMLX
PRMX2
MTMRX
PRMX4
PRMX3
FRINGRX
FSAGRX
ITMRX
CMRX
FCMX
CMLX
ITMLX
BSRMX
BSX
BSMLX
SRMX3
FSAGLX
FRINGLX
MTMLX
FPRMX
PRMX1
FSRMY
SRMX2
OMX
SRMX1
CMRY
CMLY
PRMY1
ITMRY
IMM1
IMC4
FIMC2
IMC3
ITMLY
FCMY
FPRMY
PRMY2
MTMRY
IBS
IMC2
FIMC1
IMC1
MTMLY
IMM2
Input mode cleaner
FRINGRY
FRINGLY
OMY
FSAGLY
FSAGRY
SRMY1
OBS
FSRMY
PD1
PRMY4
SRMY3
Output mode cleaner
PD2
Balanced Homodyne detection
i_2
i_1
$i_1 - i_2$
PRMY3
SRMY2
BSMLY
BSMRY
BSY
Pre-isolation stage

Coating

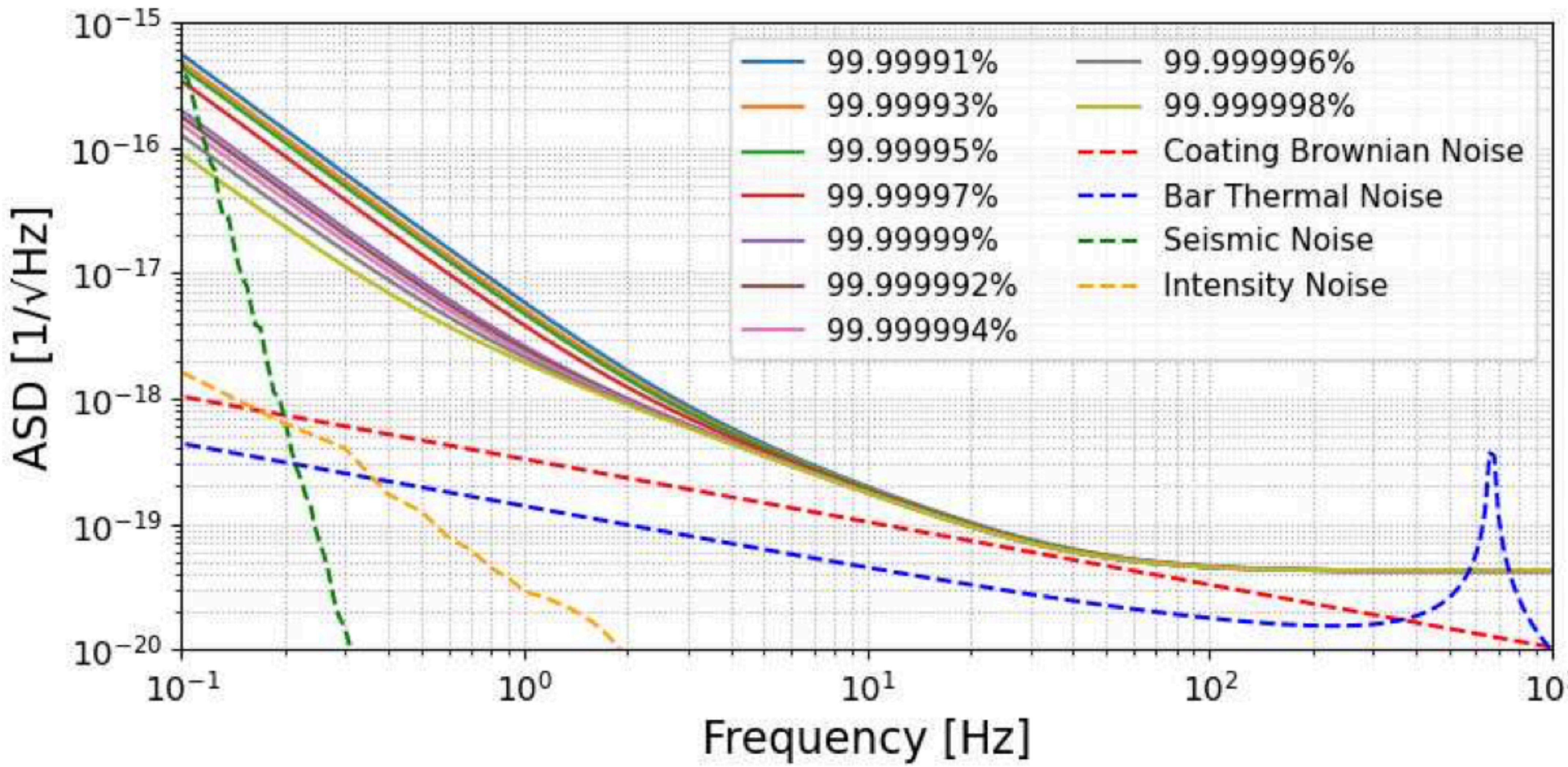


Figure 5: Total quantum-noise spectra including shot noise, radiation-pressure noise, and other technical noise sources. Coating effects dominate the sensitivity in the 0.1-10 Hz band. The intensity noise is calculated elsewhere [34].

Power recycling detuning

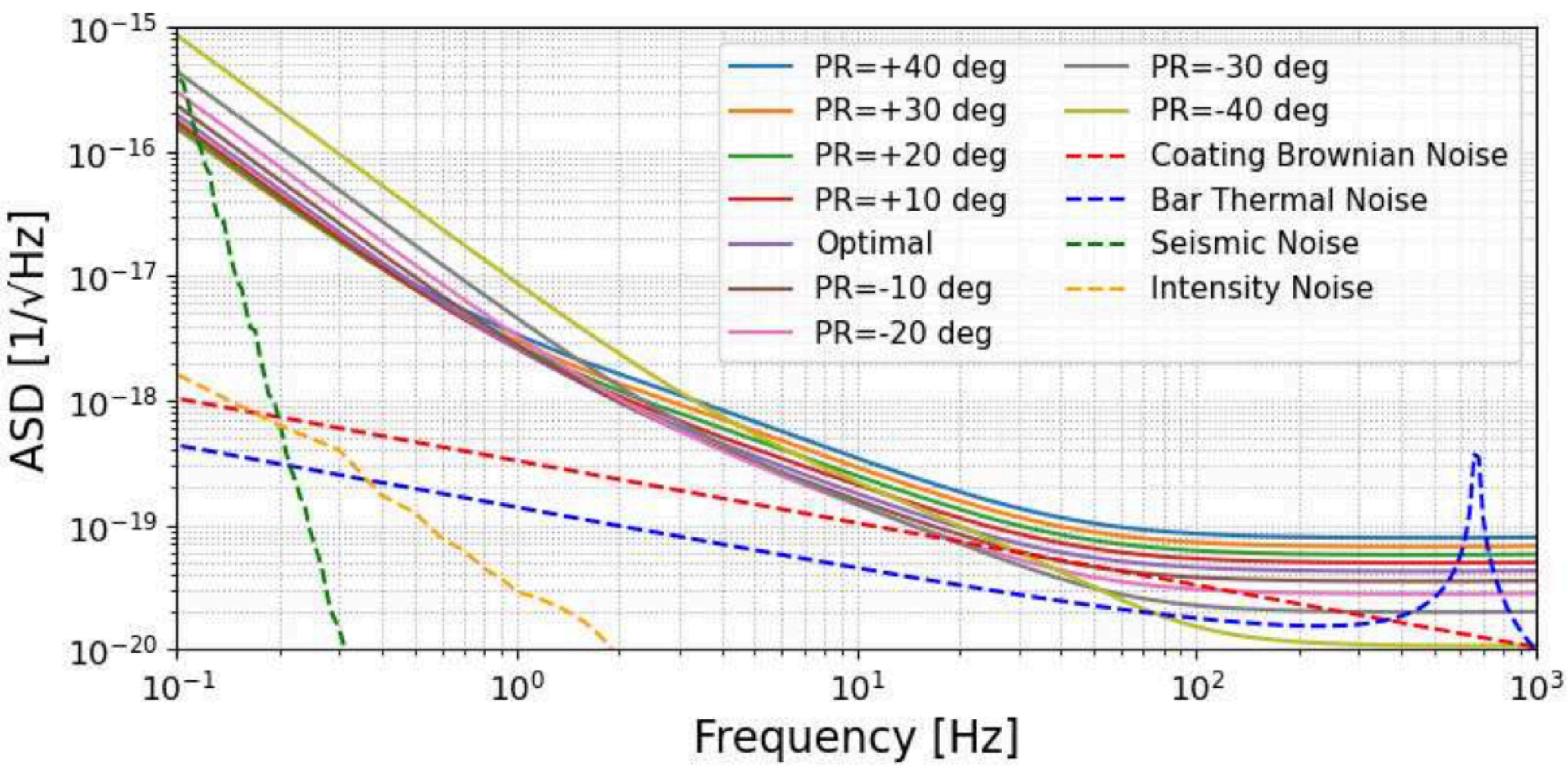


Figure 8: Total quantum-noise spectra including shot noise, radiation-pressure noise, and technical noise sources. The optimal point balances the three contributions, while detuning leads to degraded sensitivity. The intensity noise is calculated in elsewhere [34]

Signal recycling detuning

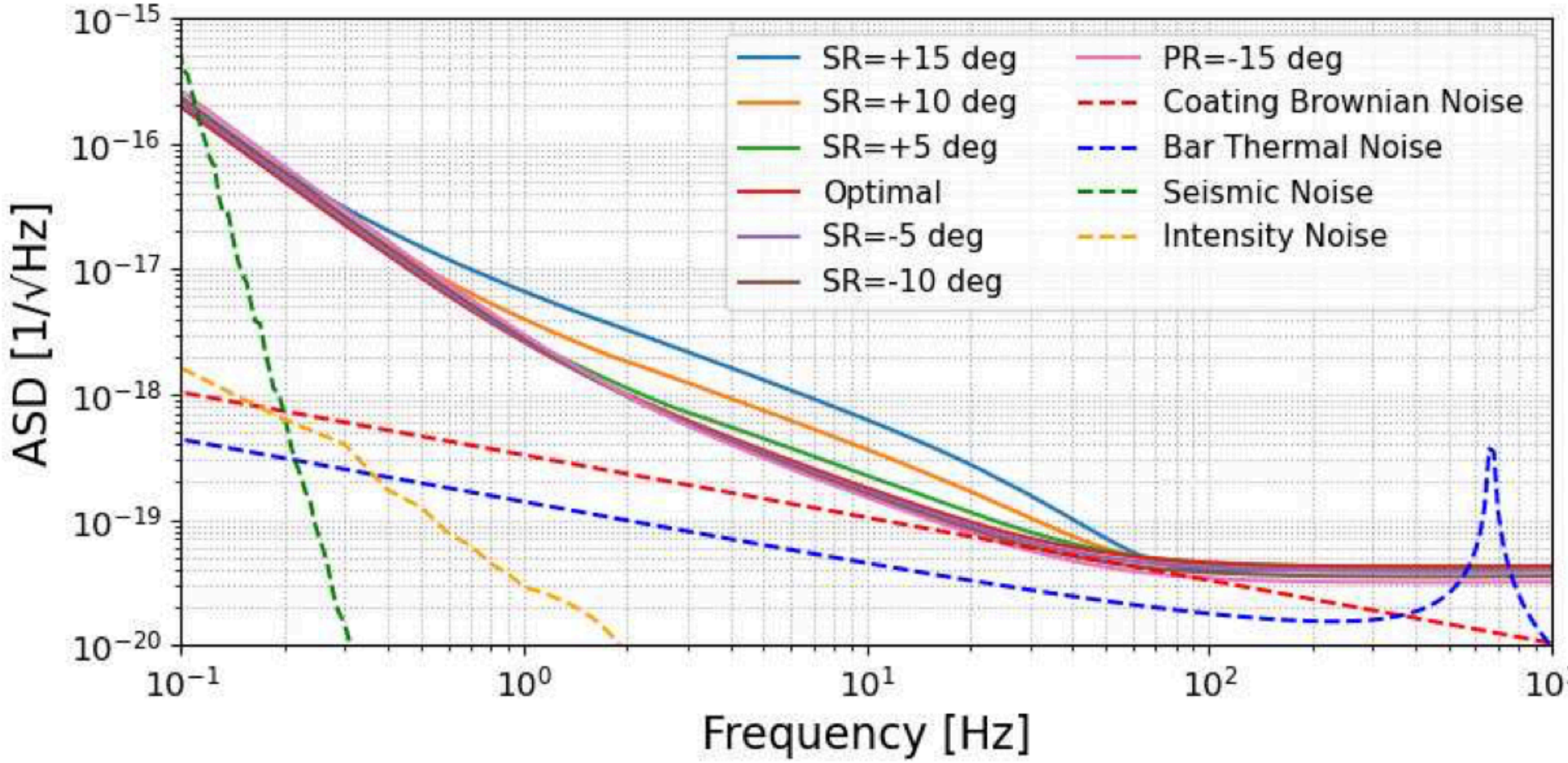


Figure 11: Total quantum-noise spectrum including shot noise, radiation-pressure noise, and technical noise. At resonance, the three contributions balance near 1–10 Hz, while detuning leads to significant degradation. The intensity noise is calculated in elsewhere [34]

Homodyne angle

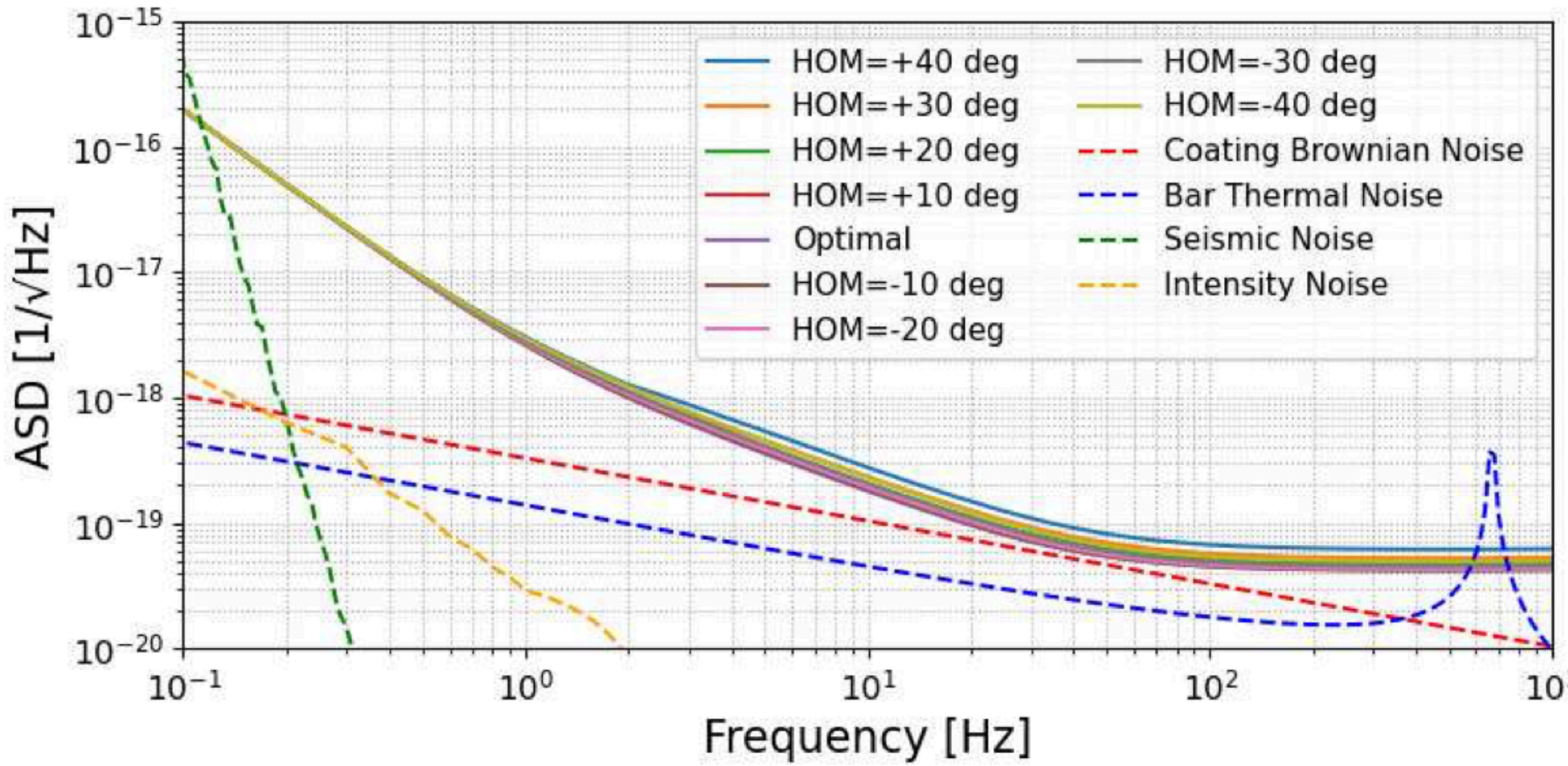


Figure 14: Total quantum-noise spectra for various homodyne angles. The optimal configuration at $\zeta_{\rm opt} \simeq 46^\circ$ achieves balanced suppression of radiation-pressure and shot noise, yielding the best sensitivity near 1 Hz. The intensity noise is calculated in elsewhere [34].

Earthquake

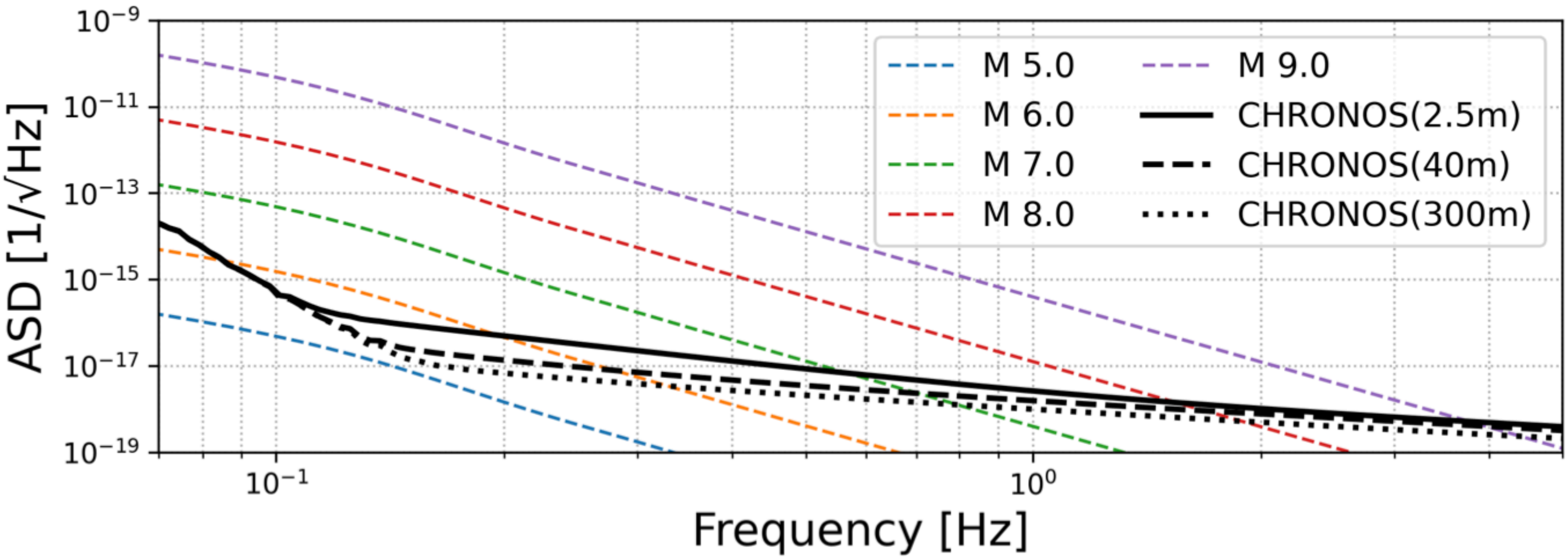


Figure 5: Predicted sensitivity to prompt gravity signals from large earthquakes. By detecting gravitational perturbations at the speed of light, CHRONOS enables warnings before surface-wave arrival.

Long arm length

Table I: Interferometer parameters for sensitivity estimates. Definitions: $R_i = r_i^2$, $R_p = r_p^2$, $R_s = r_s^2$; $P_{\rm in}$ input power, $P_{\rm arm}$ arm power; ϕ_p PRC detuning, ϕ_s SRC detuning, ζ homodyne angle; $F_{\rm ring}$ finesse, w beam radius at ETM.

	2.5 m	40 m	300 m
R_s, R_p, R_i	0.5, 0.9, 0.9999	0.5, 0.95, 0.999	0.5, 0.99, 0.995
$P_{\rm in}, P_{\rm arm}$	1 W, 444 W	20 W, 2391 W	100 W, 18.3 kW
ϕ_p, ϕ_s, ζ	$-85°, 0°, 46°$	$26°, 0°, -50°$	$41°, 2°, -66°$
$F_{\rm ring}$	3.14×10^4	3.14×10^3	6.27×10^2
w at ETM	2 mm	20 mm	35 mm