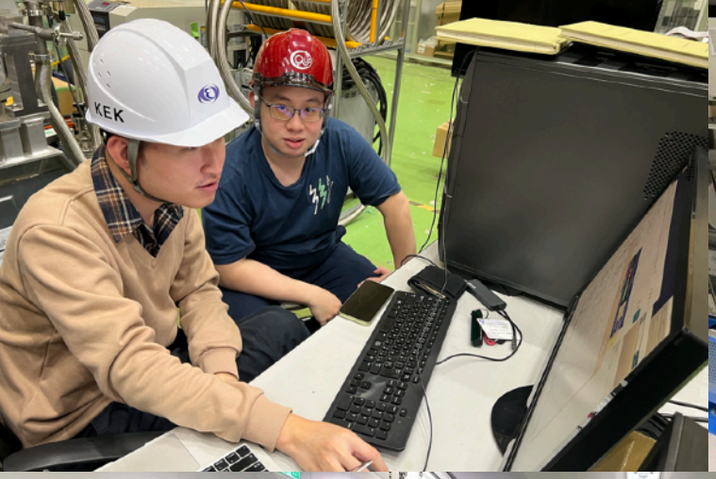
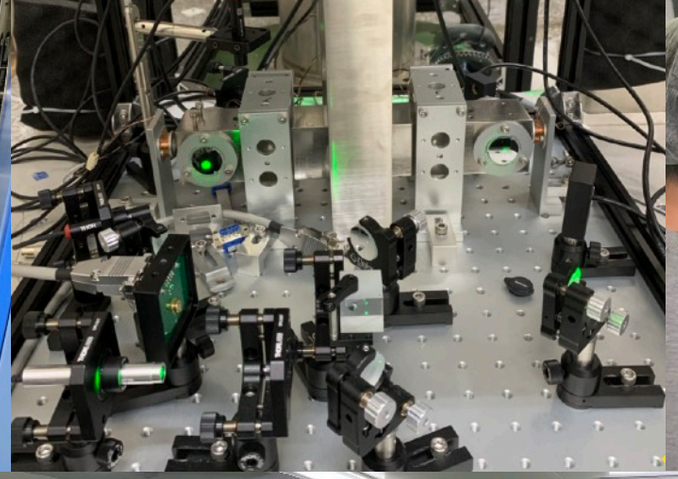
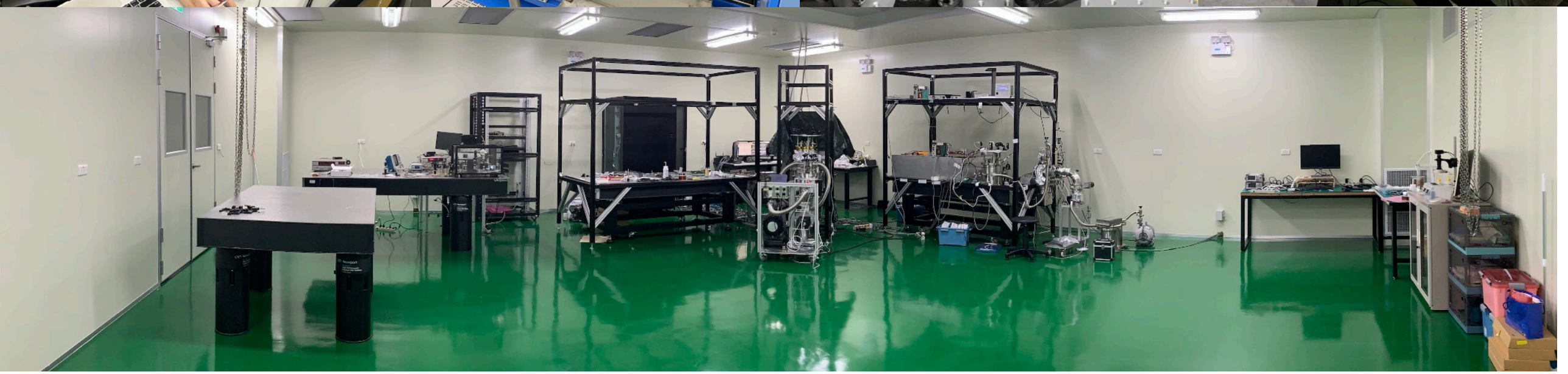






Taiwan-LIGO instrumentation group

National Central University & Academia Sinica
Yuki Inoue

2024/11/21 CHiP meeting

Outline

- Introduction
- LIGO observation
- Study for future LIGO
- R&D in Taiwan
- Summary

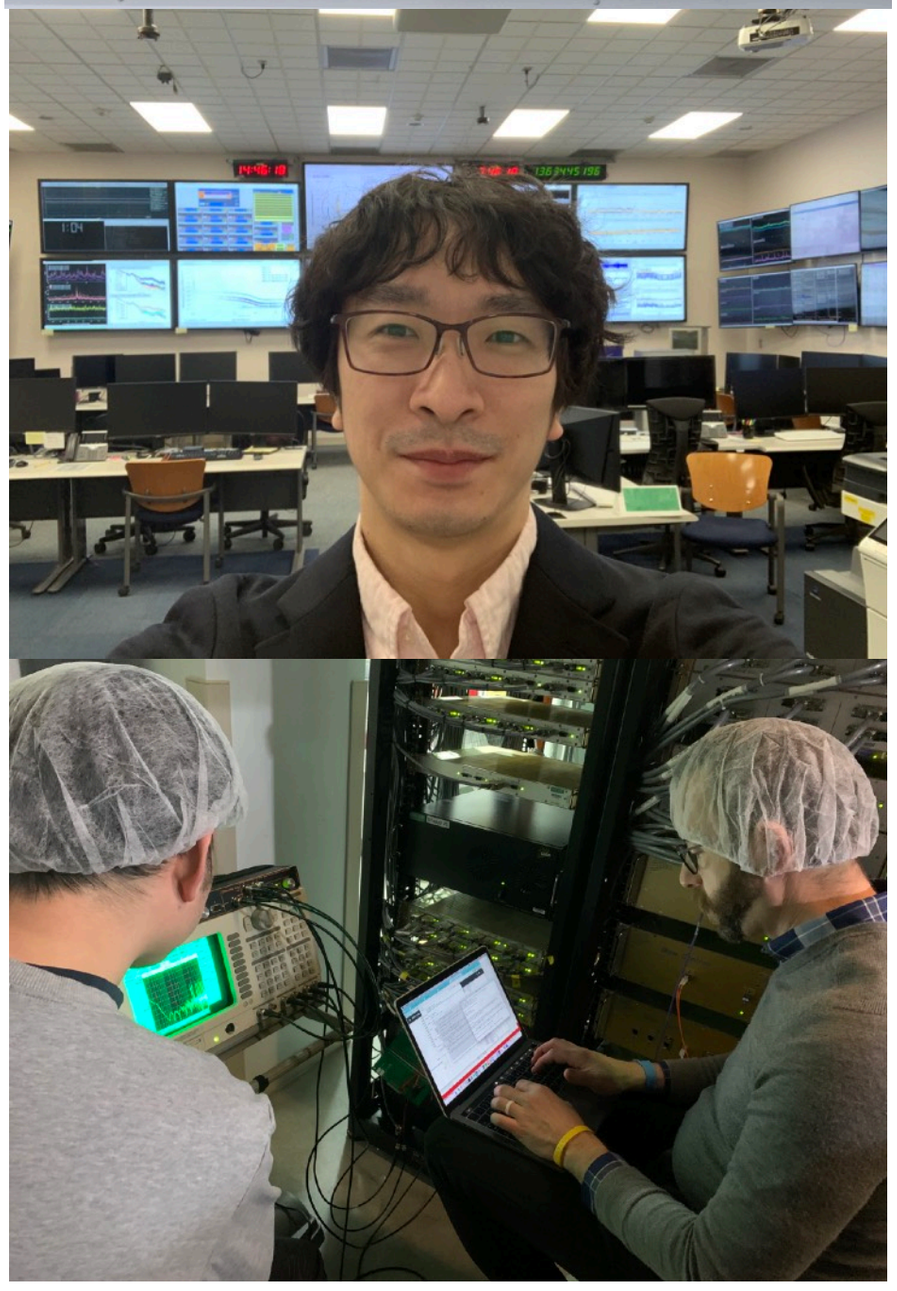
Introduction

- NCU & Academia Sinica have joined LIGO Scientific Collaboration since 2021.

- Contributing Calibration and Optical coating.

- Newly start the stochastic background study.

- We also study the R&D of future GW technologies.



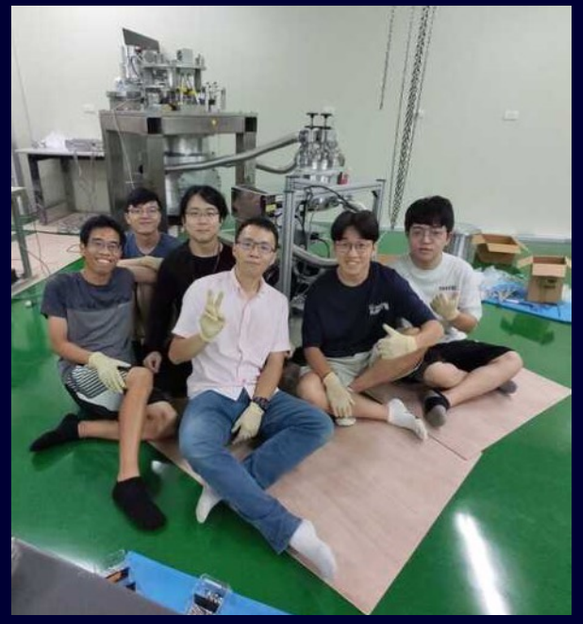
Taiwan-LIGO instrumentation group

National Central University

Yuki Inoue (PI)
Miftahul Ma'arif
Dennis
Yoyo
You-Ru Lee
Hsiang-Yu Huang
Eason Lin
John Chen
Avani Patel
Kun-Yao Chang

Academia Sinica

Tsz-King Wong
Feng-Kai Lin
Hsiang-Chieh Hsu
Daiki Tanabe
Vivek Kumar

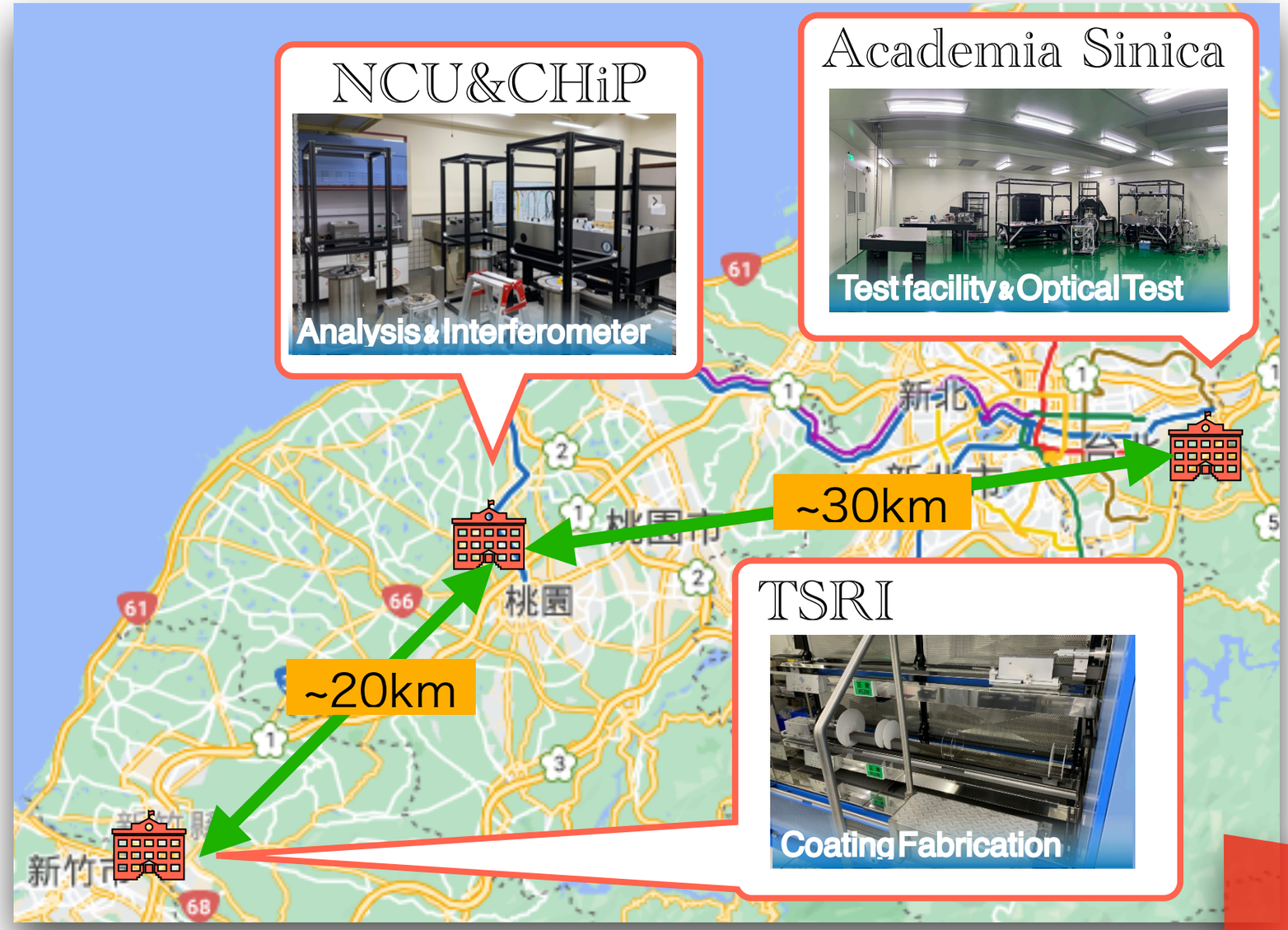


NTHU

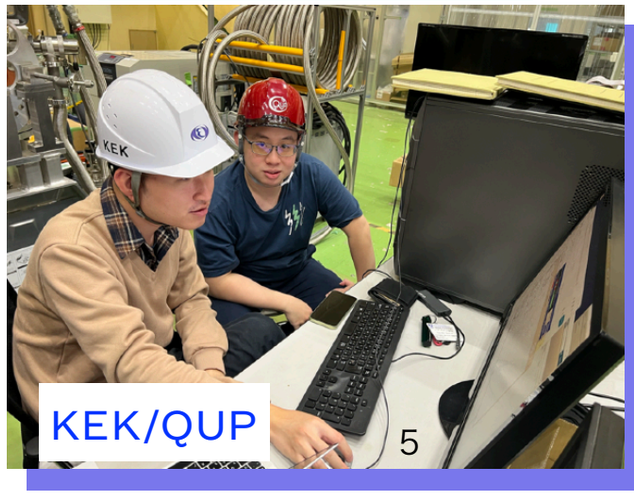
Chao Shiuh

16 staffs and students join our group

Taiwan-LIGO instrumentation group and World



LSC fellow (future)



LSC fellow

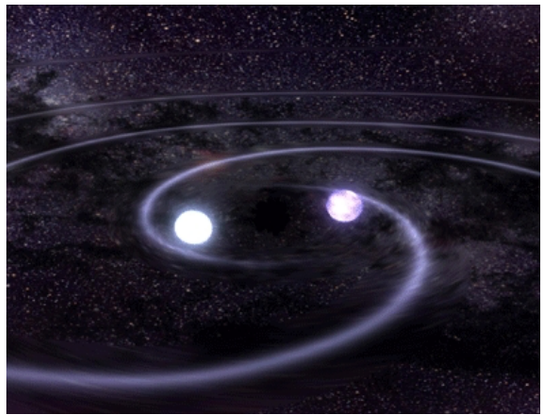
LSC fellow

QUP internship

LIGO observation

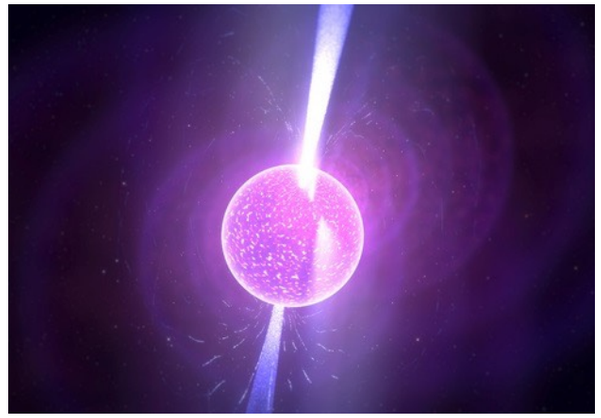
LIGO science

BINARY SYSTEMS

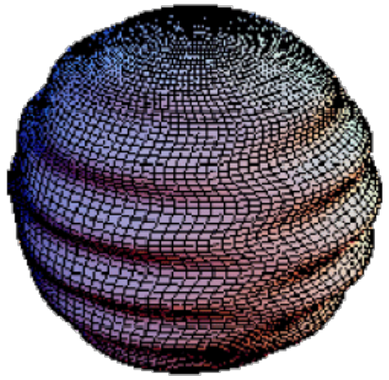


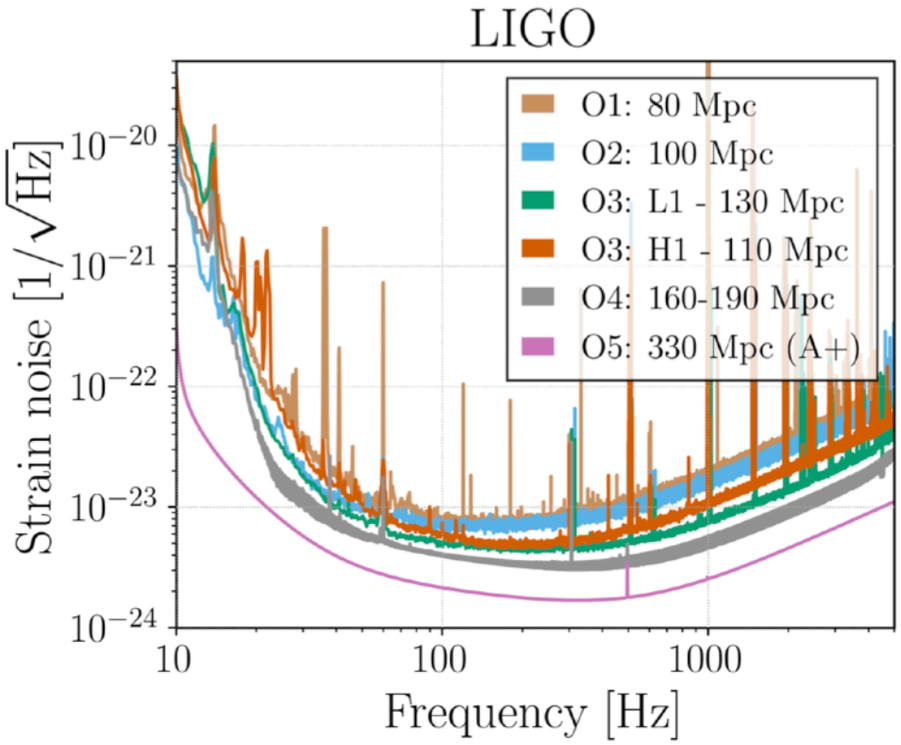
SUPER NOVA

PULSER



STOCHASTIC BACKGROUND



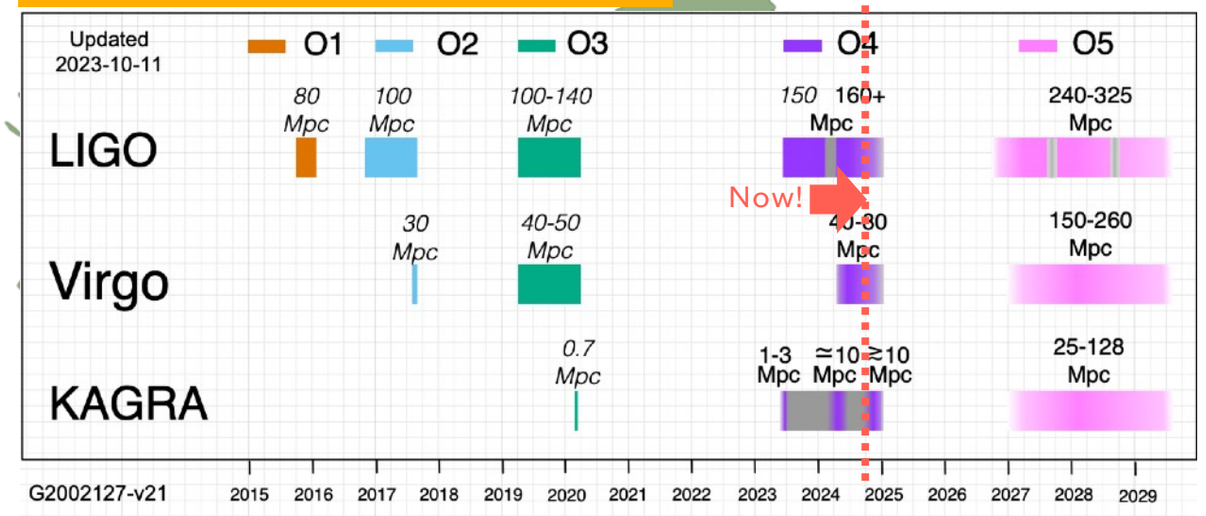


- Dual Recycring Fabry Perot Michelson interferometer

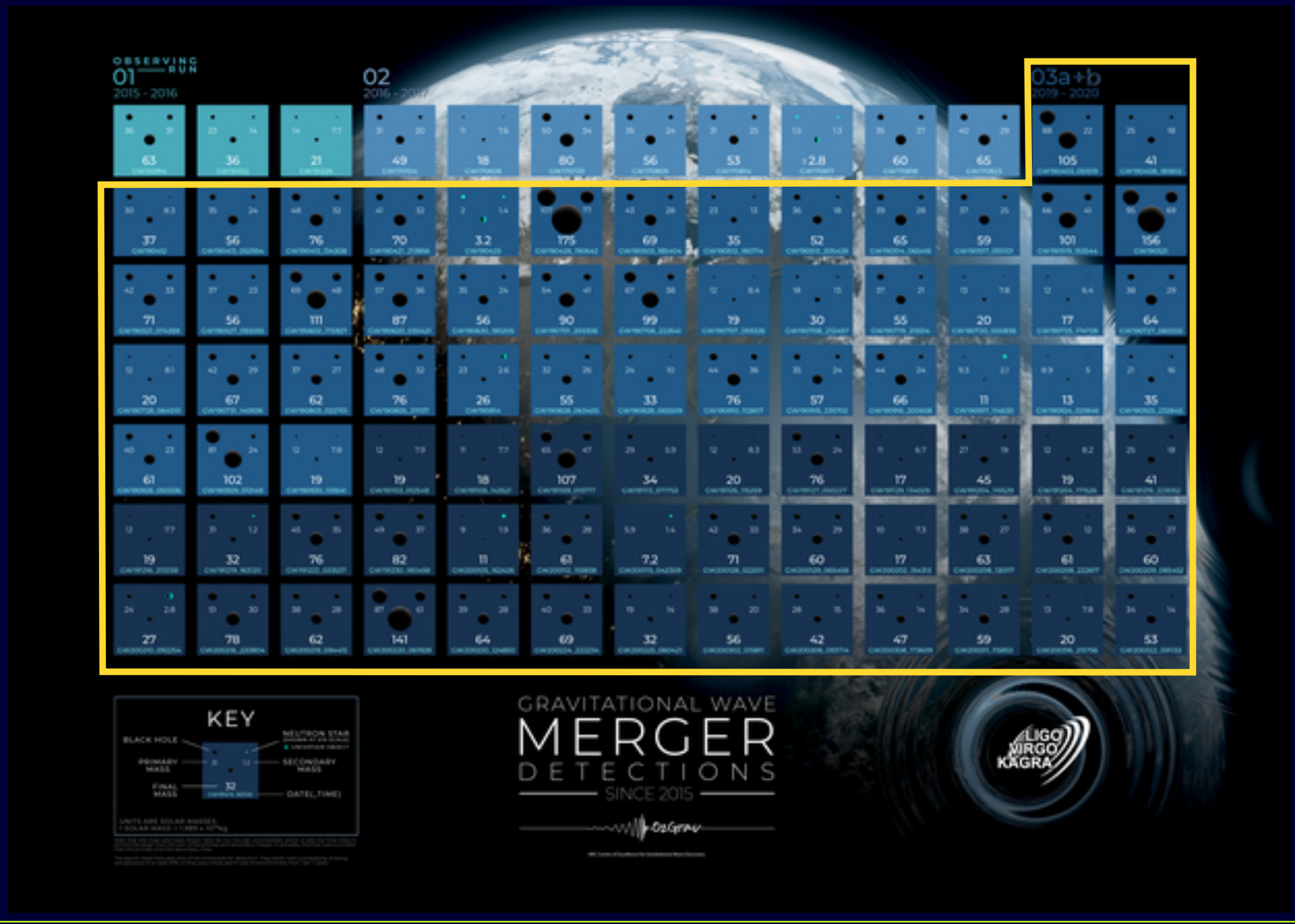
- Frequency 10Hz-5000Hz

Gravitational wave observation network

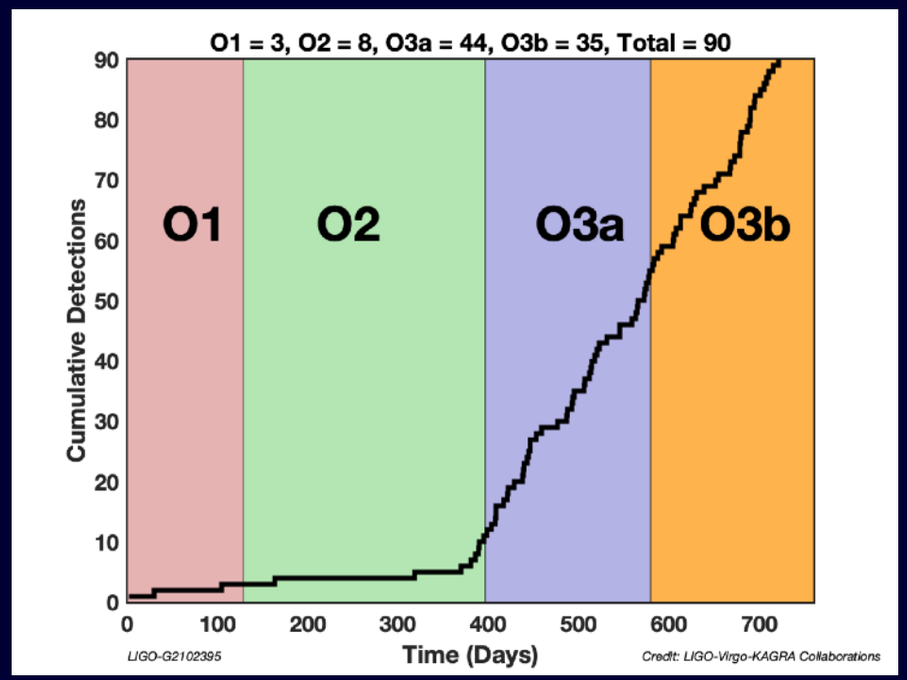
O4 will finish at June. 7

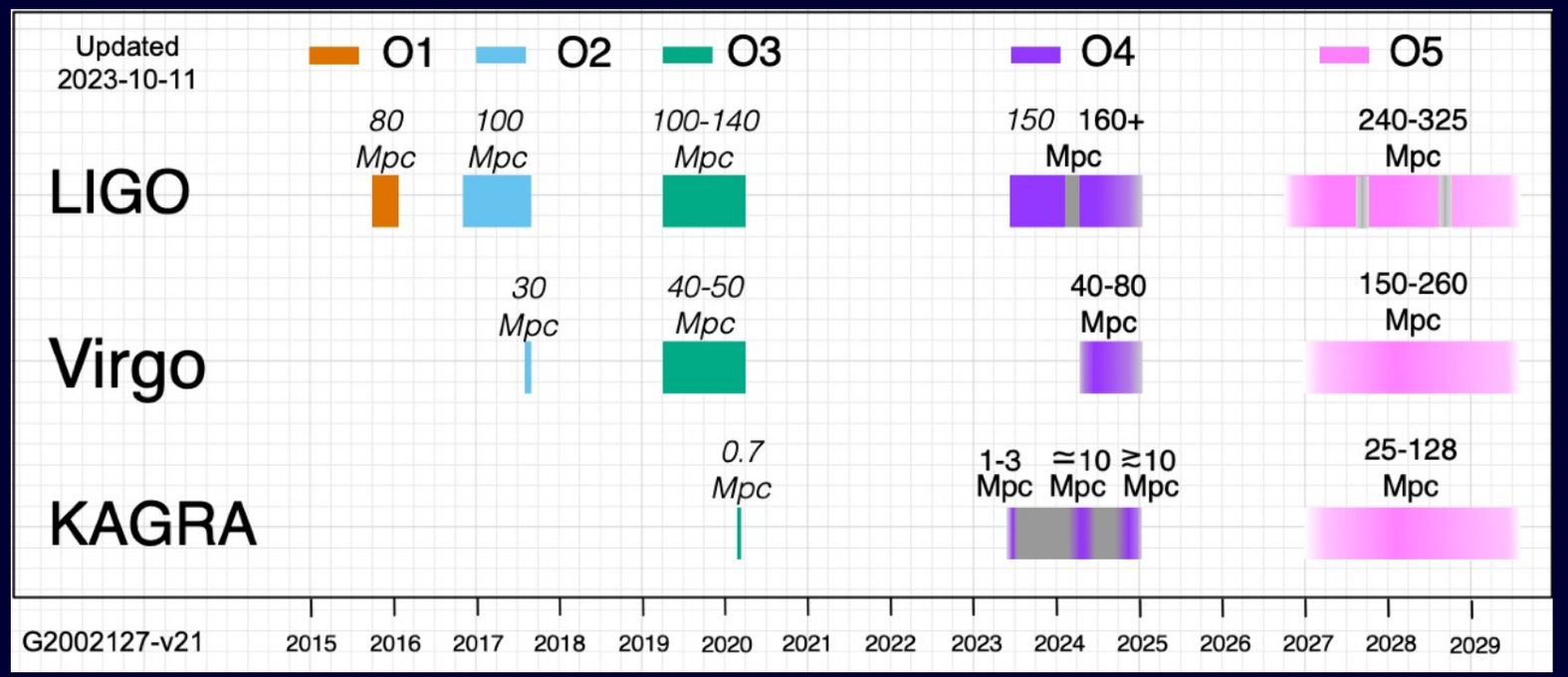


Observation 3 result (GWTC3)



Observation 4





- Observation 4b is ongoing. Every 2.8 days, LIGO and Virgo observe Black hole-Black hole merger event.

Publication and Data release

O4a (7month)	GWTC-4 (Early 2025)
O4b (9.5 month)	GWTC-5 (End of 2025)
O4c (4.5 month)	GWTC-6 (2026)

Significant contribution for O4

New formula of sensing function

Current model (pyDARM)

$$C^{anti}(f) = H_c \exp(-2i\pi f\tau)\frac{1}{1+i\frac{f}{f_{cc}}}\frac{f^2}{f^2 - if_s\frac{f}{Q} + f_s^2}$$

$$C^{pro}(f) = H_c \exp(-2i\pi f\tau)\frac{1}{1+i\frac{f}{f_{cc}}}\frac{f^2}{f^2 + if_s\frac{f}{Q} - f_s^2}$$

$$\vec{\lambda}_C = \left(H_C \;\; f_{CC} \;\; \delta\tau_C \;\; f_S \;\; Q_S^{-1}\right)^T$$

Unify!

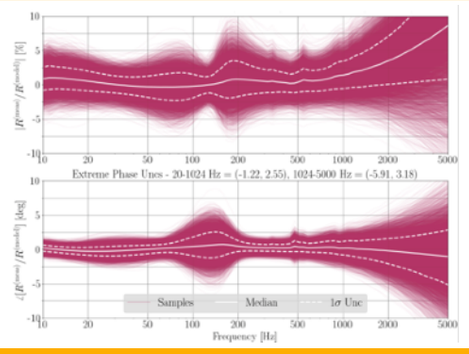
New formula

$$C^{[2]}(f) = H_c \exp(-2i\pi f\tau)\frac{1}{1+i\frac{f}{f_{cc}}}\frac{f^2}{f^2 - 2if_s^2\frac{f}{f_{cc}} + f_s^2}$$

$$\vec{\lambda}_C = \left(H_C \;\; f_{CC} \;\; \delta\tau_C \;\; f_S^2\right)^T$$

New formula is accepted for current LIGO analysis

pyDARM development (systematic error)



New software is released and used in Analysis

Half members are from NCU.

Contributed FIR filter, MCMC, GPR. and Time dependent collection factor

front-end and low latency analysis on site

You-Ru Lee and Avani Patel will go to LLO.

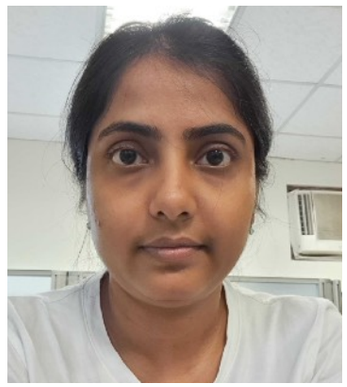
You-Ru will analyze all calibration data in O4 (Jan-Mar).

Avani Patel woll go LLO (Apl.-May.)

All detected events are calculated by these achievement!

Study for Future LIGO

Future LIGO



Avani's talk

2015-2029(O1-O5)

- LIGO-Virgo-KAGRA (Improve coating and software)

2030-2035(Post-O5)

- Upgrade of LIGO Hanford and Livingston 100kg test mass

Daiki Tanabe found new systematic error

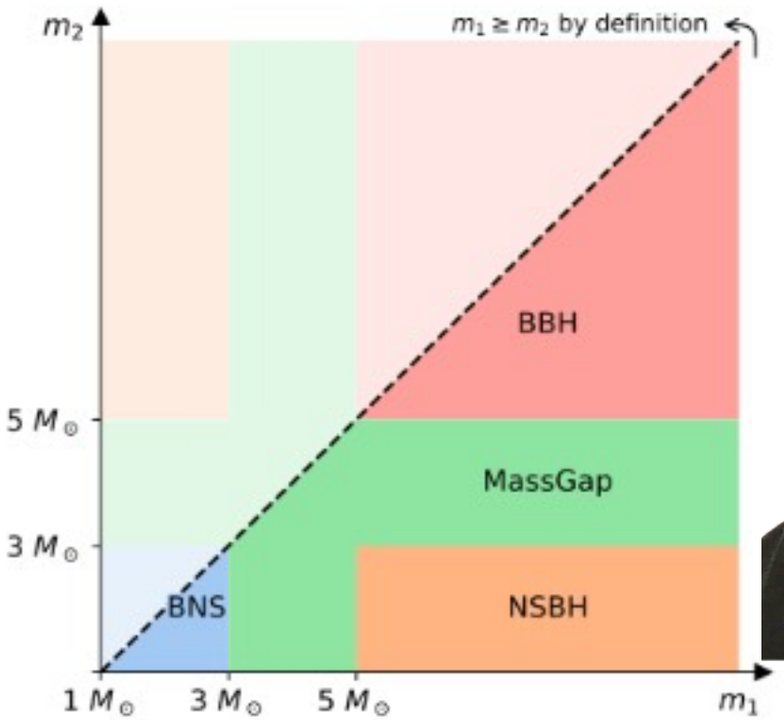
- LIGO Aundha (The third observatory)
- LIGO Voyager upgrade (Caltech 40m →LLO or LHO)

Kun-Yao's talk

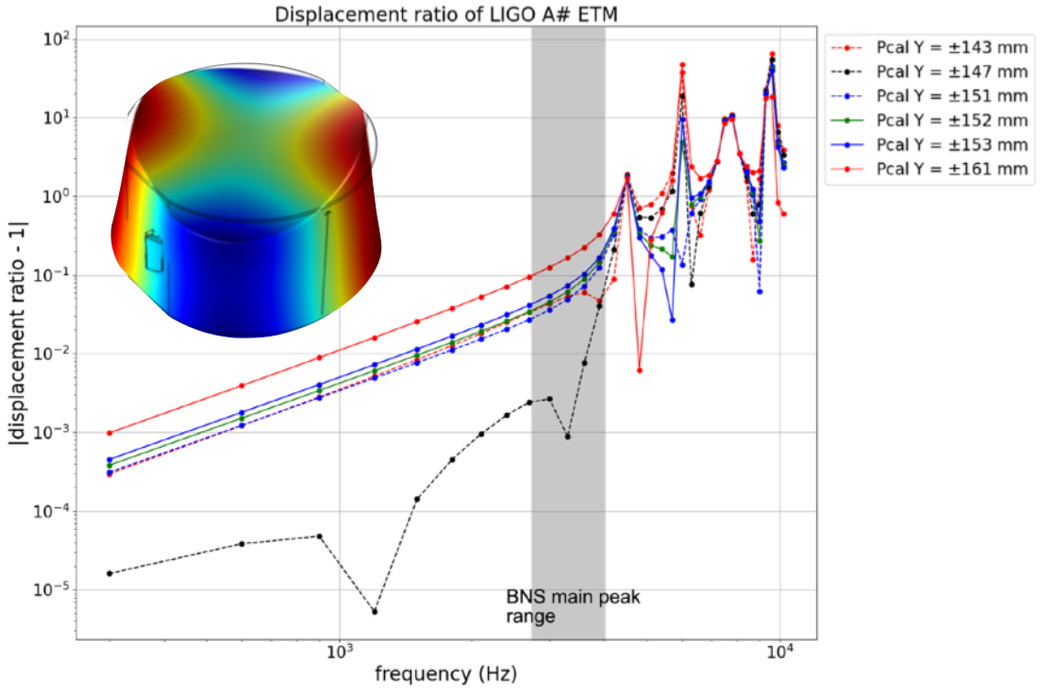
2035-2045

- Cosmic Explorer - Einstein telescope - LIGO india

Border of NS and BH?

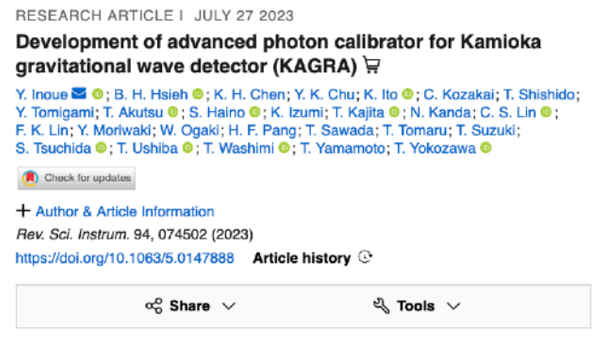


Dr.Daiki Tanabe found new systematic error due to internal mode of 100kg test mass.



- Mass gap region is unsolved problem for NS and BH science
- Depend on spin and Equation of state of NS
- Observation of second peak of NS-NS marger (2000-4000Hz region)
- Require O(100kg) test mass due to statistical error (plan to install it in Post-O5)
- The internal mode peaks in around the BNS second peak region.

3G Photon Calibrator



RESEARCH ARTICLE | JULY 27 2023

Development of advanced photon calibrator for Kamioka gravitational wave detector (KAGRA)

Y. Inoue; B. H. Hsieh; K. H. Chen; Y. K. Chu; K. Ito; C. Kozakai; T. Shishido; Y. Tomigami; T. Akutsu; S. Haino; K. Izumi; T. Kajita; N. Kanda; C. S. Lin; F. K. Lin; Y. Moriwaki; W. Ogaki; H. F. Pang; T. Sawada; T. Tomaru; T. Suzuki; S. Tsuchida; T. Ushiba; T. Washimi; T. Yamamoto; T. Yokozawa

Check for updates

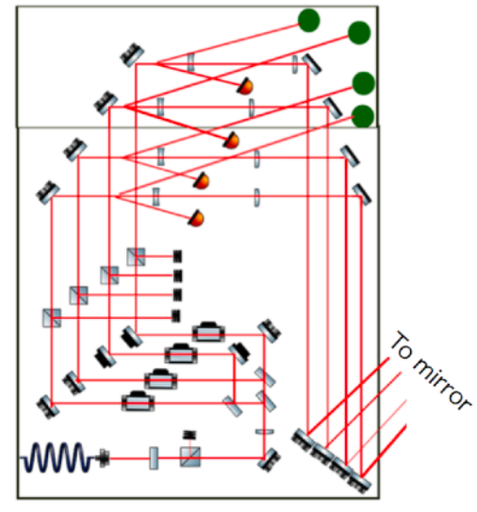
Author & Article Information

Rev. Sci. Instrum. 94, 074502 (2023)

https://doi.org/10.1063/5.0147888 **Article history**

Share Tools

4G Photon Calibrator



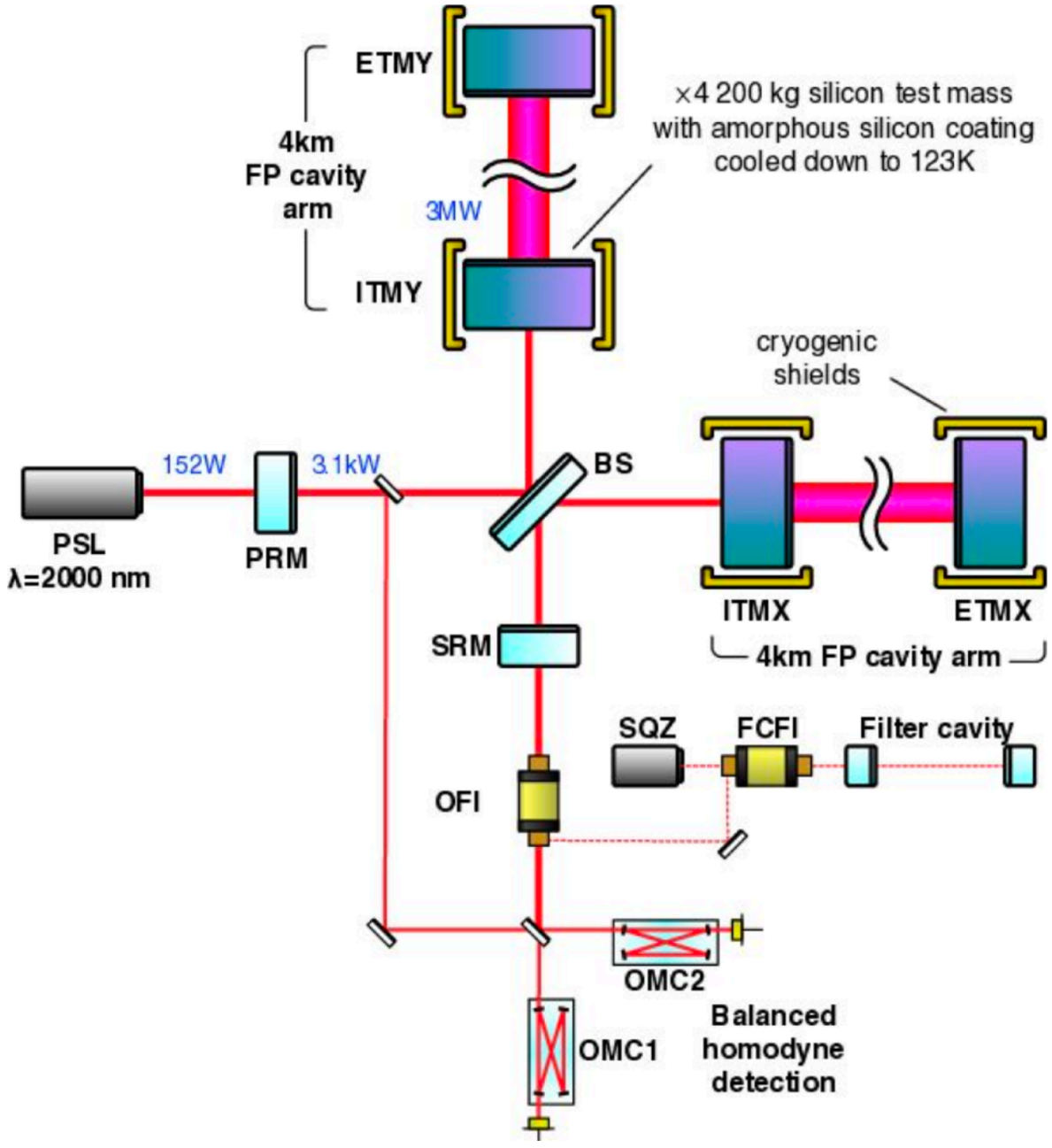
LIGO Aundha observatory

- Reuse LHO second detector (H2)
- Approved by government in India
- Stochastic background systematic error for next discovery (Collaborate with Dr.K.Shivraj)
  - Next MOU on January!

- Avani visit ICUAA and discuss the future collaboration
  - support software test of Initial calibration and commissioning (Avani)
- Preparing NSF proposal for joint observation

LIGO Voyager

- Future experiment after O5
- Cryogenic LIGO
- Coating study is ongoing.
- Cryogenic coating characterization system is necessary.



Low Pressure CVD Coating

Kun-Yao's talk

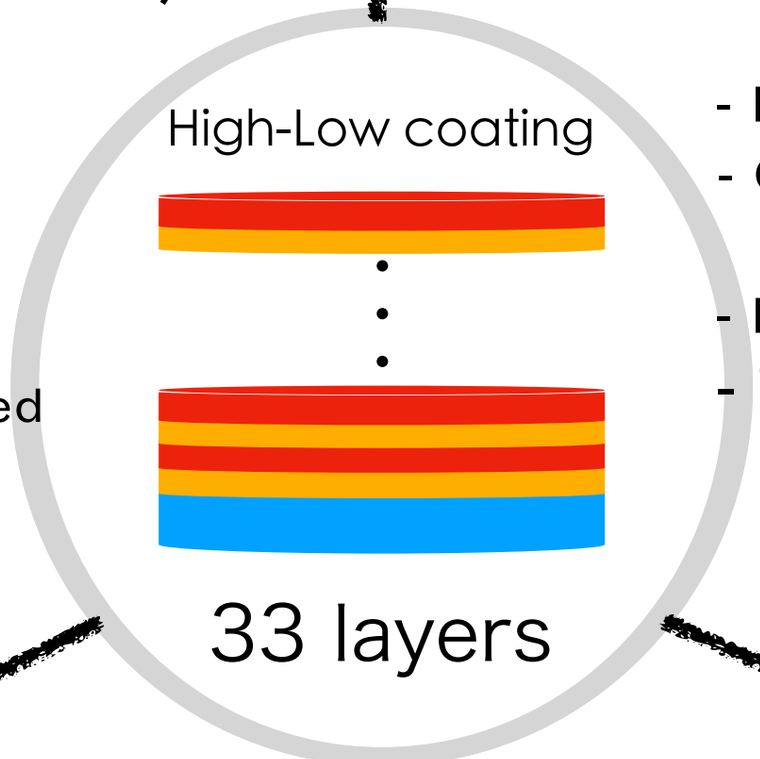
a-Si coating (n =~3.48)

-Fabrication: on going

-Optical absorption: Ongoing

- Mechanical loss: Ongoing

-Stanford and UCB demonstrated



SiNO coating (n =~1.62)

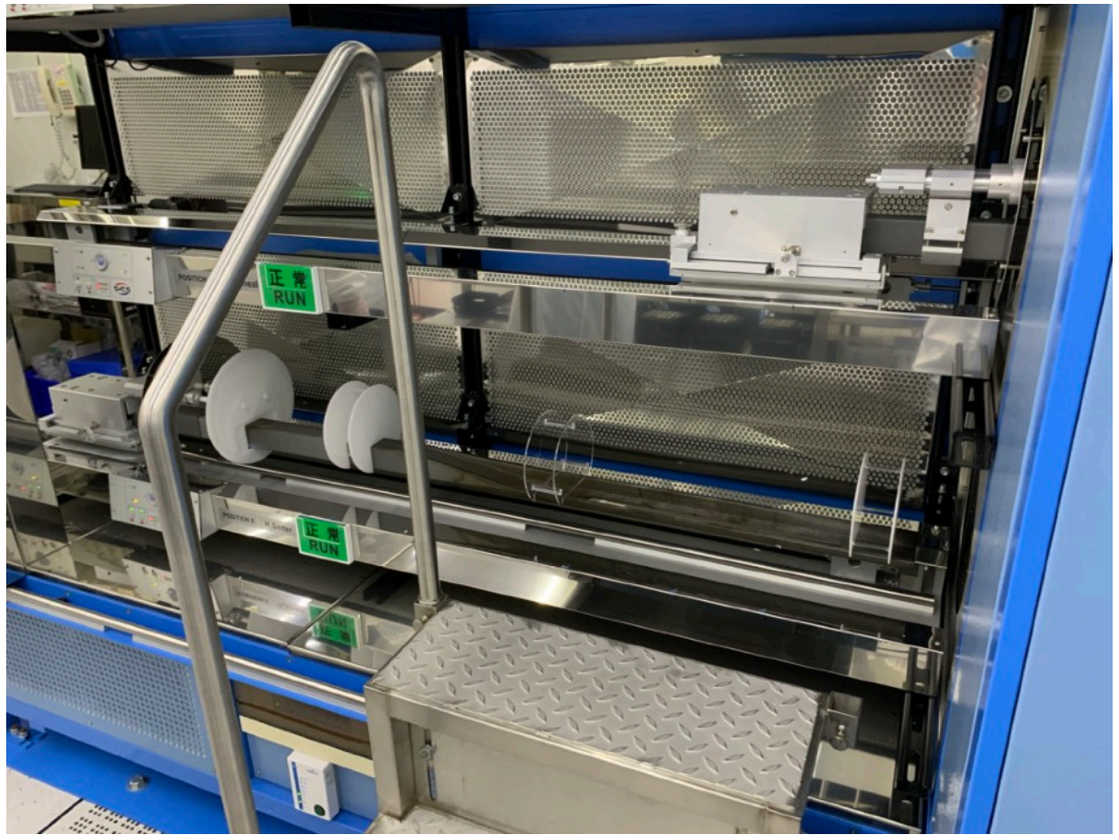
- Fabrication: Done
- Optical absorption:2.8e-6@1550nm (Preliminary)
- Mechanical loss: Ongoing
- Taiwan demonstrated with PECVD

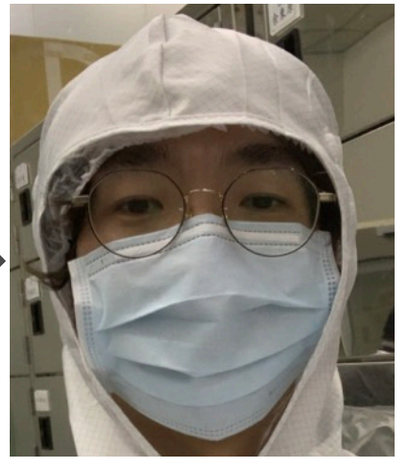
SiN coating (n =~2.68)

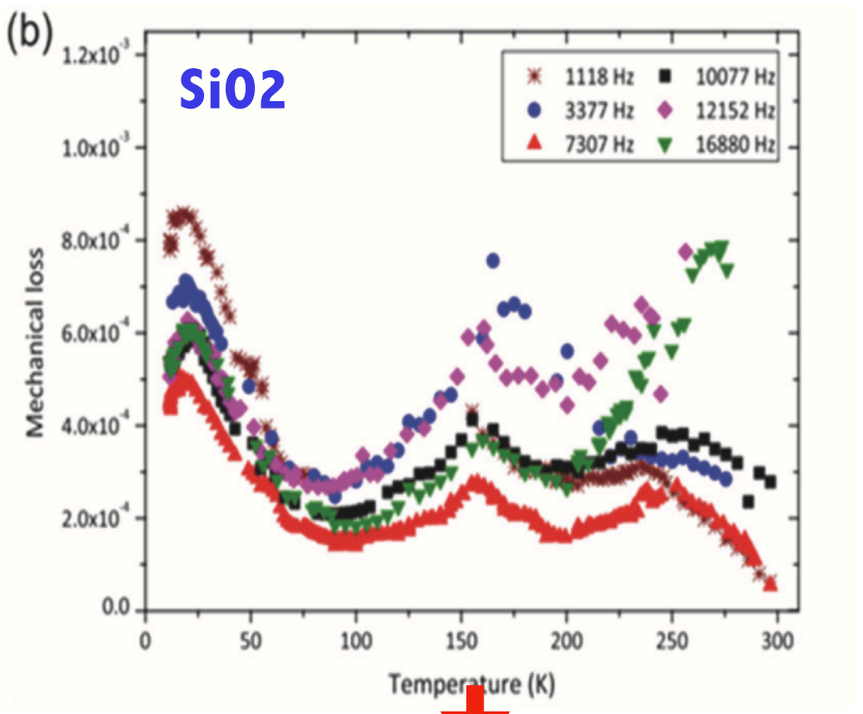
- Fabrication: Done
- Optical absorption:5.8e-6@1550nm
- Mechanical loss: Ongoing
- Taiwan demonstrated with PECVD

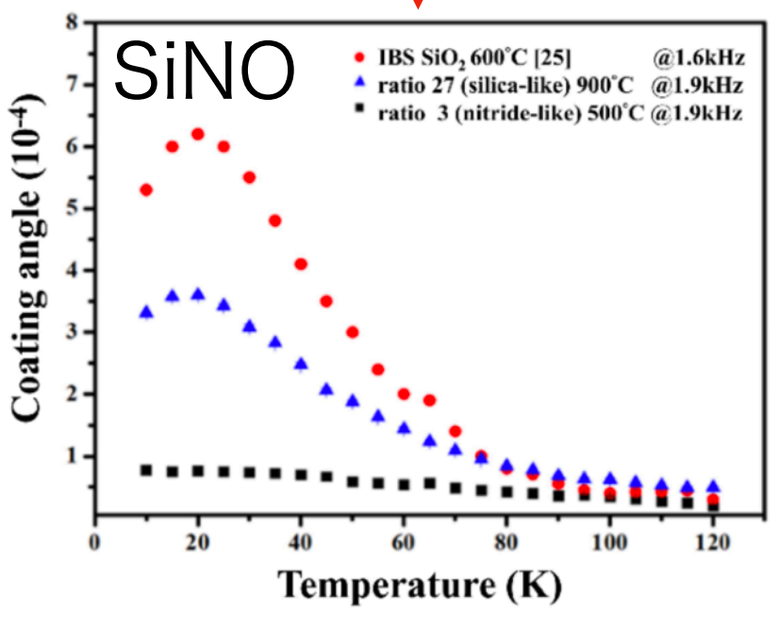
Nobody have tried three combinations! Candidate of LIGO voyager.

Collaboration with Caltech







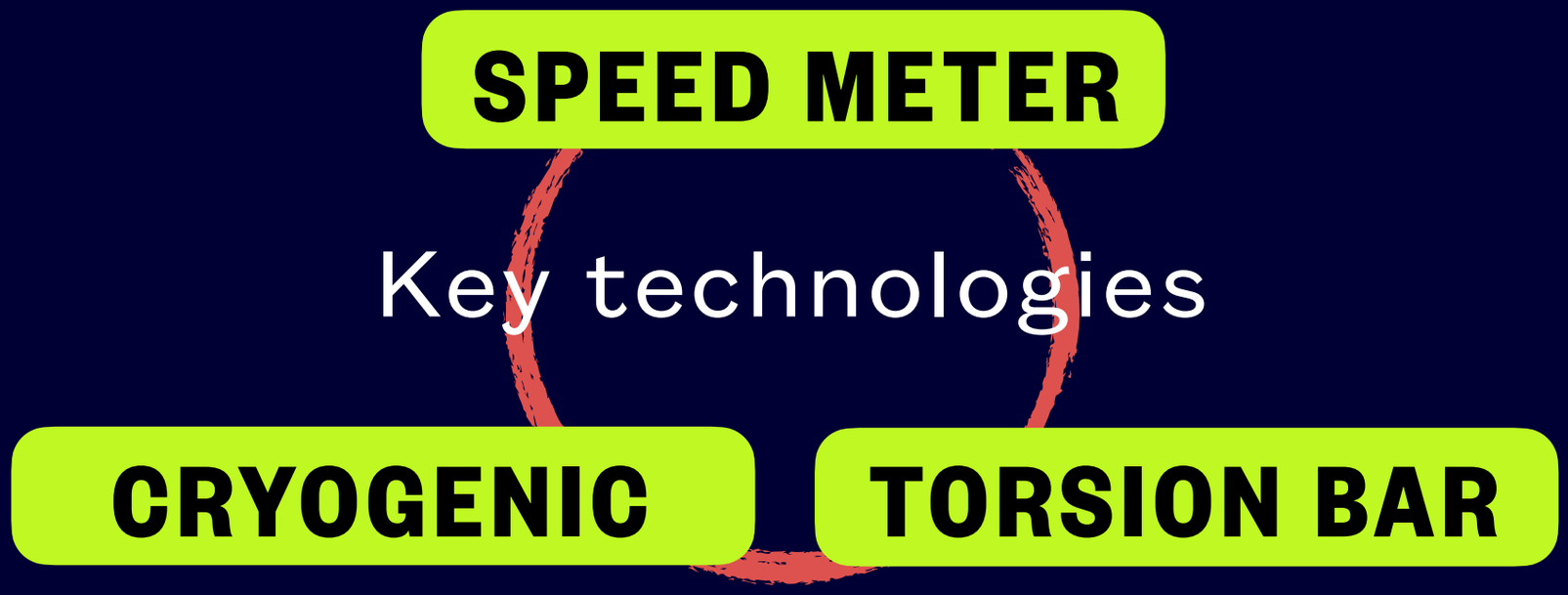


Collaborate with Prof.R.Adhikari in Caltech

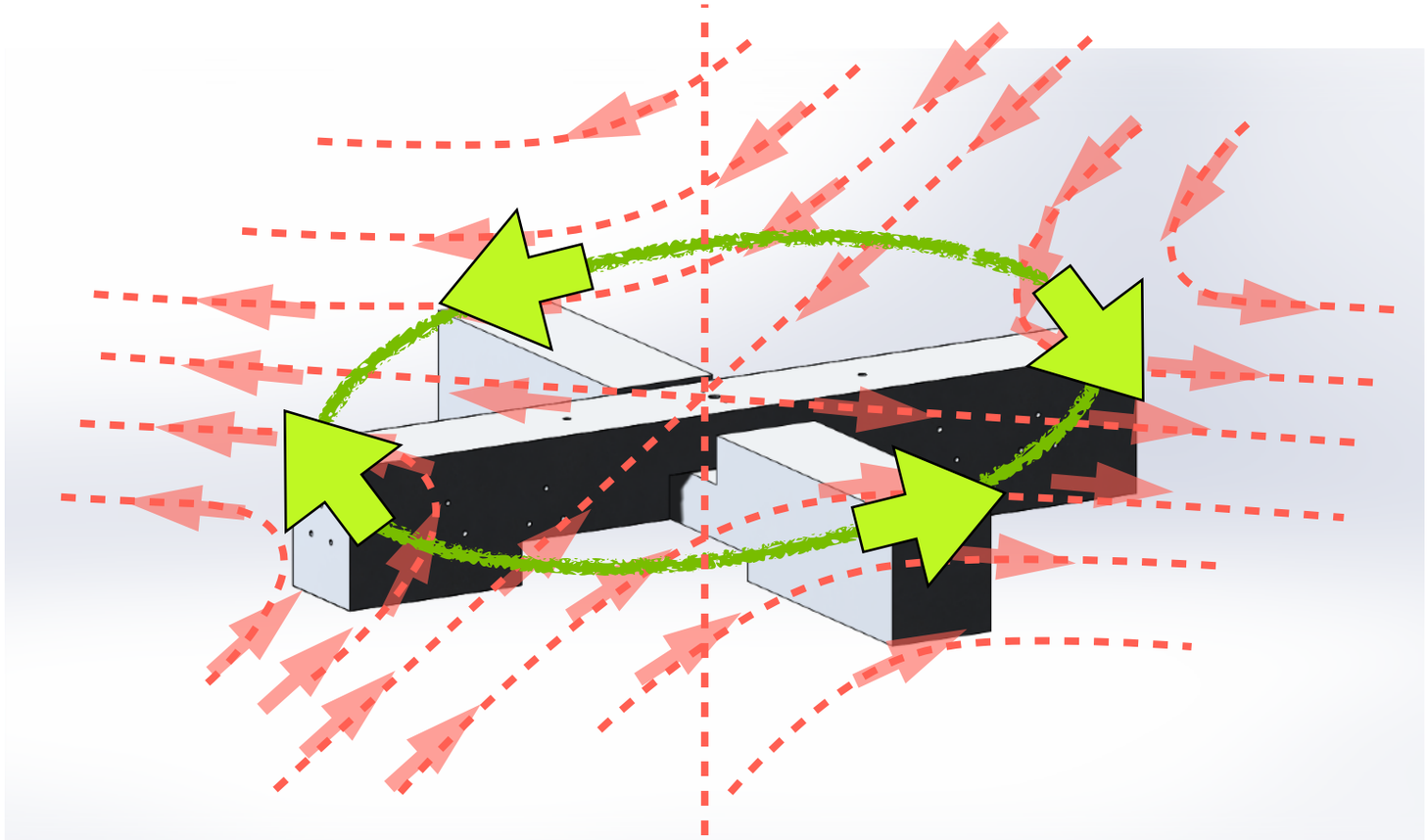
R&D in Taiwan

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

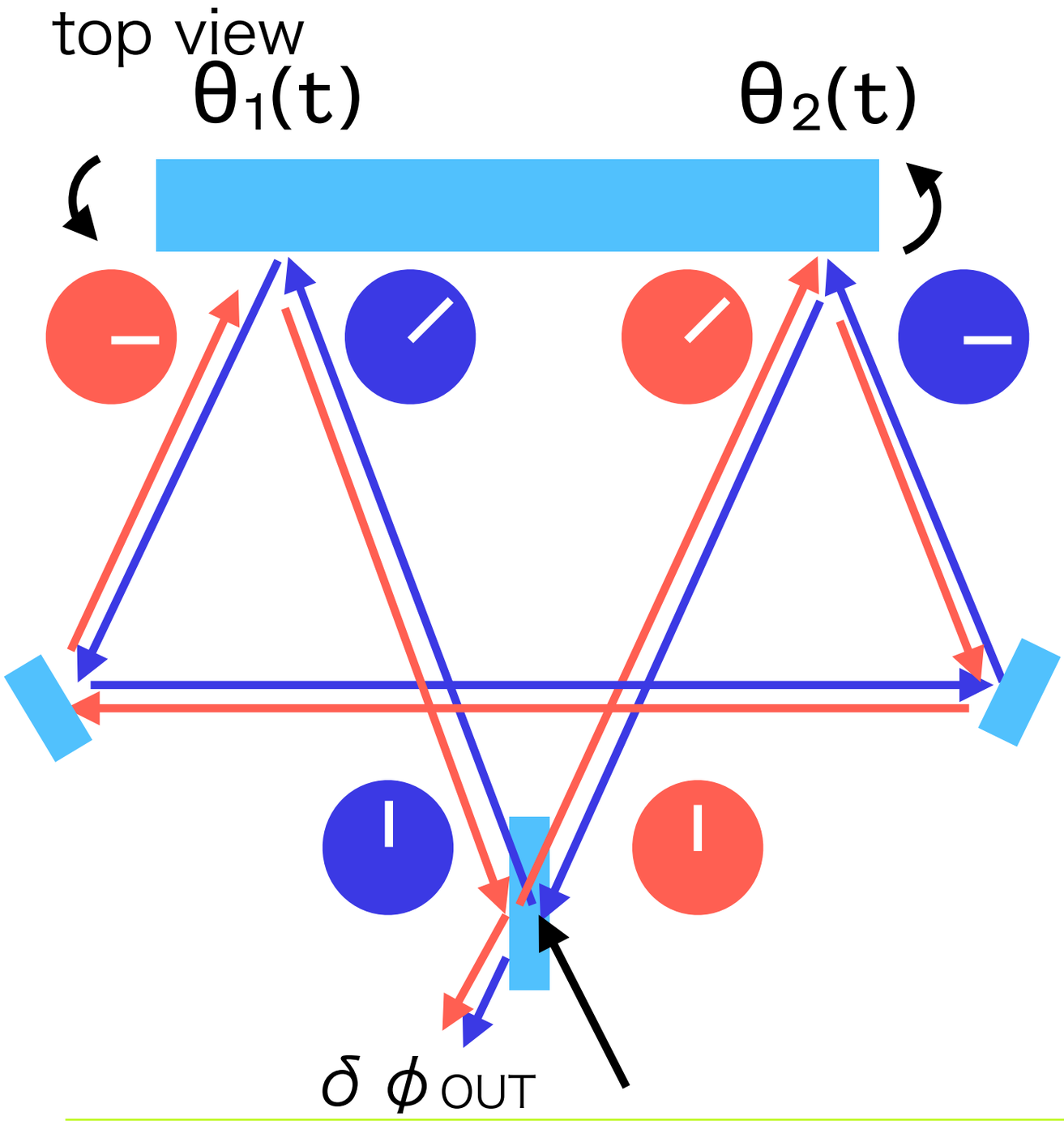


Torsion bar in Gravitational Wave



- Torsion bars keep staying through the metric
- Tensor mode metric perturbation (= Gravitational wave) change the relative angle of cross bars
- By measuring relative angle, we can reconstruct the gravitational wave foam, h(t).

Speed meter technique

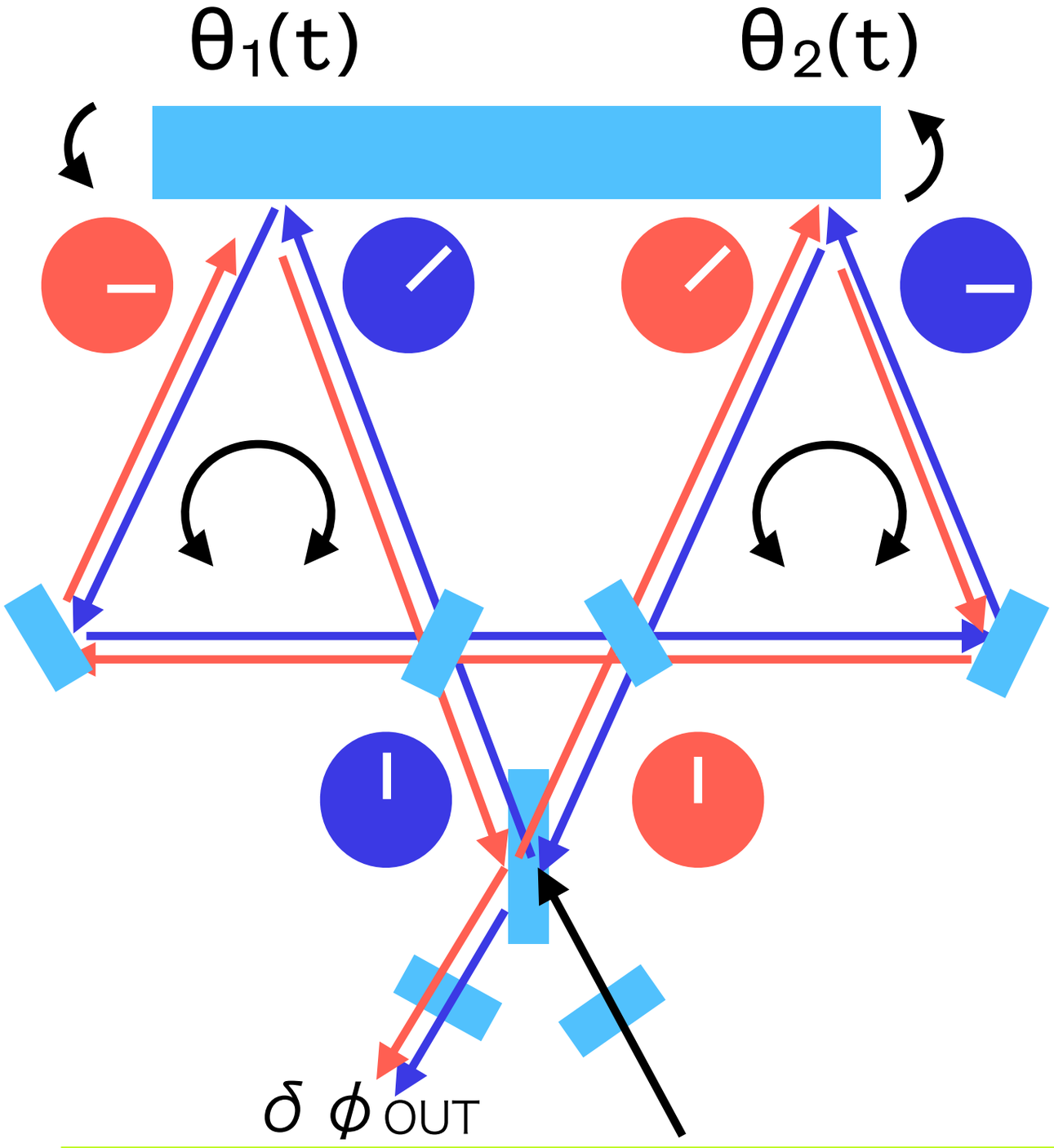


- $\delta\ \phi_{CW} \propto\ \theta_1(t)+\theta_2(t+\tau)$
- $\delta\ \phi_{CCW} \propto\ \theta_2(t)+\theta_1(t+\tau)$
- $\delta\ \phi_{OUT}=\tau\ (\omega_{CCW}-\omega_{CW})$

- We measure the phase delay of CW and CCW beams.
- Time interval, τ, should be same.

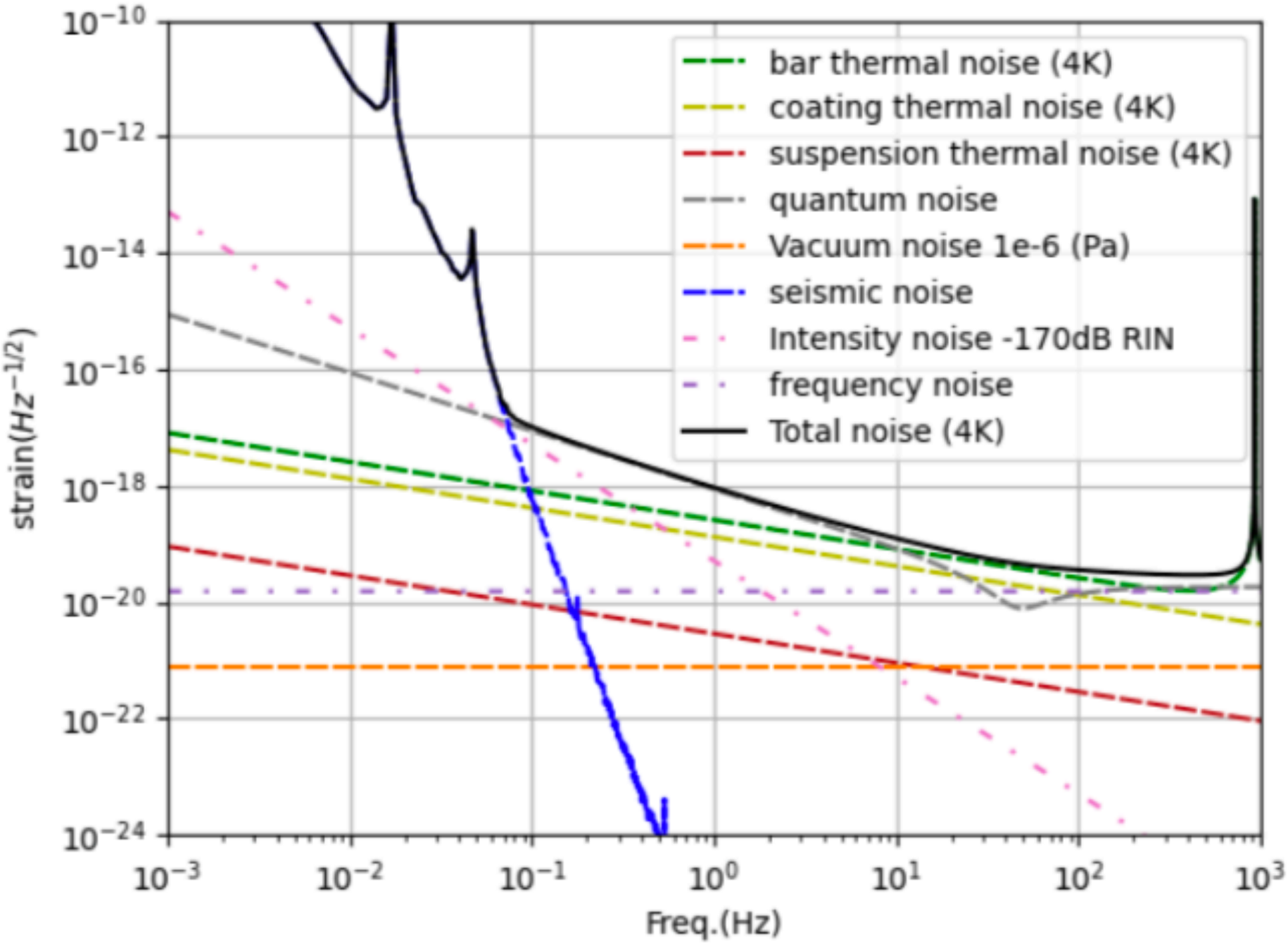
- Similar to Sagnac Gyroscope.

Speed meter technique

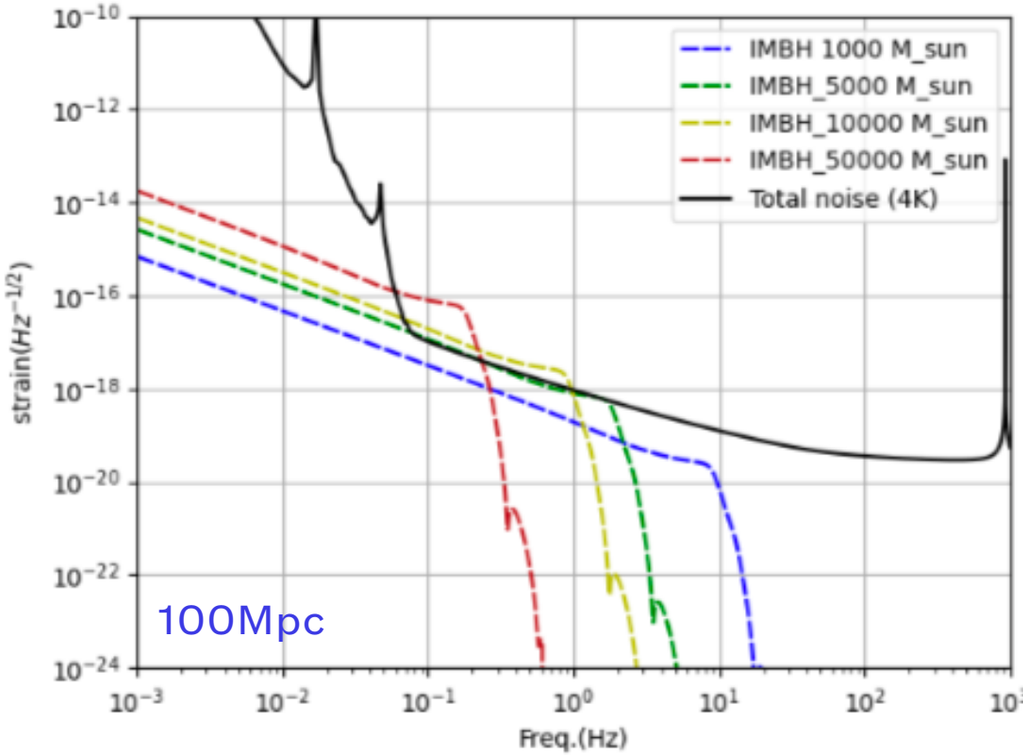


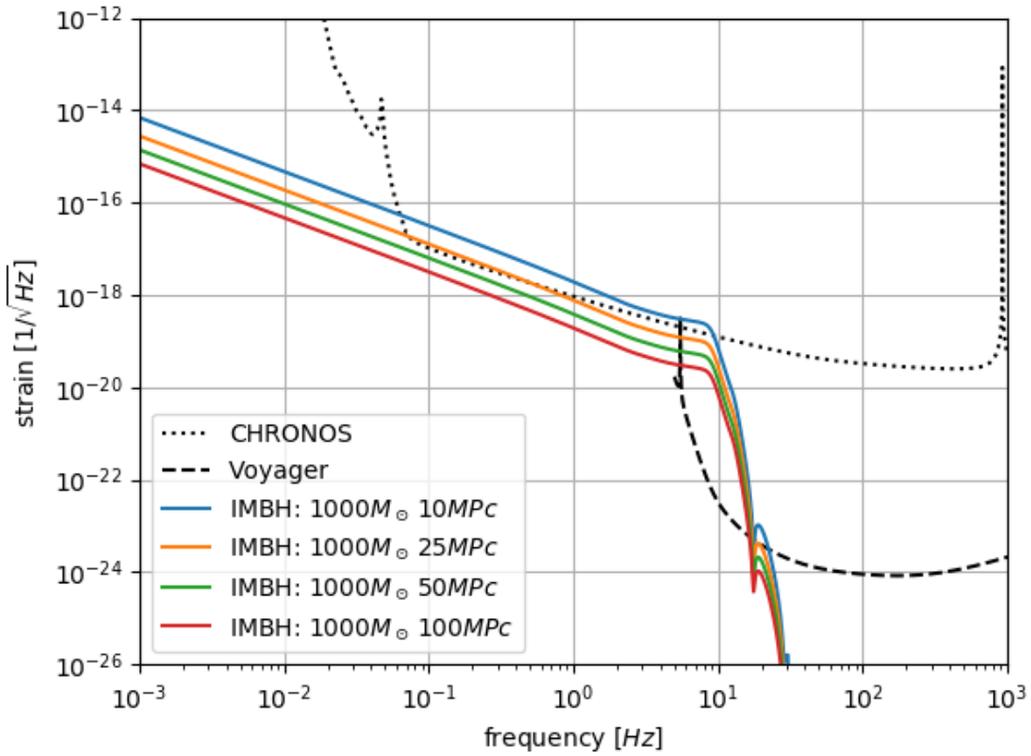
- $\delta\,\phi_{CW} \propto\ \theta_1(t)+\theta_2(t+\tau)$
- $\delta\,\phi_{CCW} \propto\ \theta_2(t)+\theta_1(t+\tau)$
- $\delta\,\phi_{OUT}=\tau\,(\omega_{CCW}-\omega_{CW})$
- Install the ring cavity to amplify the signal.
- Power recycling cavity and Signal recycling cavity are also employed
- Differential angular velocity.
- High finesse coating

Sensitivity

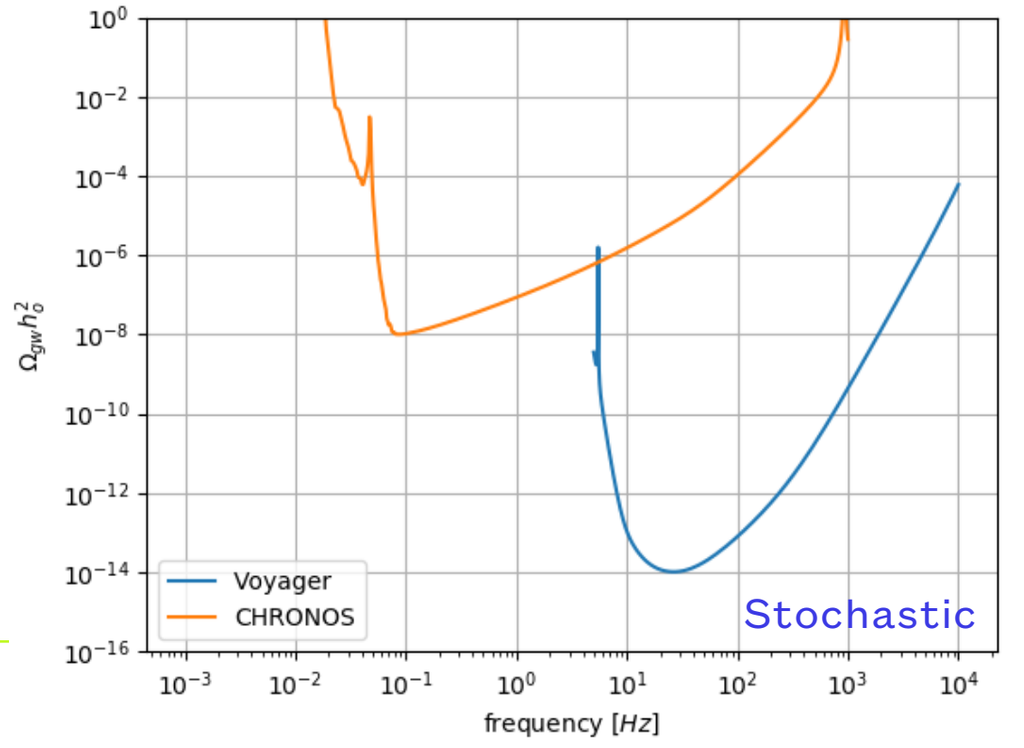


Expected Science

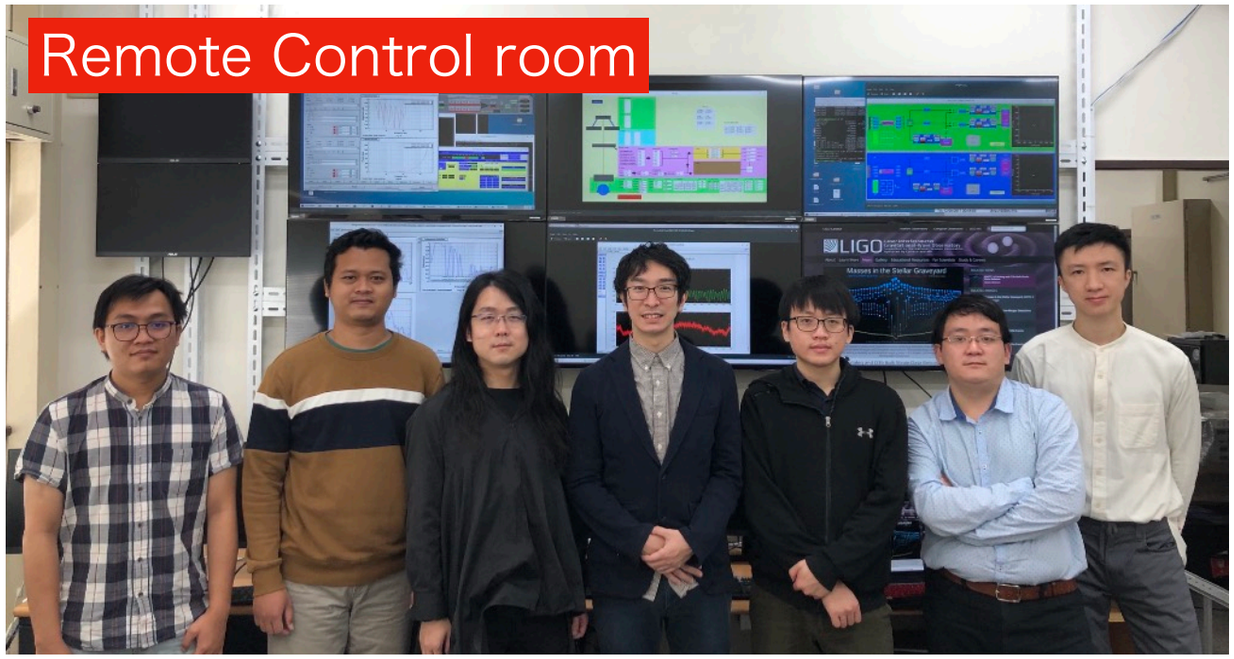




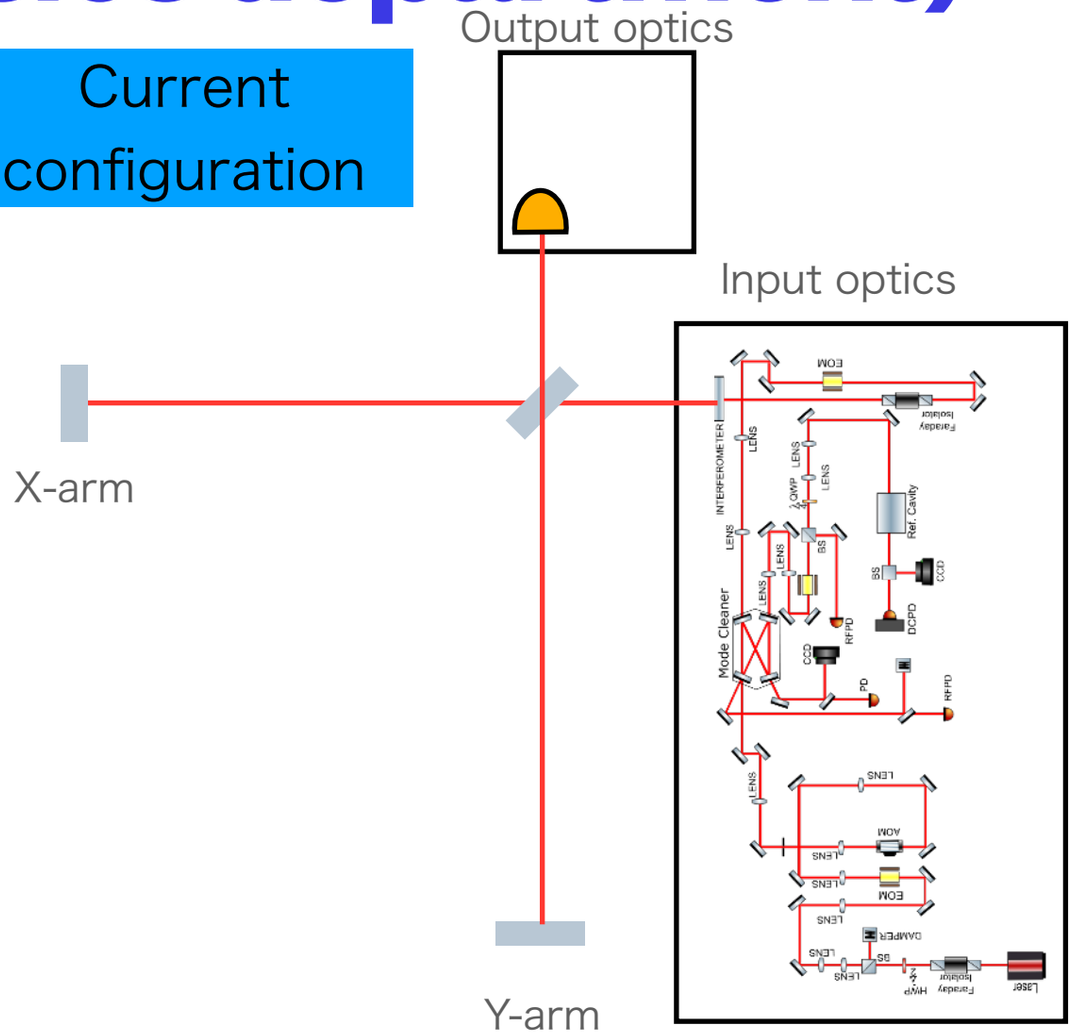
- O(10⁴M◉) Black hole marger
- Stochastic background
- Newtonian Noise



NCU observatory (Physics department)

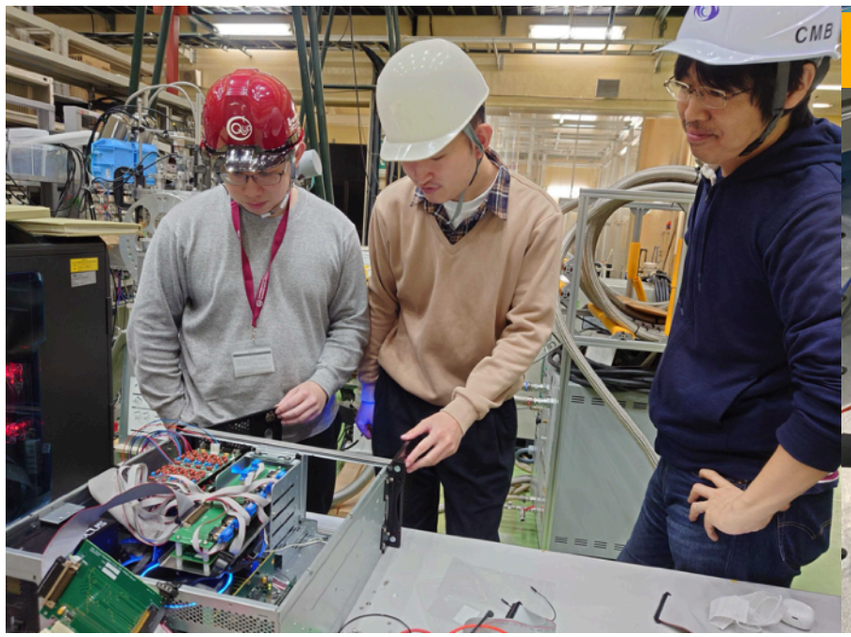


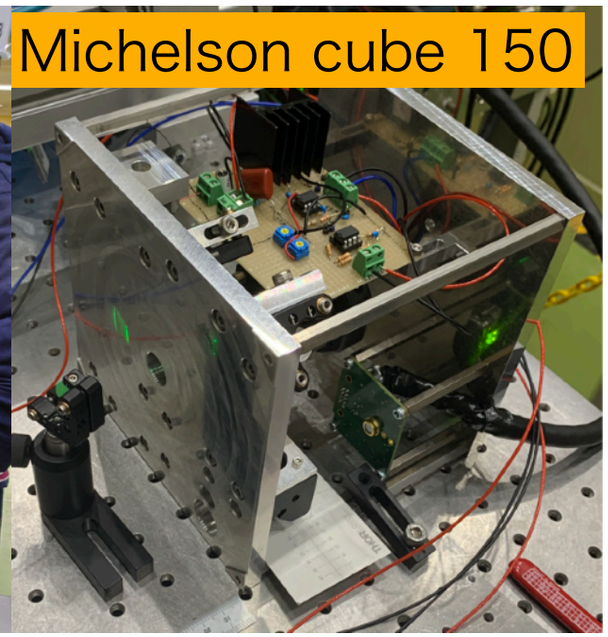
Current configuration



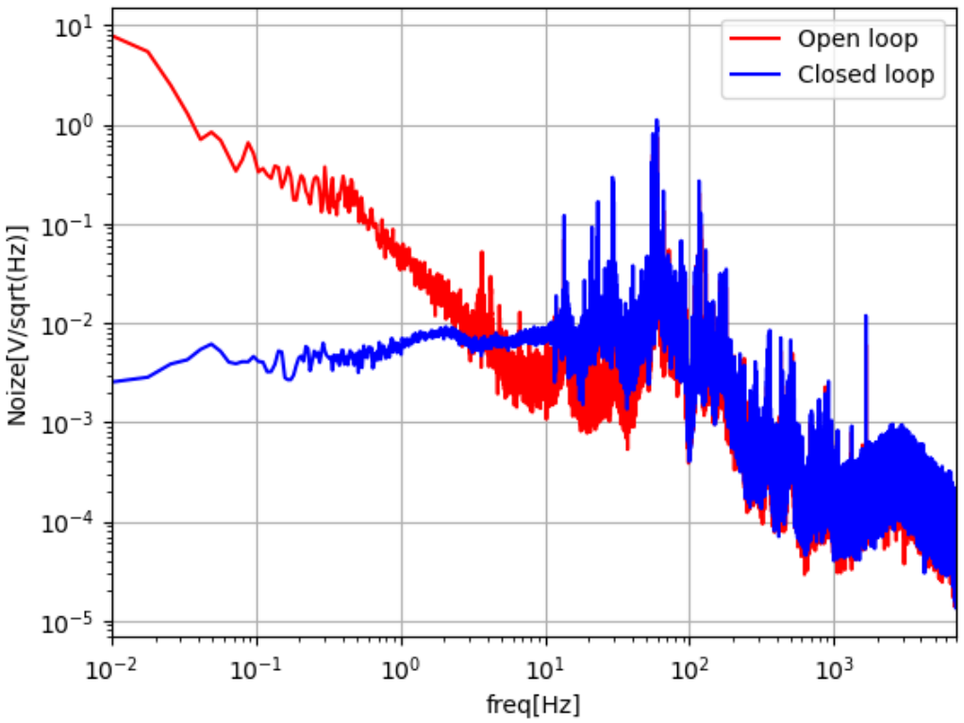
Develop the interferometer control technique for future experiment.

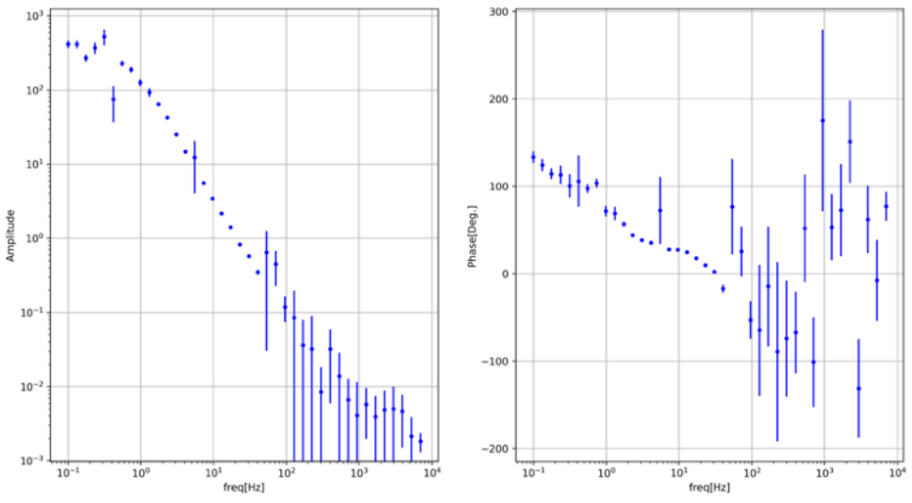
Collaboration with QUP/KEK





- Achieved feedback control in NCU
- Small Michelson interferometer for the local displacement sensor
- Improve NS sytem and Interferometer
- Collaborate with Prof.Masaya Hasegawa
- KEK/QUP will use the sensor for vibration isolation for cryogenic system
- Student stay in QUP/KEK 1.5 month for the test.



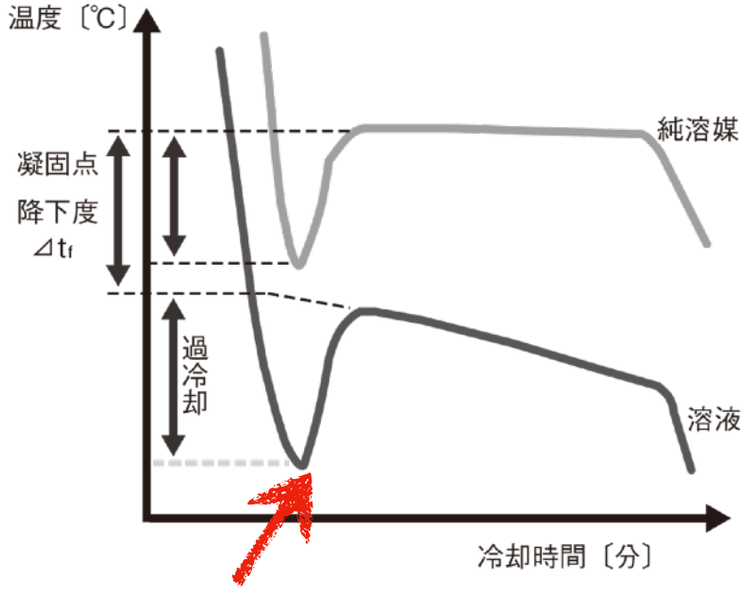


Middle fringe lock is achieved

Application of GW technology for 鮨

Michelin-starred chef: Izumi Kimura

Undercooling break



vibration + core

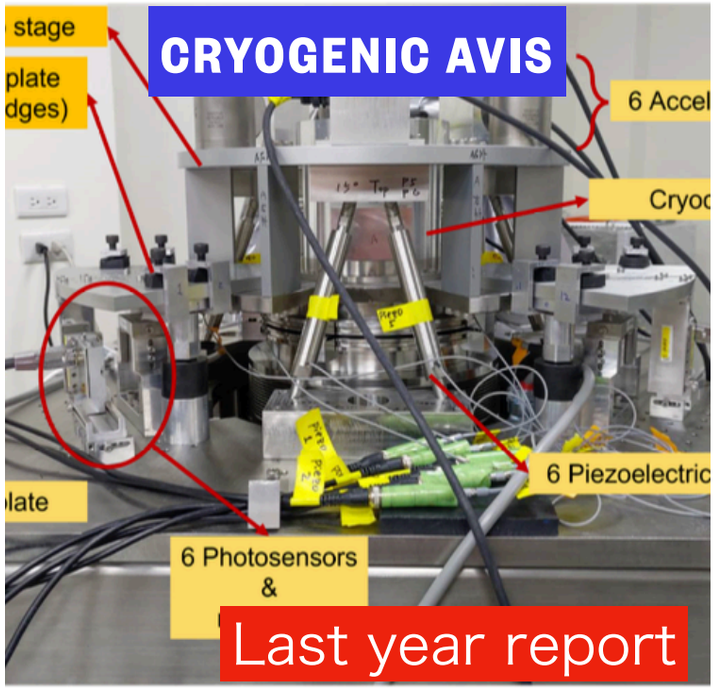
Cell of raw fish is broken by frozen process.

By controlling temperature and vibration,

he want to keep the undercooling state

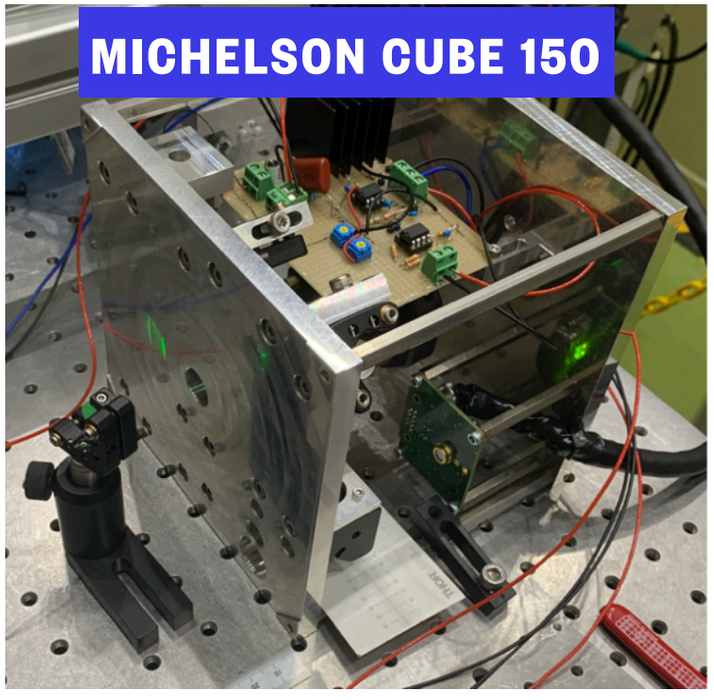
for raw fish. To test it, he ask me to build the cryogenic vibration isolation refrigerator with our technology.

Cryogenic Vibration Isolation System and 鮨

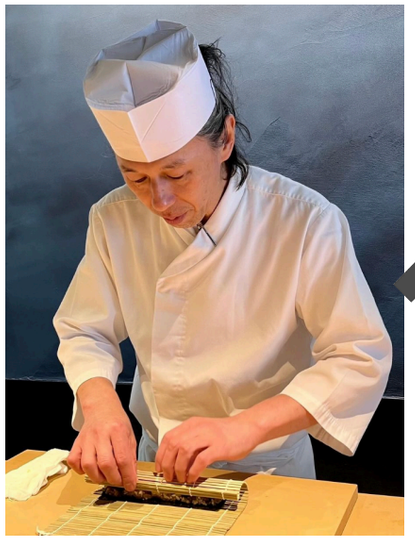


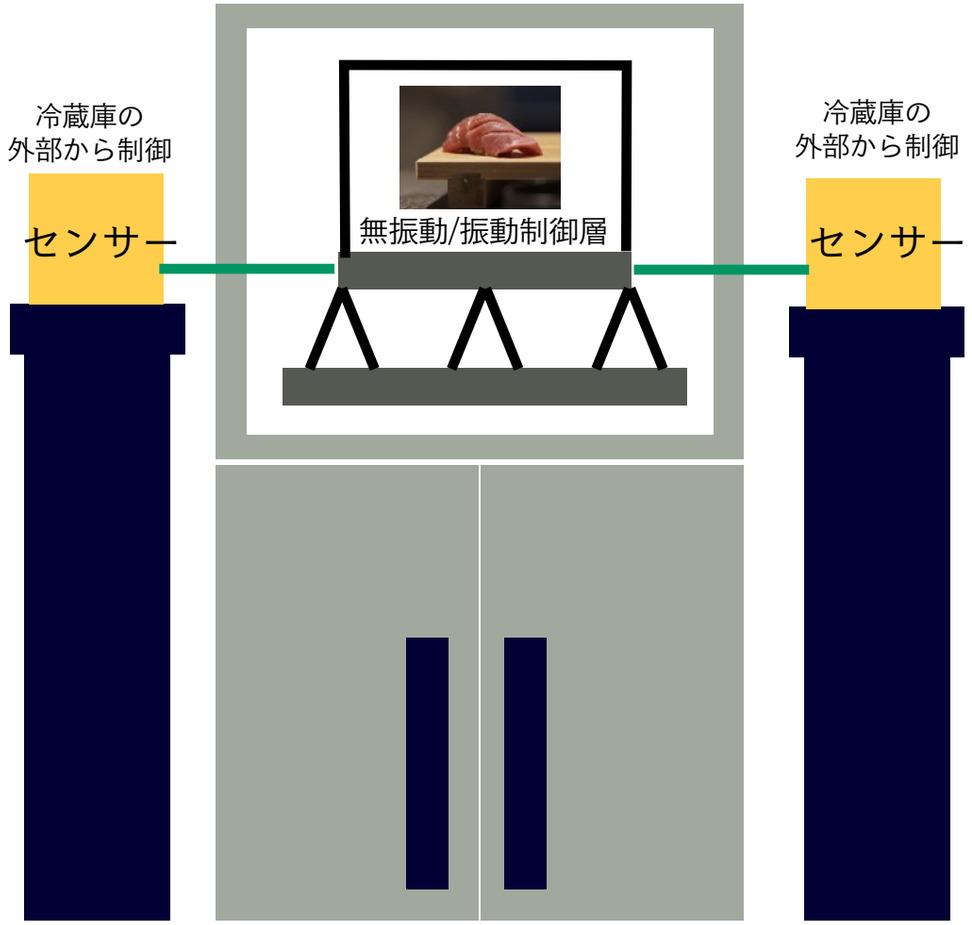
CRYOGENIC AVIS

Last year report



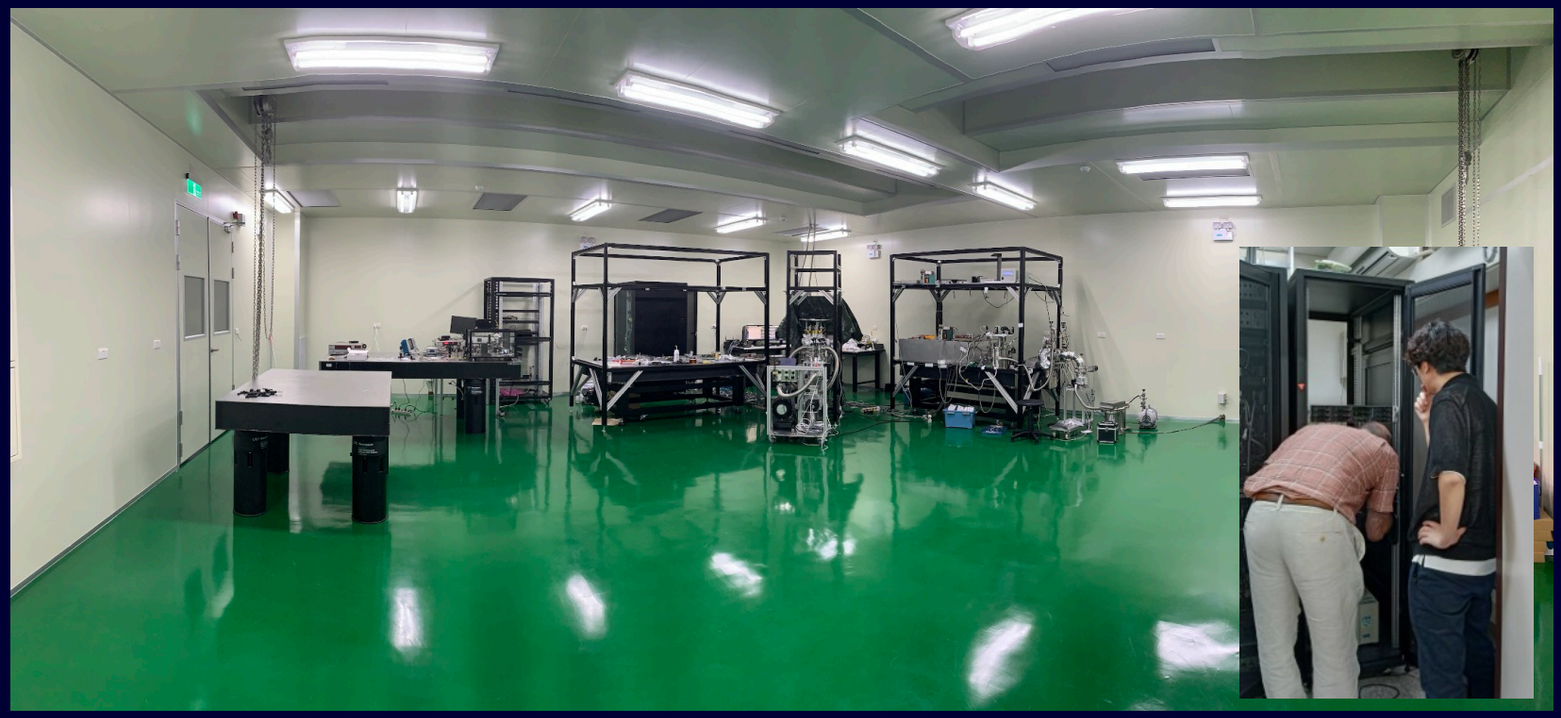
MICHELSON CUBE 150

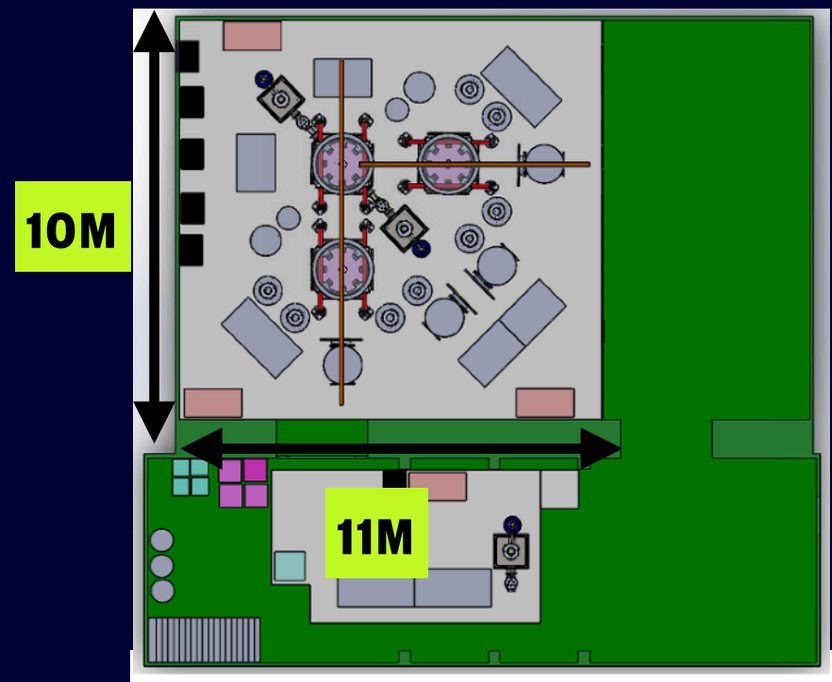


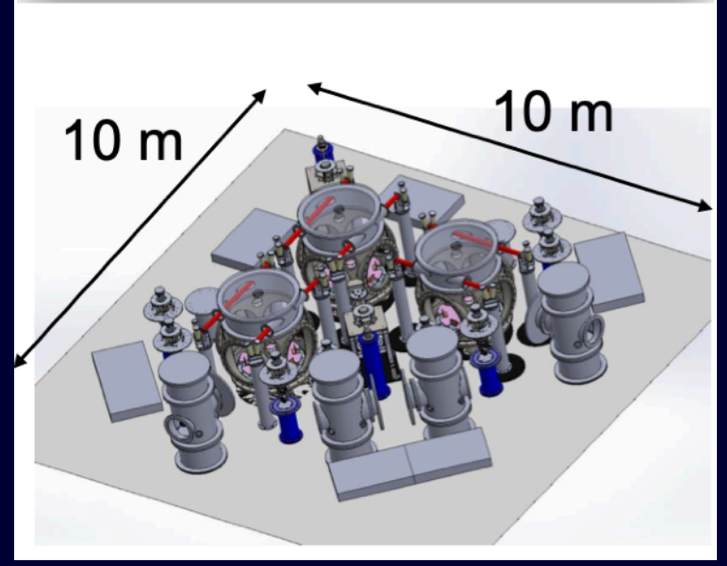


- Develop the keeping technology of raw fish with undercooling break phenomena.
- 220K demonstration with refrigerator.
- This is good demonstration for CHRONOS test.
- Izumi Kimua will visit Taiwan on 2025 Jan 13-14.
- If they decide to develop the system, he will provide instruments and human resources for R&D.
- we will collaborate with him and build the system in Taiwan.

Academia Sinica Gravitational physics Research Facility (*ASGRAF*)



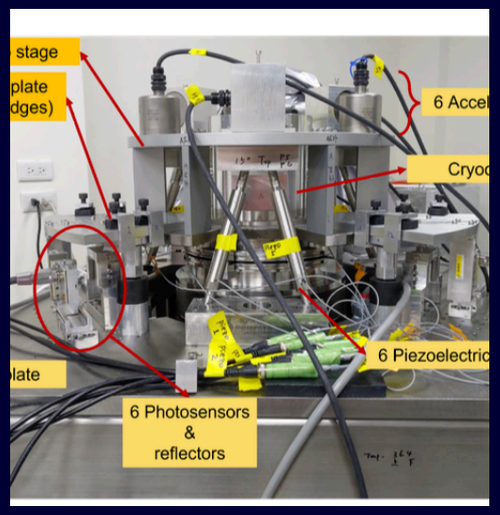




- Test facility for LIGO
- Controlled by LIGO's Digital Control System
- Class 10000 clean room
- Optical coating characterization instruments

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



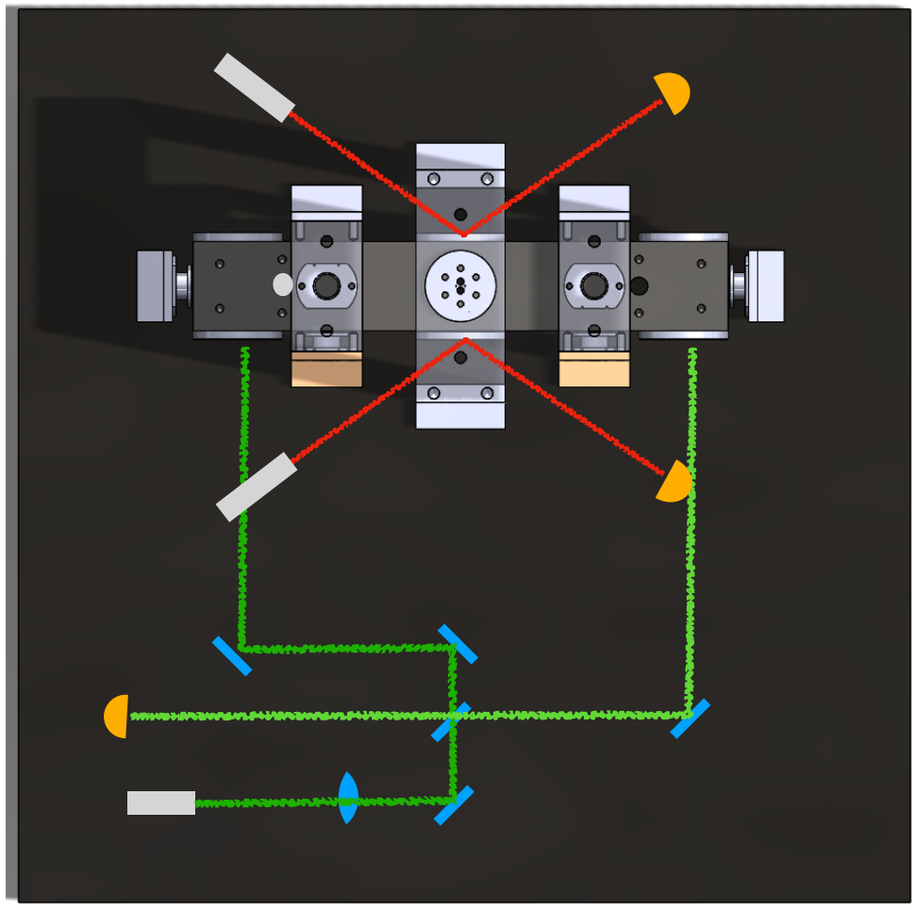
Key technologies

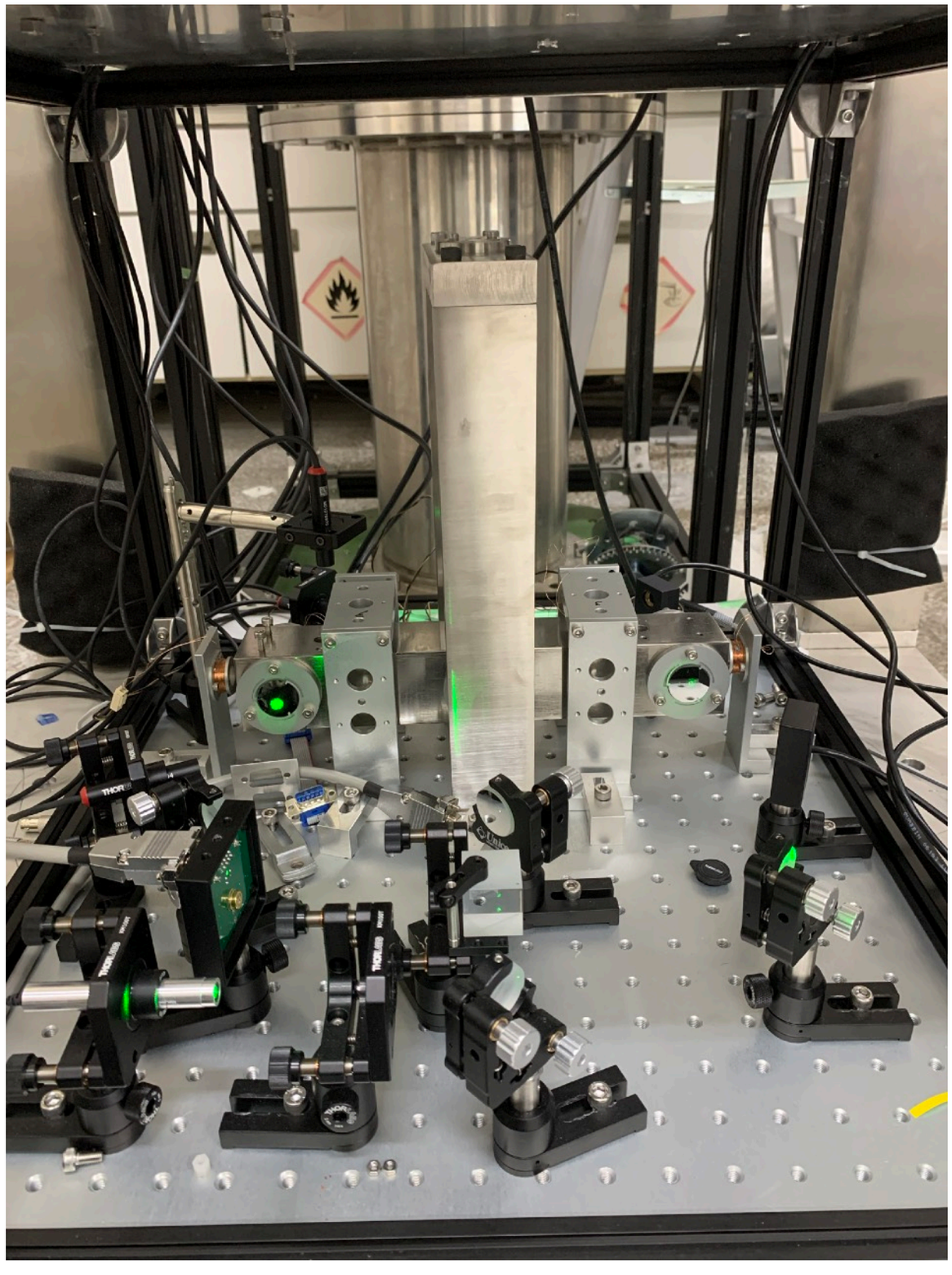
SPEED METER

CRYOGENIC ✓

TORSION BAR Next!

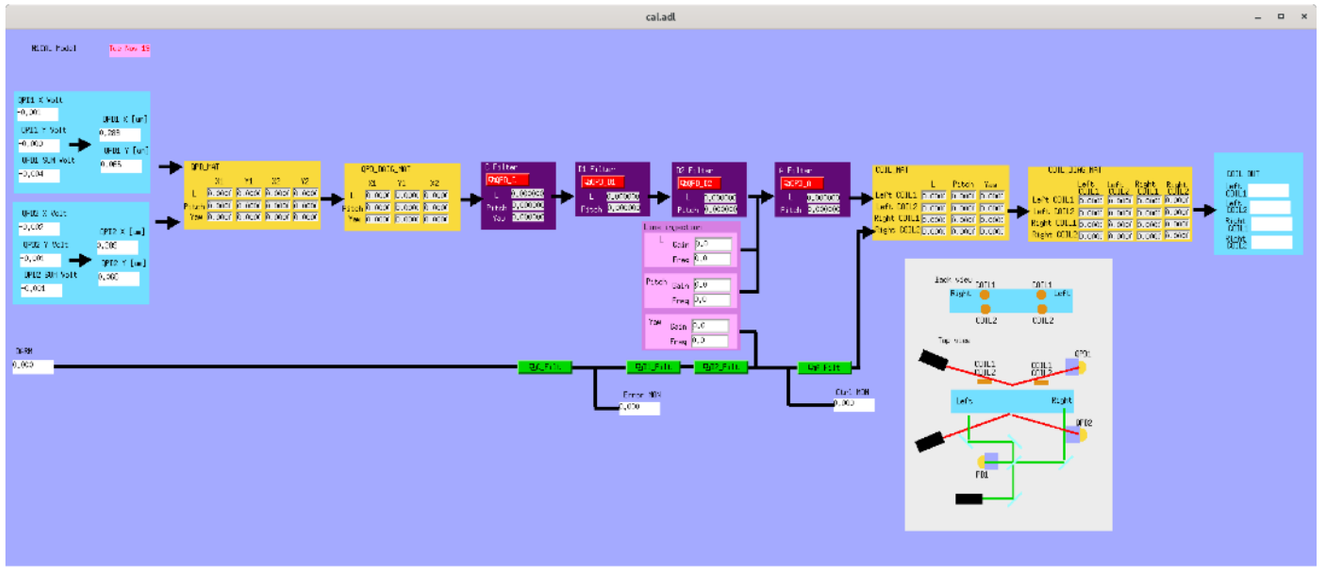
Mini-CHRONOS
Demonstration of Torsion bar technique

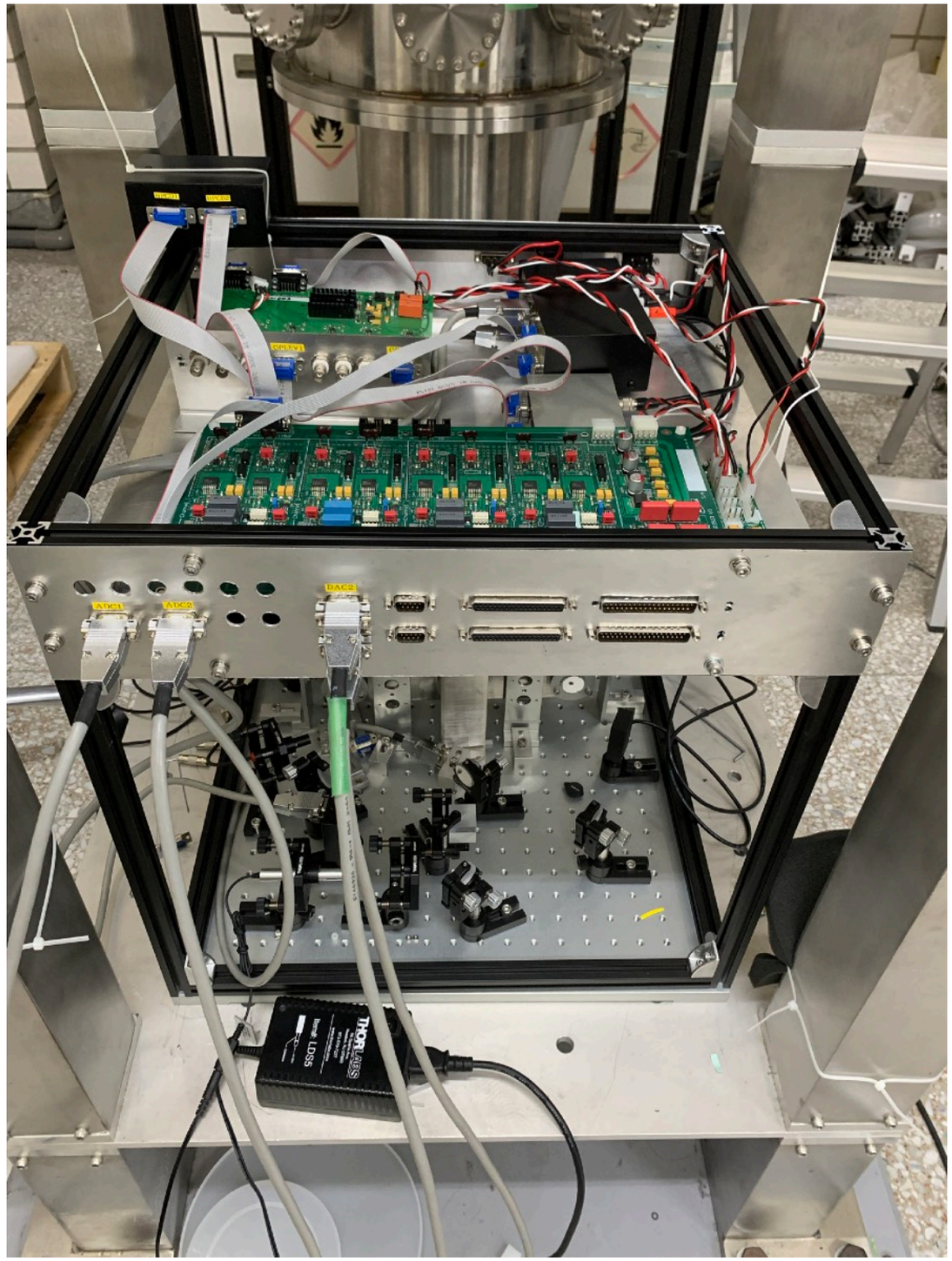




- 30cm torsion bar
- Apply MC150 control technique
- Sensor: Michelson interferometer
- Actuator: Coil
- Local sensor: Optical lever
- Goal: Demonstration of Torsion bar with Digital feedback control

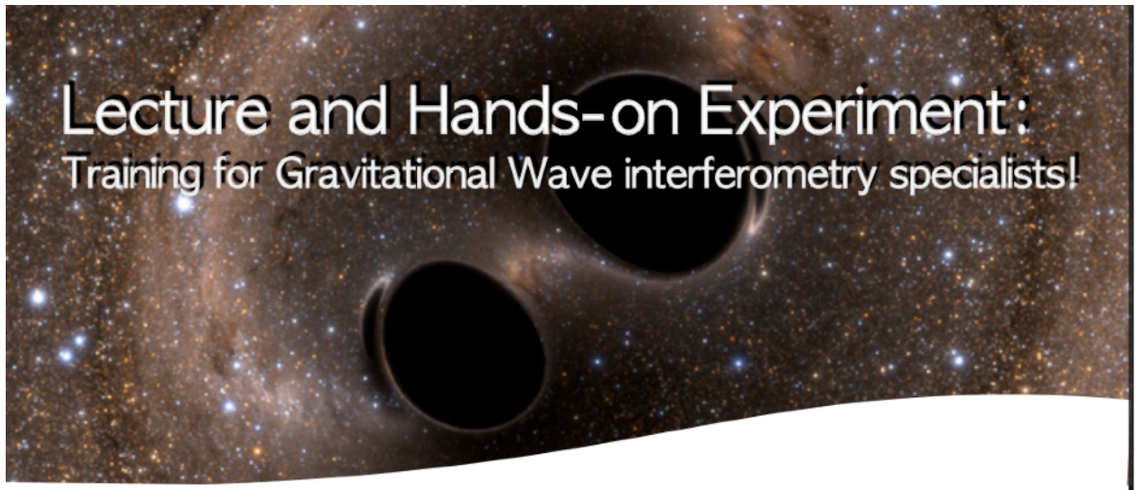
Readout





- Combination with analog and digital circuit
- Upgraded Michelson Cube 150 control system
- Made in Taiwan
- Start the commissioning run from Dec. 2024

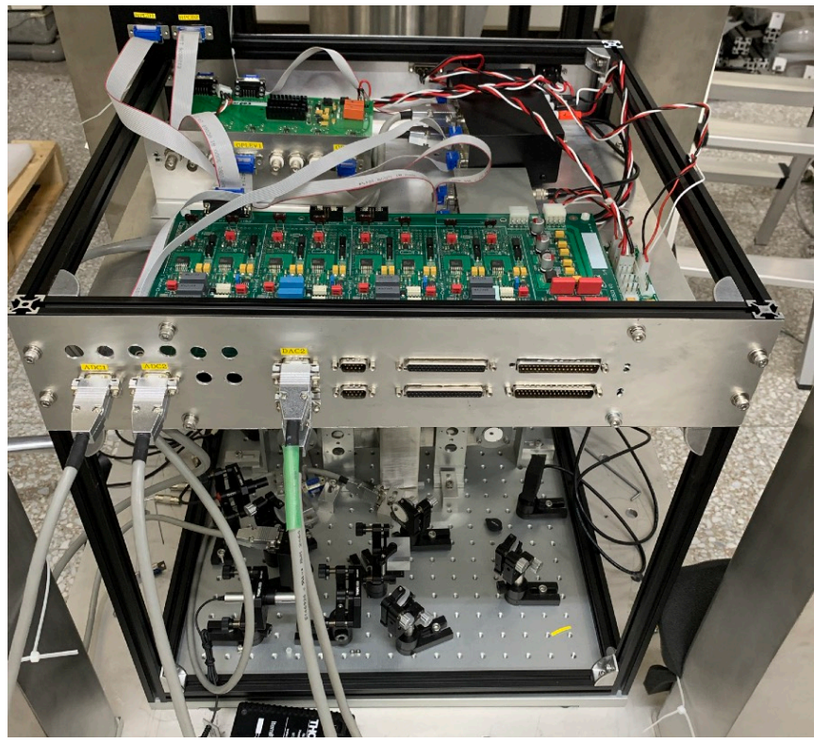
GW Winter school in CHiP



Development period: only 150days!

LIGO friend: Why so fast???

→9year History of Taiwan GW development!!

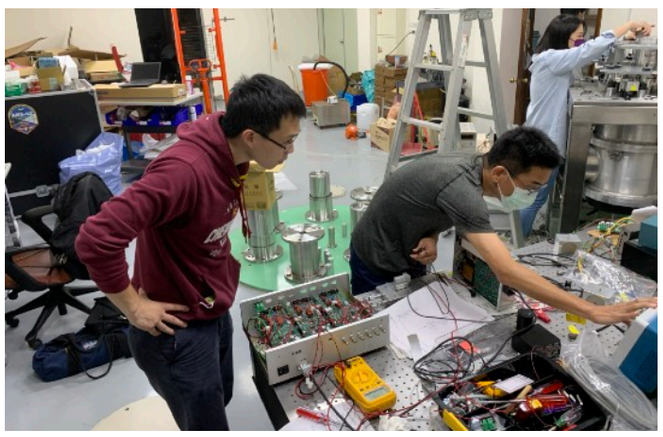


Great thanks!!

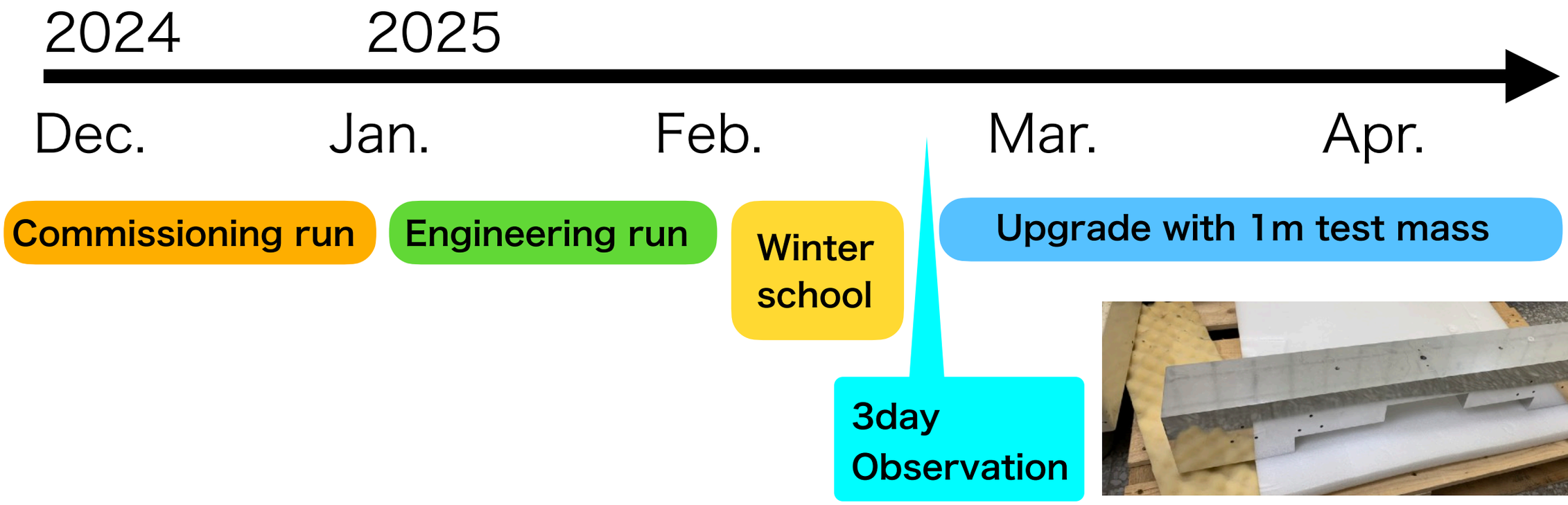
Originally, Supported by AS research scientist!

Chih-Hsun, Lin

Fong-Kai, Lin



Schedule of mini-CHRONOS



Goal

Commissioning run: Stable control and improvement of noise

Engineering run: reconstruct h(t) with modern reconstruction pipeline

3day Observation: Take 3 days data

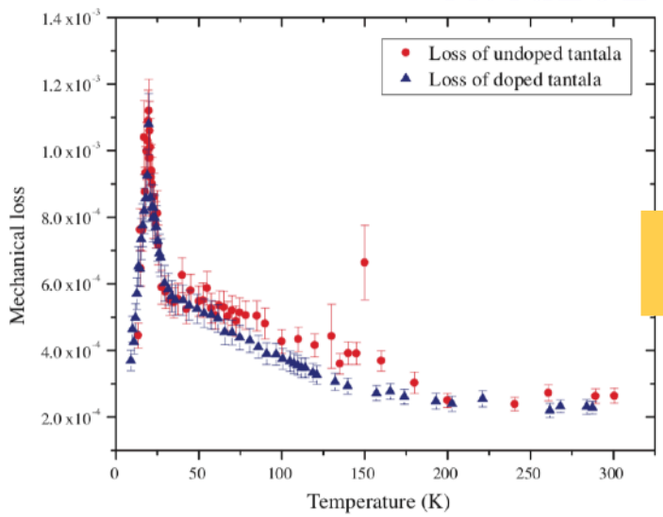
Summary

- Observation 4 is ongoing. Taiwan has a lot of contribution in particular calibration analysis.
- Development of O4 has almost done and start to focus on O5 study.
- Both Dr.Daiki Tanabe and Dr.Avani Patel are playing significant role for next LIGO.
- Development and characterization of new coating are ongoing. We have started to characterize the parameter of samples.
- CHRONOS R&D is ongoing. Michelson Cube 150 was developed. By applying this technology, we developed the mini-CHRONOS system. We will start the commissioning and engineering run from Dec.

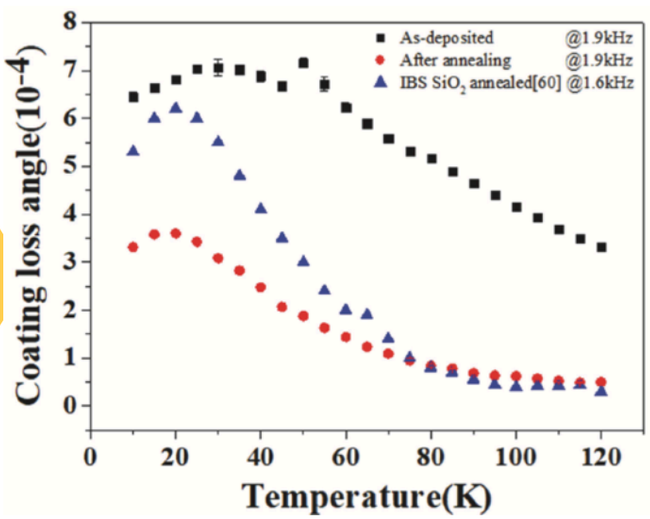
Approaches

High index material

Ti:Ta2O2



Plasma enhanced CVD method — **SiNX**



Optical absorption: 1.4e-5 @1550nm

Low pressure CVD method — **SiNX**

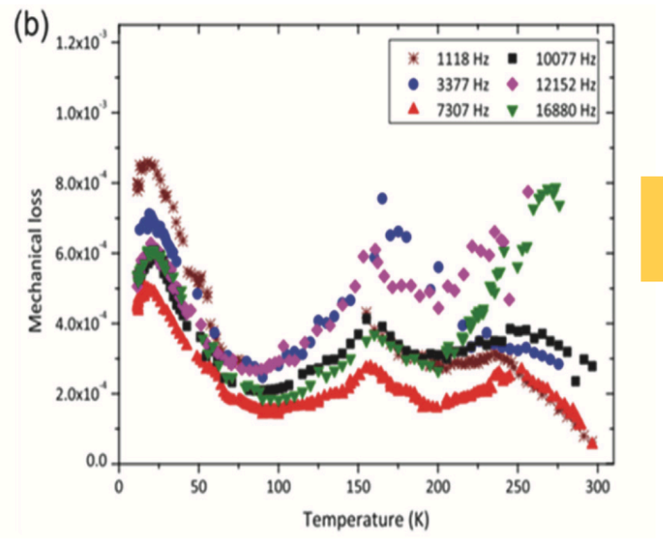
Fabrication: Done!!

Developing GNS system

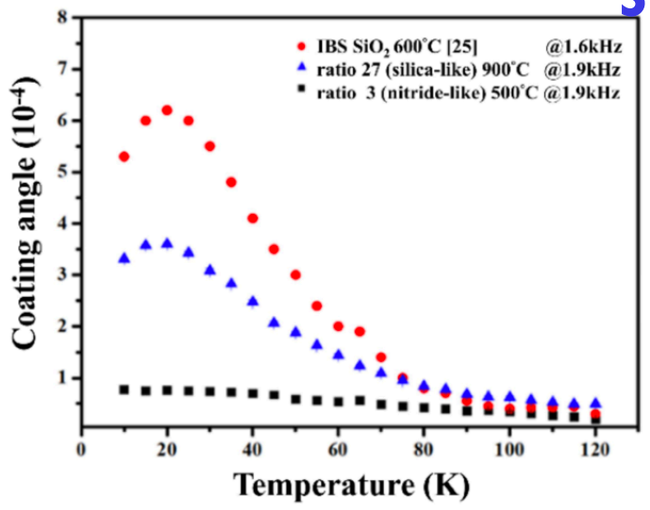
Optical absorption:5.8e-6@1550nm

Low index material

SiO2



Plasma enhanced CVD method — **SiON**



Optical absorption:5.8e-7@1550nm

Low pressure CVD method — **SiON**

Fabrication:
Gas line this Winter

Developing GNS system

Optical absorption: Ongoing