Taiwan-LIGO instrumentation group

National Central University & Academia Sinica
Yuki Inoue

2023/11/24 CHiP meeting

Outline

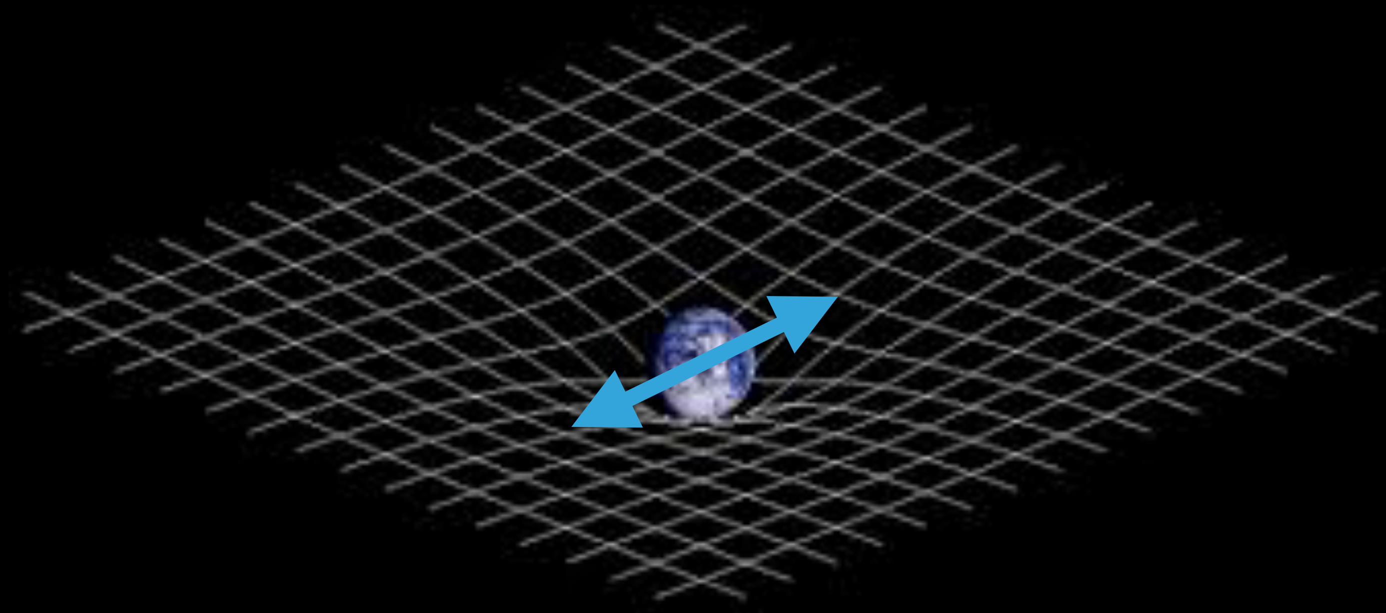
- Introduction
- Science
- LIGO interferometer
- Taiwan-LIGO instrumentation group
    - Calibration
    - Coating
    - Future study
- Summary

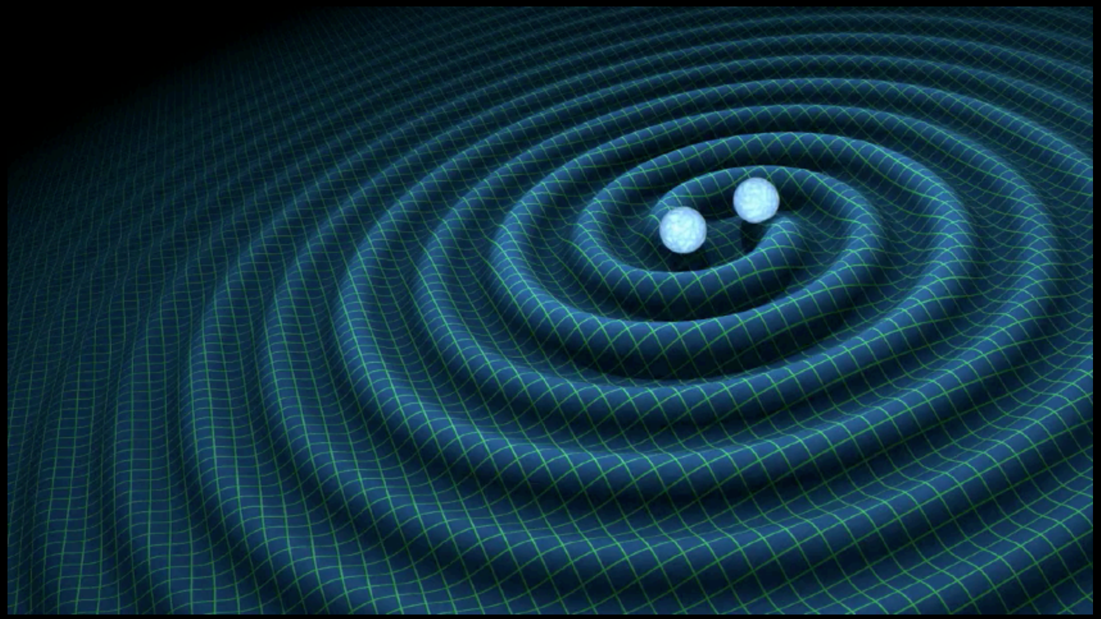
Introduction

- NCU have contributed GW science since 2017.
- NCU is one of the institute of LIGO scientific collaborations
- Taiwan-Instrumentation group (NCU-AS-NTHU) are joining LIGO and do the studies of Coating and Calibration
- Worldwide observation is ongoing (From Mar.25 2023). NCU students also join commissioning work of observation 4 at Hanford Observatory.
- ASGRAF is constructed and installation work is ongoing.
- R&D for future studies is also on going.

Science

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

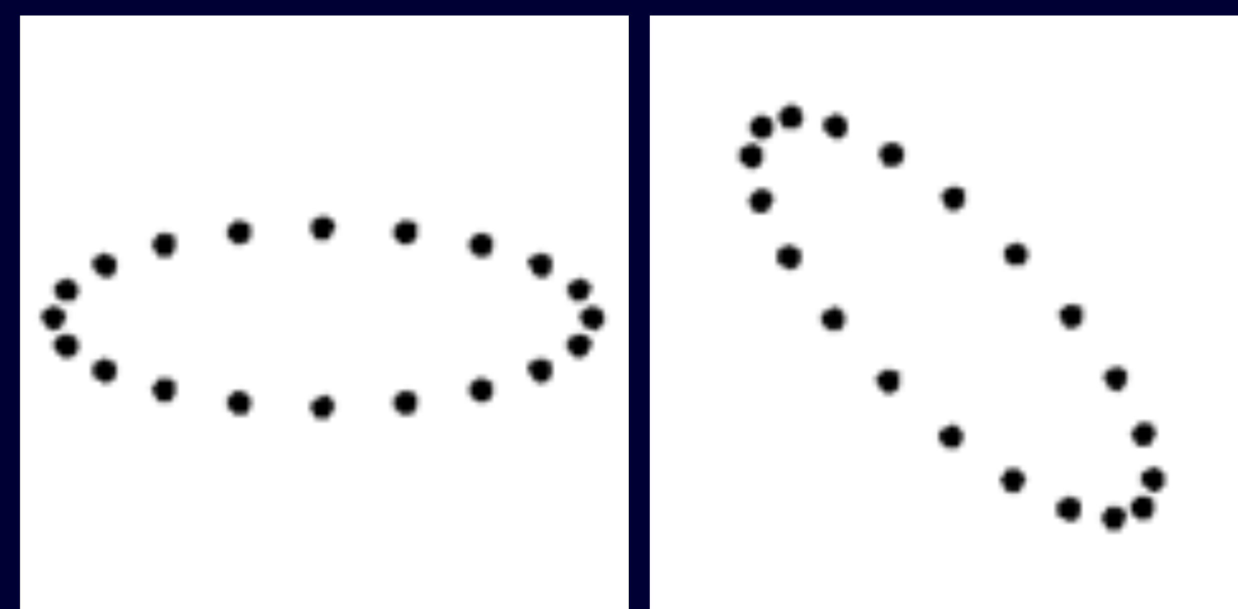
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Perturbation

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

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

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



Typical gravitational wave strain sensitivity

$$h \sim \frac{2G}{c^4 R}\ddot{I} \sim \frac{r_g}{R} = \frac{\text{Schwarzschild radius}}{\text{Distance from the source}}$$

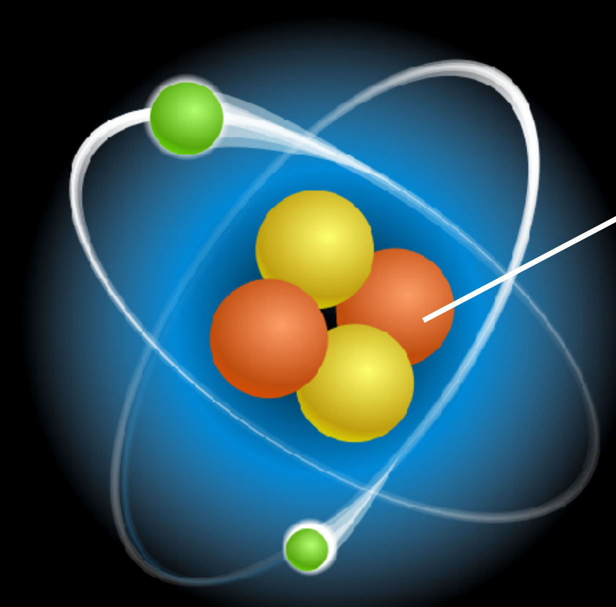
Solar mass NS-NS: r_g~3km

Typical distance: 100Mpc

$h \sim \delta L/L \sim 10^{-21}$

$\delta L \sim 2000\,\text{km} \times 10^{-21}$

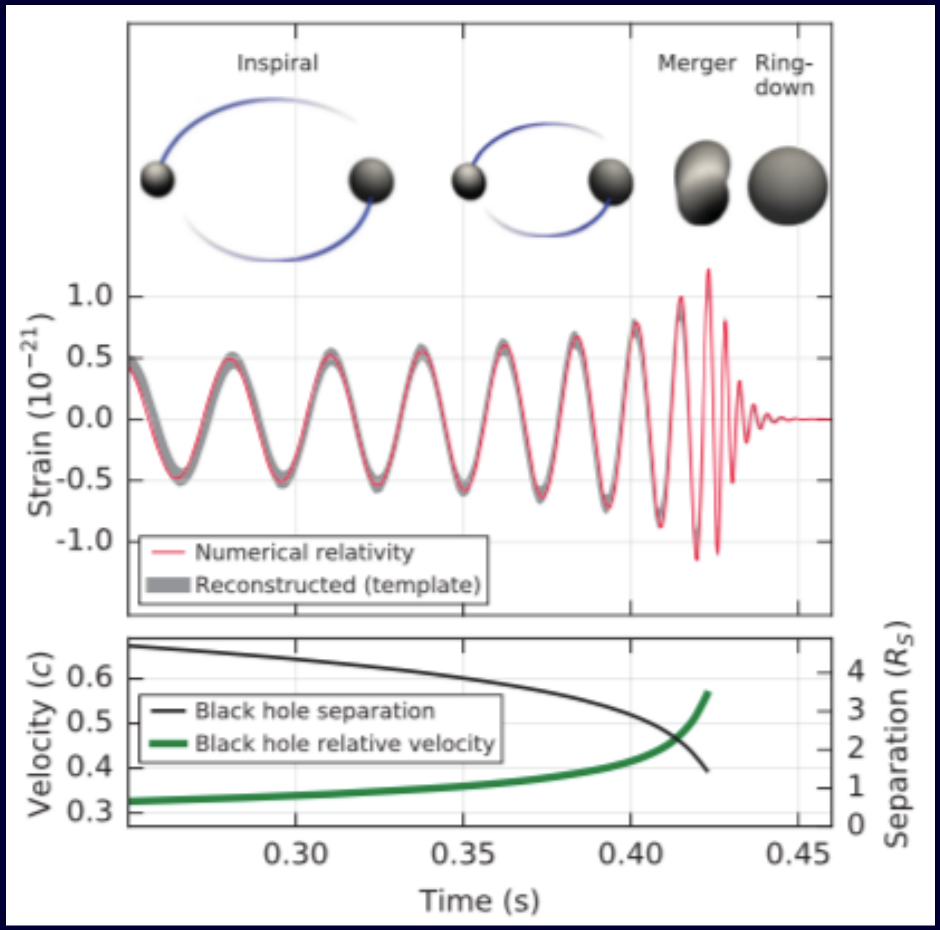
$\sim 10^{-15}\,\text{m} \sim 1\,\text{fm}$

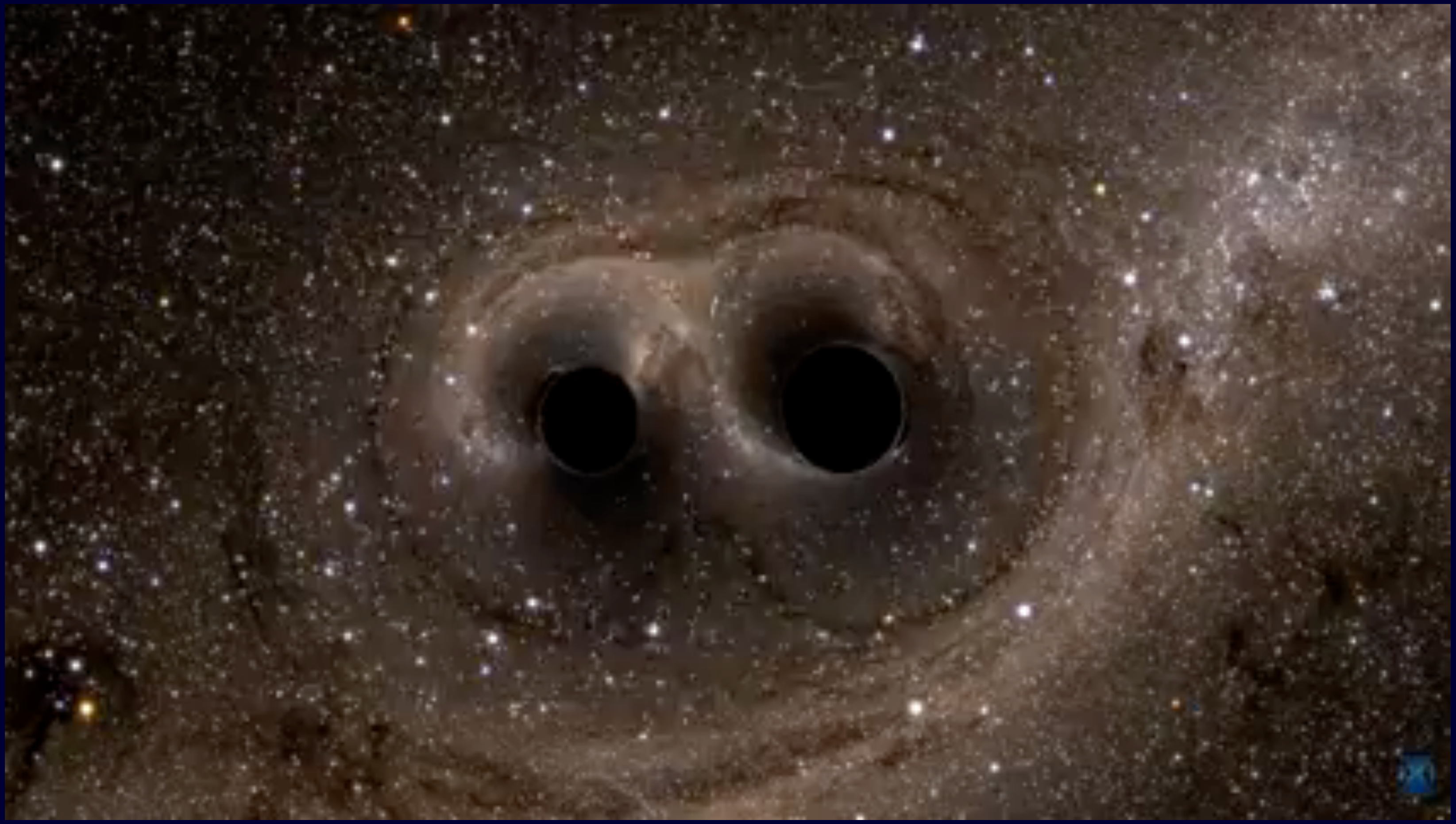


Proton radius

Amplitude of GW is very tiny

Compact Binary Coalescence

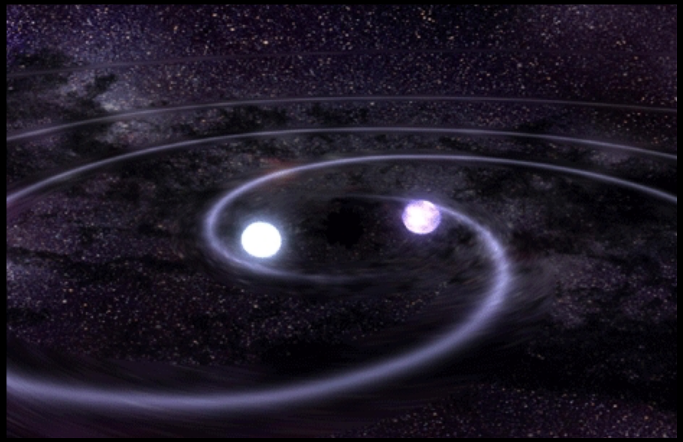




- BH-BH, BH-NS, and NS-NS (BH= Black hole, NS= Neutron Star)
- Observed as Unique Chirp signal
- LIGO and Virgo can observe it every 3 days

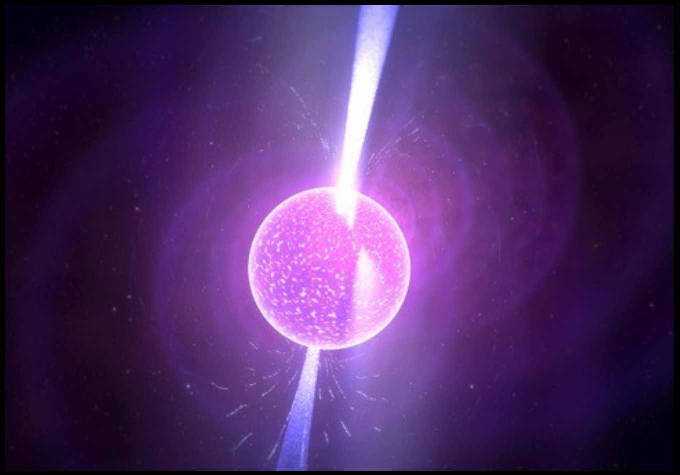
Gravitational wave source

BINARY SYSTEMS

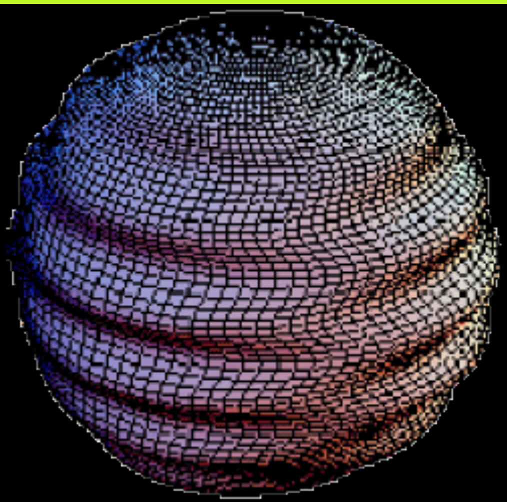


SUPER NOVA

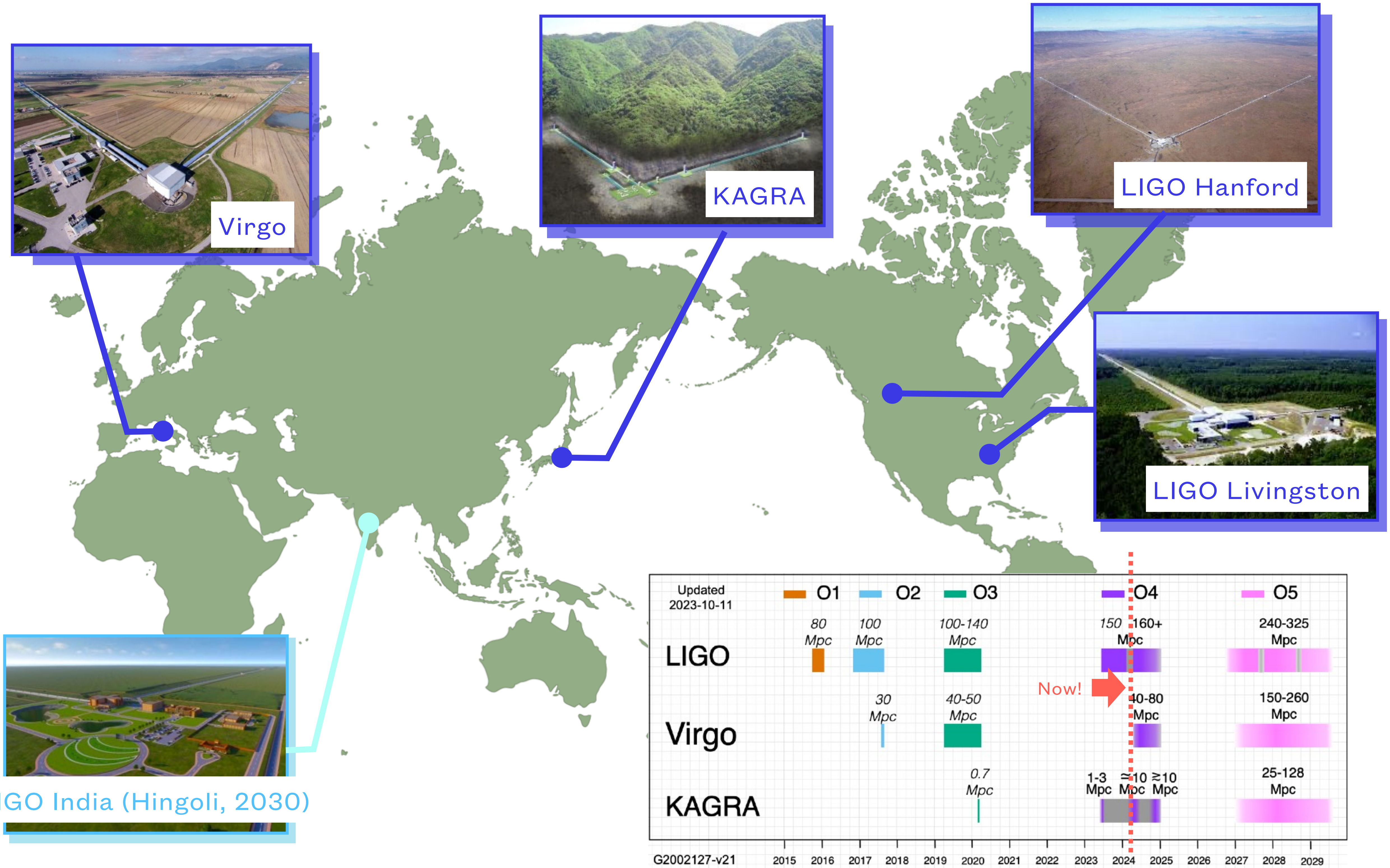
PULSER



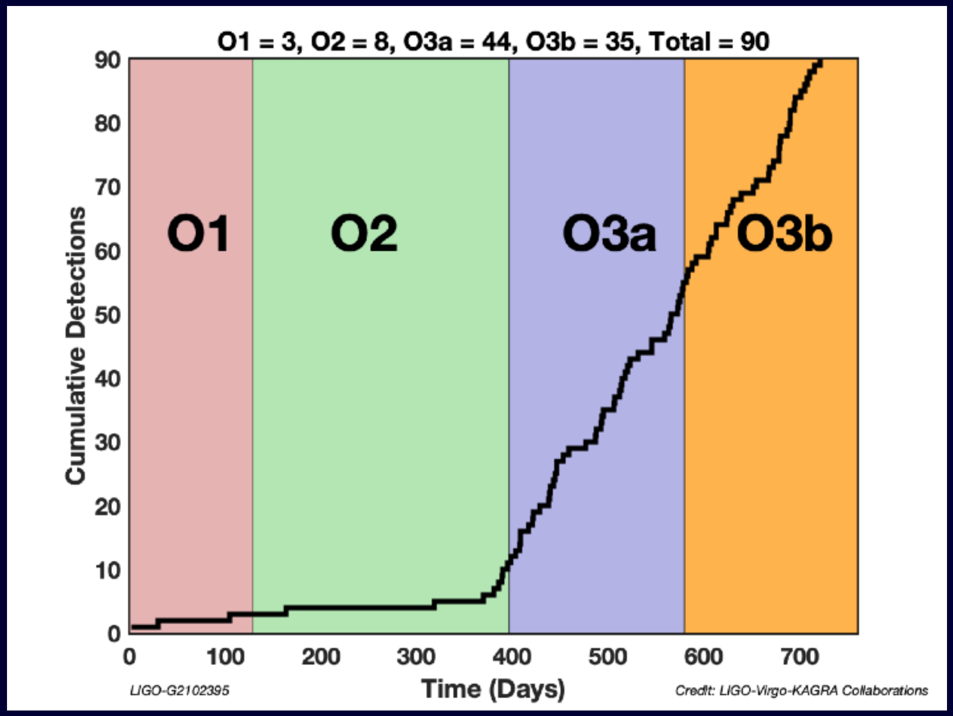
STOCHASTIC BACKGROUND

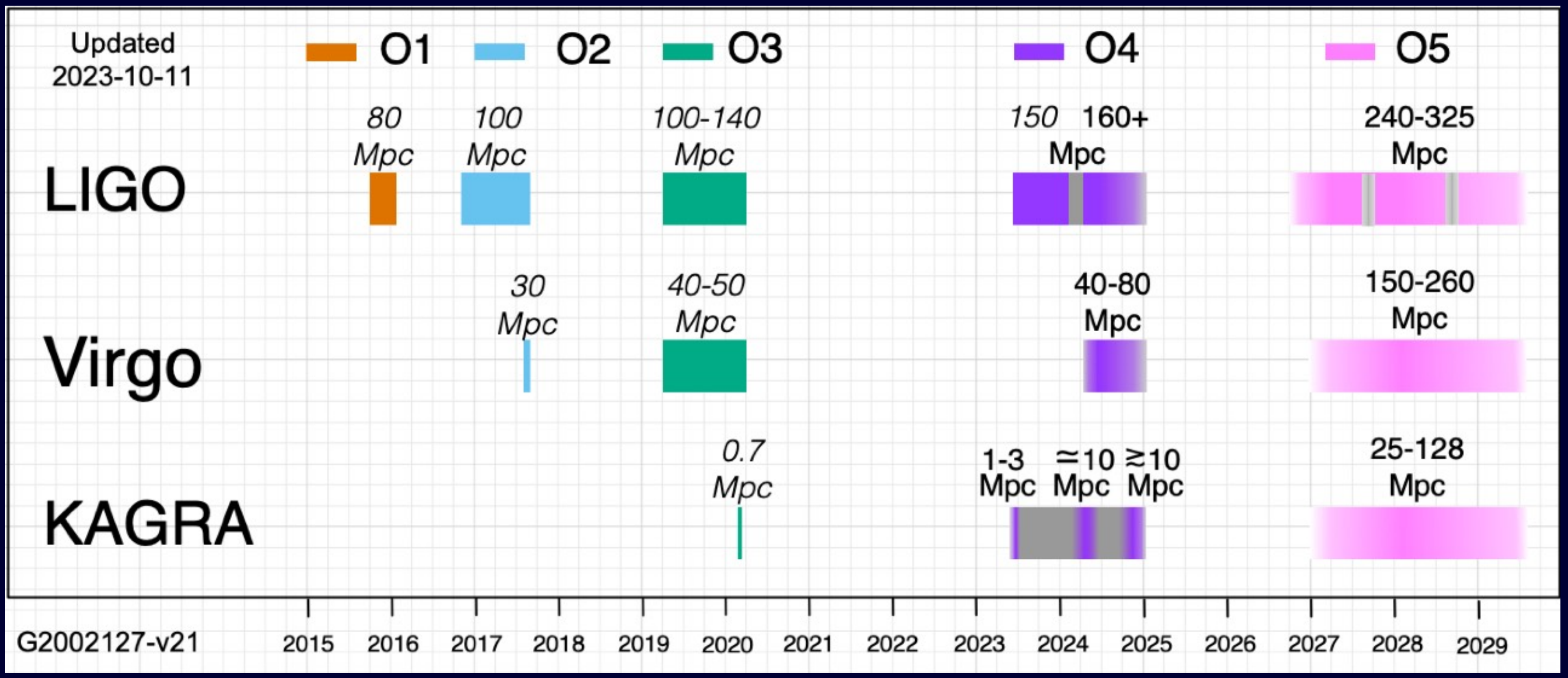


Gravitational wave observation network



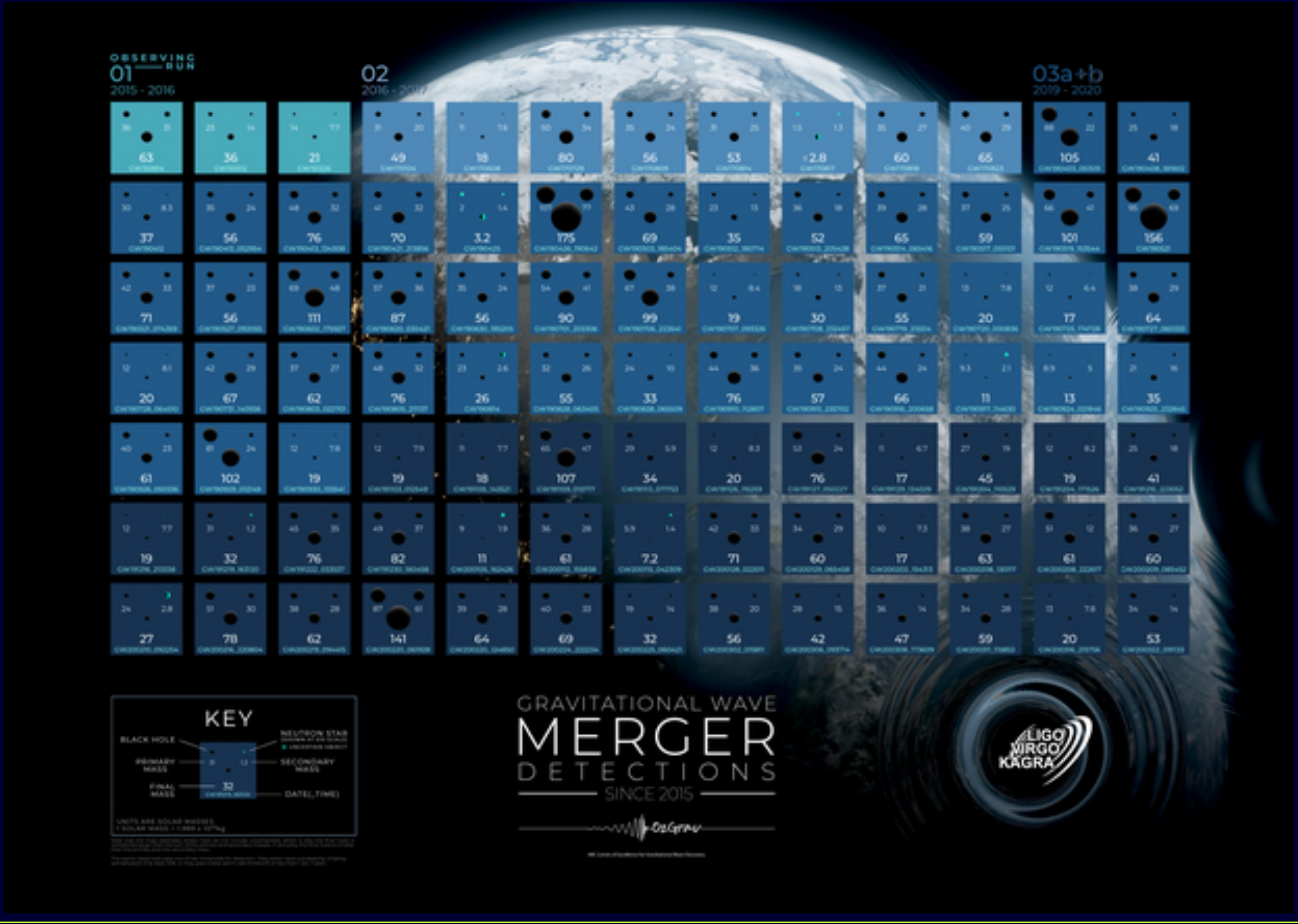
Observation 4



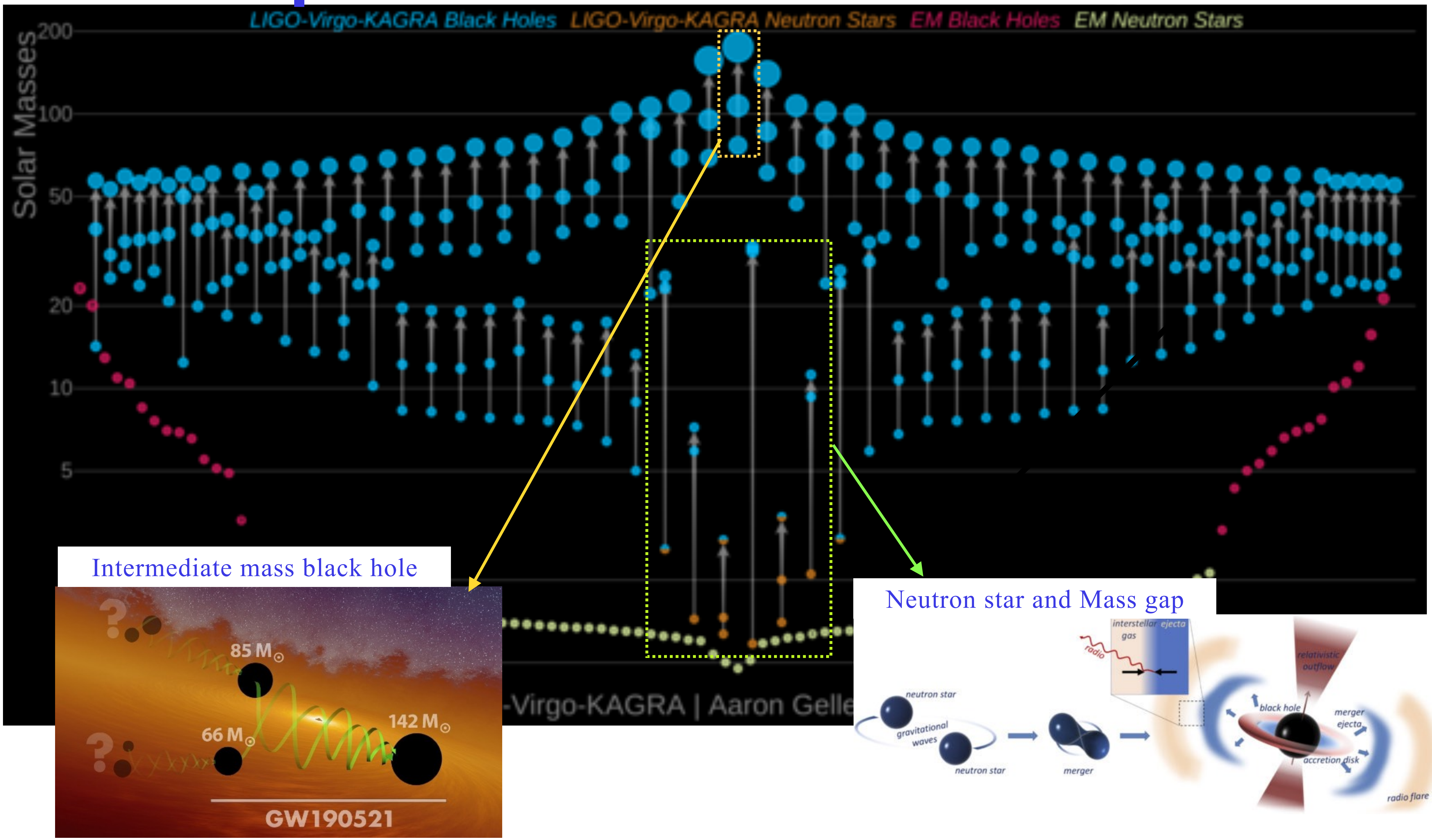


- Observation 4 has started from end of May. Livingston and Hanford are taking data well. 64 events are detected.
- We detect the gravitational wave event every 3 days.
- Commissioning break b/w O4a and O4b will be held on next January.
- Data release is planed middle 2024 for O4a

Observation 3 result



Some important events in O3



LIGO interferometer

Interferometer of LIGO

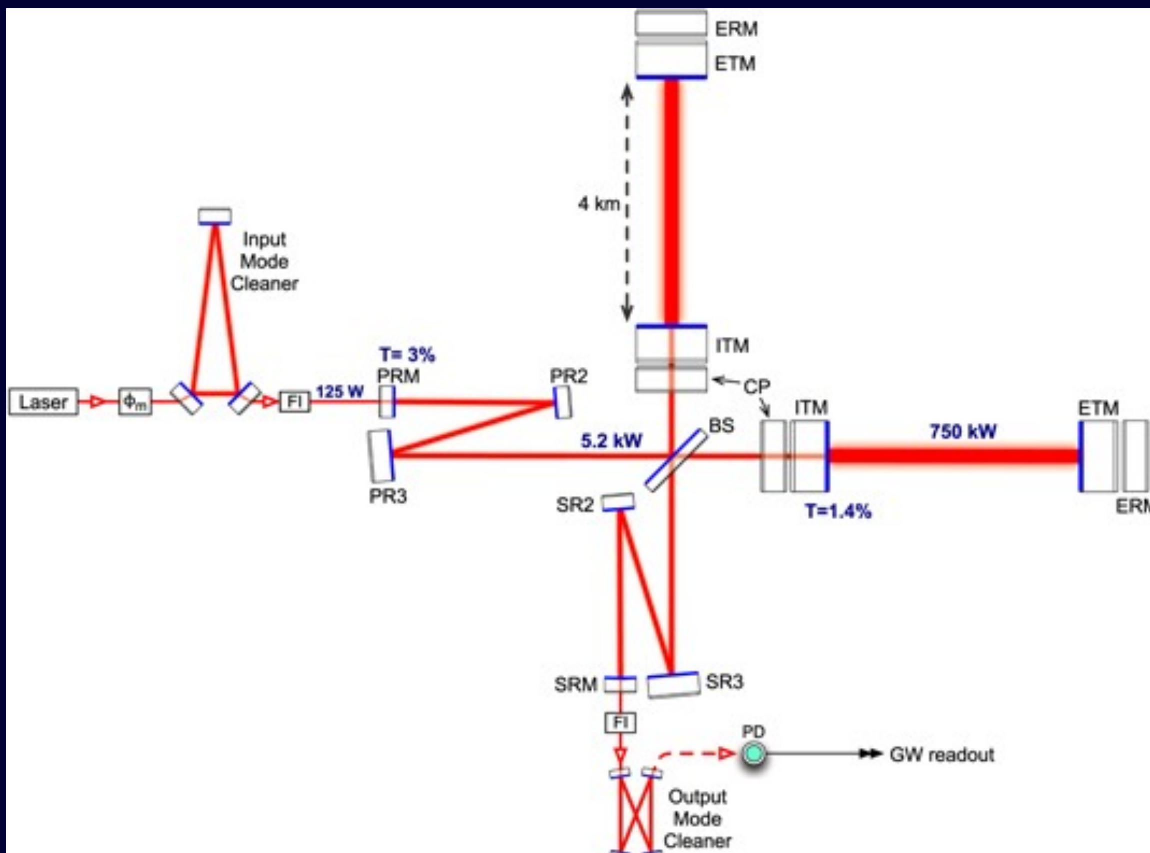
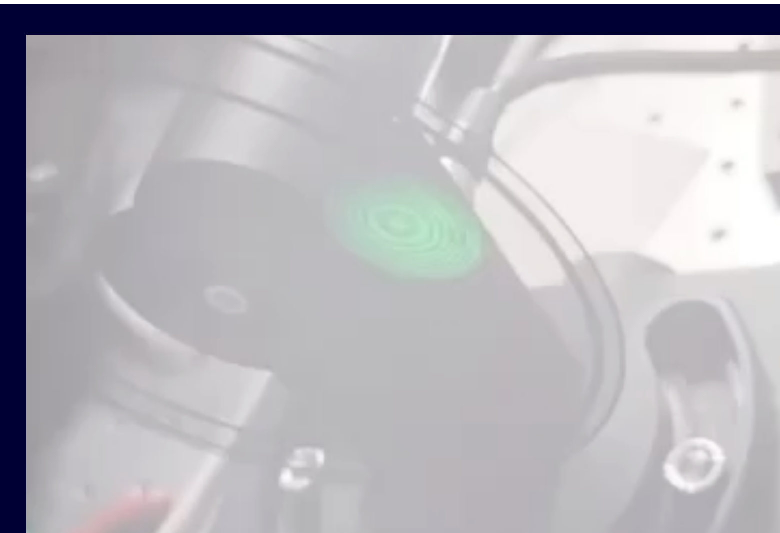


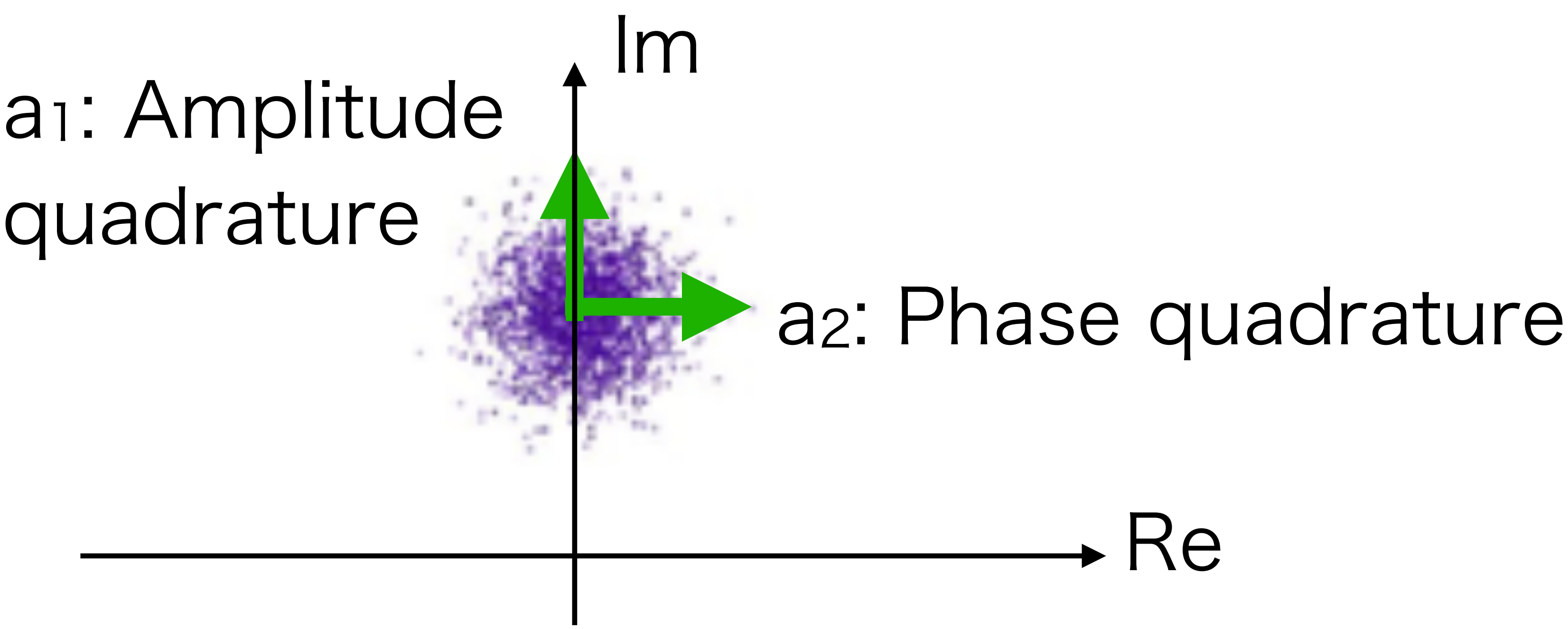
Table 1. Main parameters of the Advanced LIGO interferometers. PRC: power recycling cavity; SRC: signal recycling cavity.

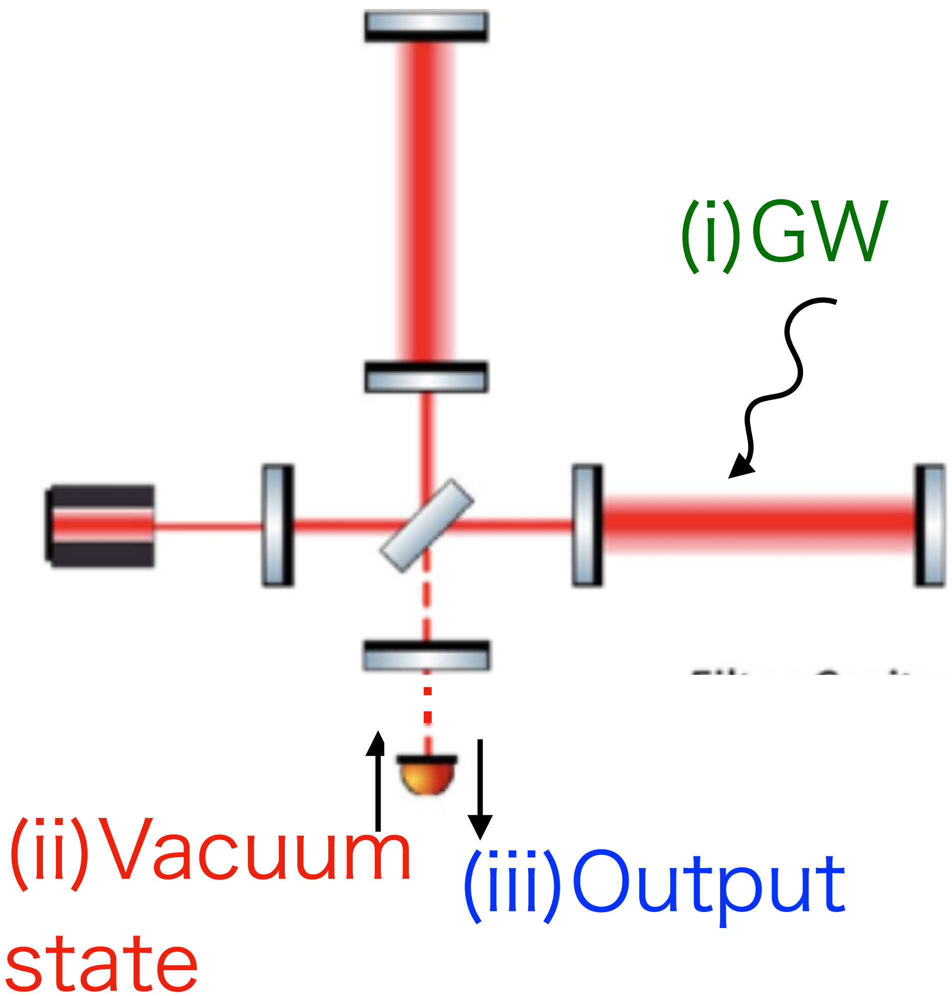
Parameter	Value
Arm cavity length	3994.5 m
Arm cavity finesse	450
Laser type and wavelength	Nd:YAG, $\lambda = 1064$ nm
Input power, at PRM	up to 125 W
Beam polarization	linear, horizontal
Test mass material	Fused silica
Test mass size & mass	34cm diam. x 20cm, 40 kg
Beam radius ($1/e^2$), ITM / ETM	5.3 cm / 6.2 cm
Radius of curvature, ITM / ETM	1934 m / 2245 m
Input mode cleaner length & finesse	32.9 m (round trip), 500
Recycling cavity lengths, PRC / SRC	57.6 m / 56.0 m

- Dual recycling Fabry Perot Michelson Interferometer
- 40kg test mass
- 125W laser



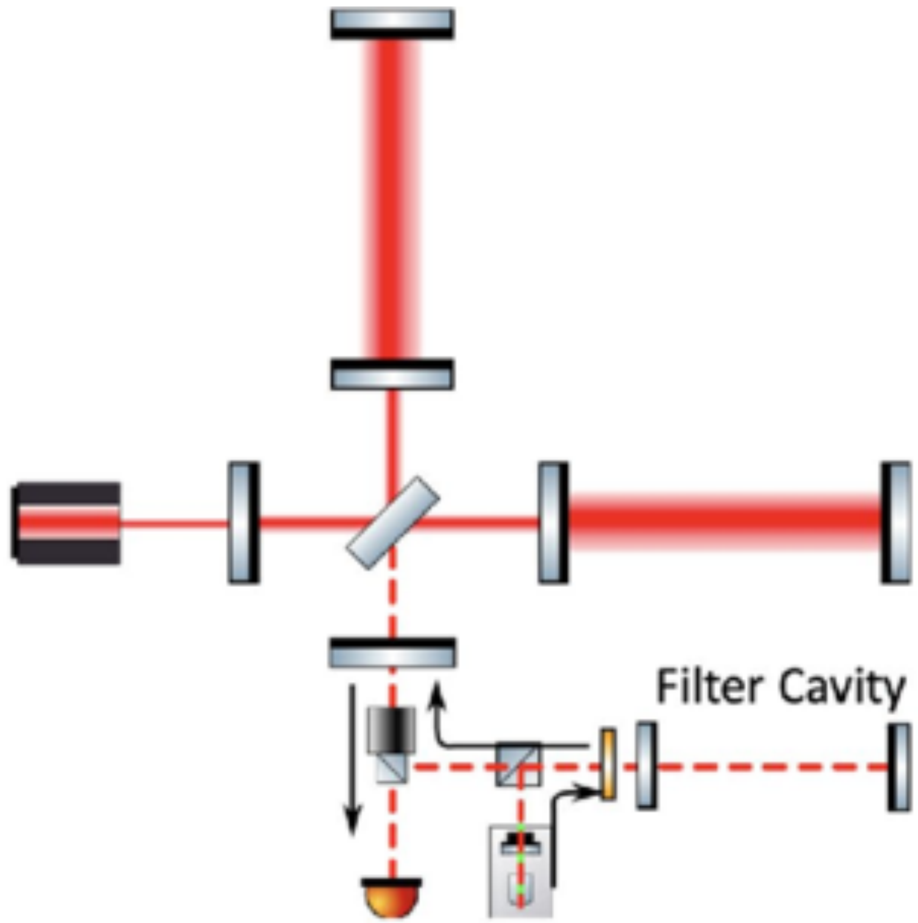
Squeezing

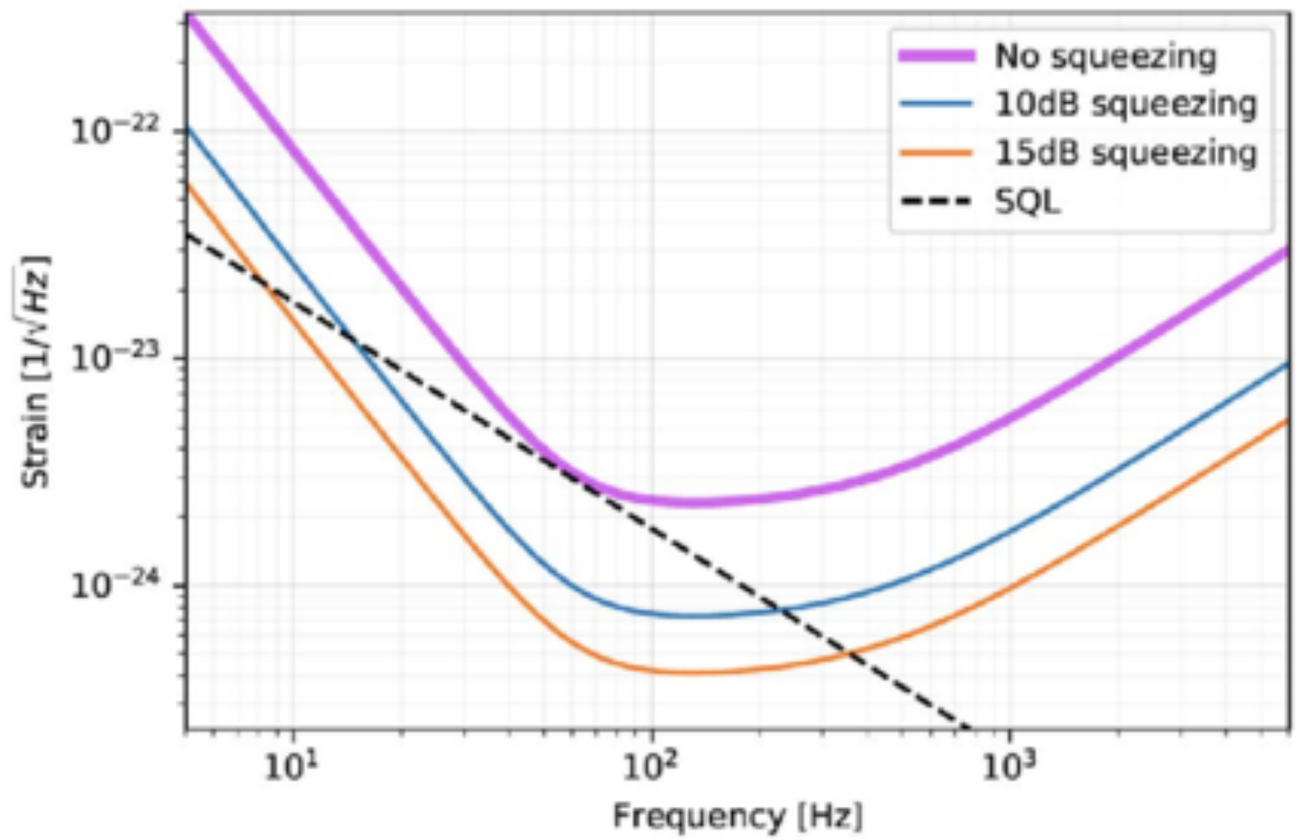




$$
\begin{aligned}
b_\zeta &= b_1 \sin\zeta + b_2 \cos\zeta \\
&= \frac{1}{M}[e^{2i(\beta_- + \Phi_s)}(C_{11}\sin\zeta + C_{12}\cos\zeta)a_1 + e^{2i(\beta_- + \Phi_s)}(C_{21}\sin\zeta + C_{22}\cos\zeta)a_2 \\
&+ \sqrt{2K}t_s e^{i(\beta_- + \Phi_s)}(D_1\sin\zeta + D_2\cos\zeta)\frac{h}{h_{SQL}}]
\end{aligned}
$$

Frequency dependent Squeezing

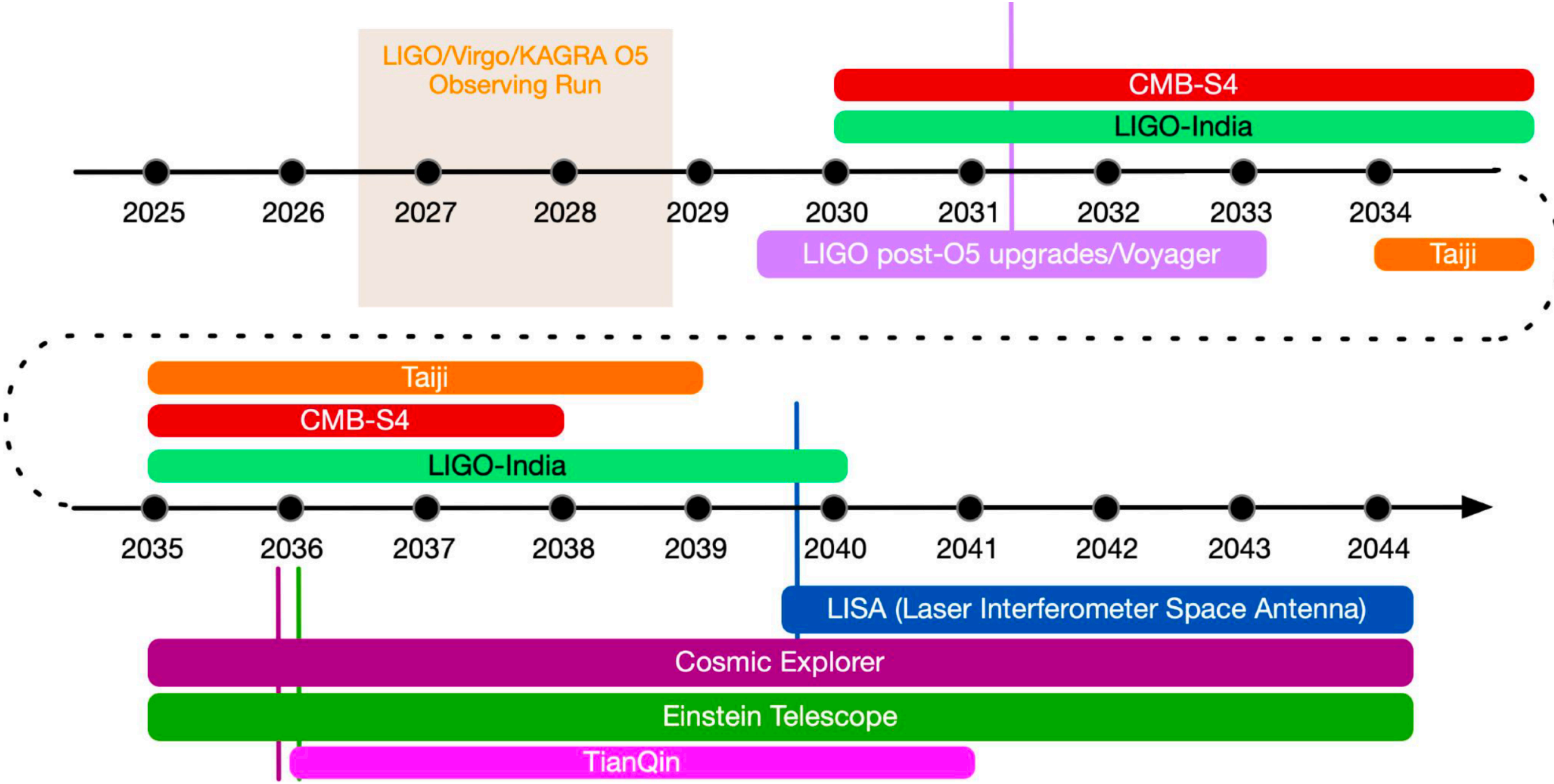




LIGO and Virgo will test this technology in O4b.

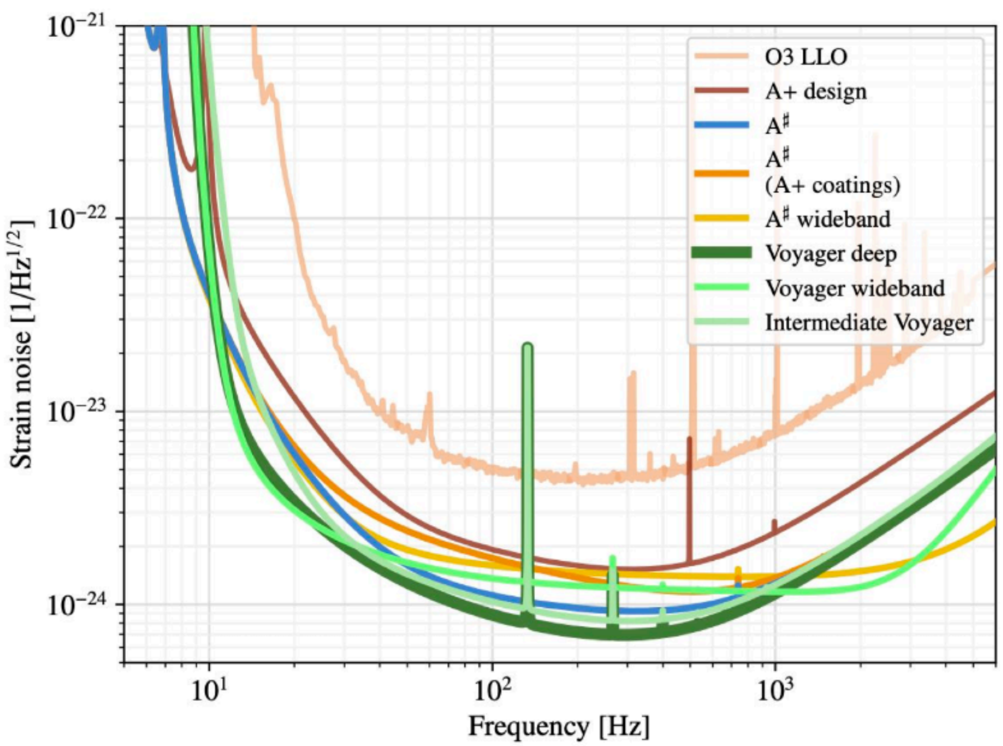
LIGO Hanford

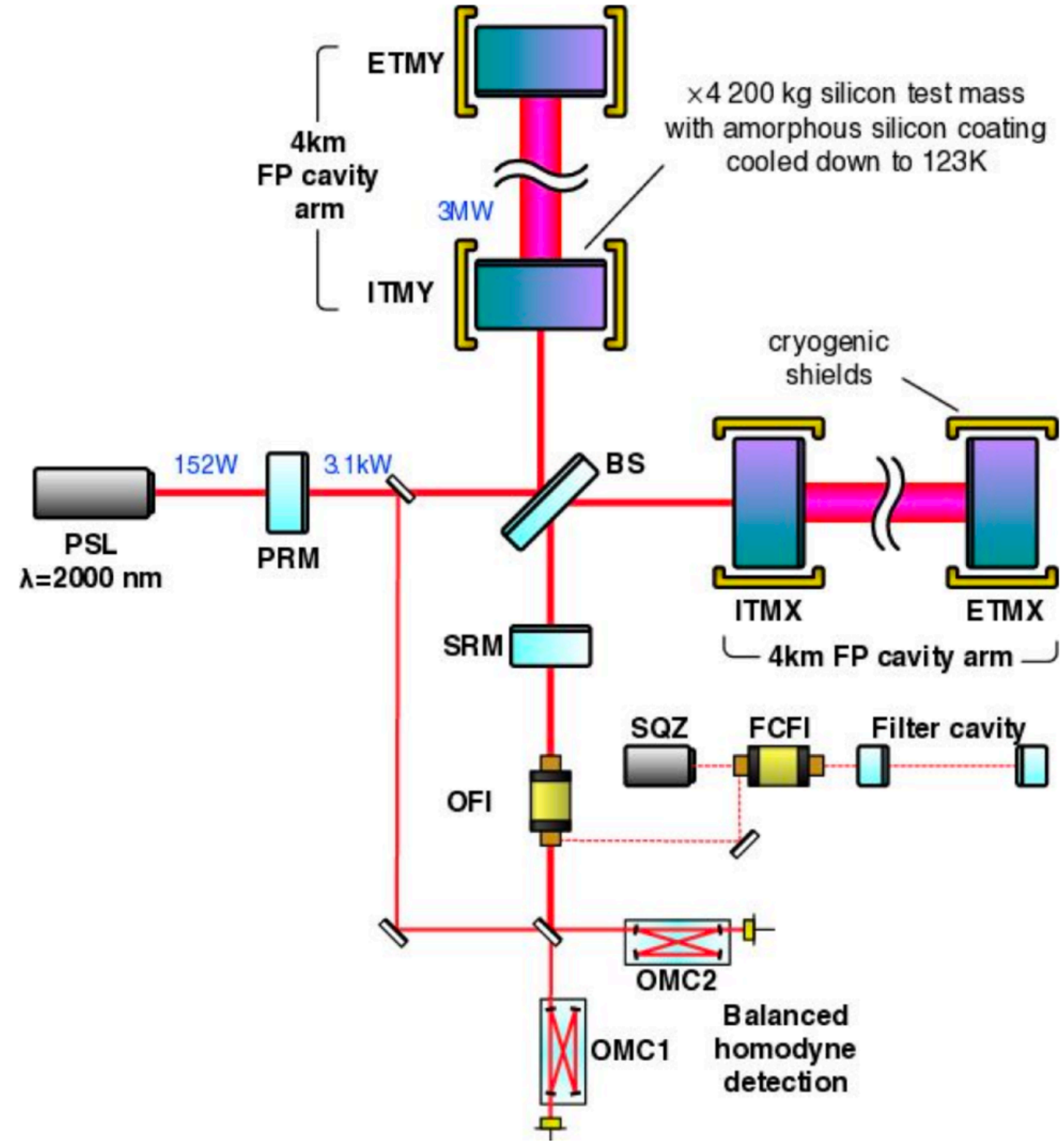
Schedule of future experiment



LIGO Voyager

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





Activities of Taiwan-LIGO instrumentation group

Taiwan-LIGO instrumentation group

National Central University

Yuki Inoue (PI)
Ko-Han Chen
Miftahul Ma’arif
Dennis
You-Ru Lee
Hsiang-Yu Huang
Eason Lin
John Chen
Avani Patel
Niko Alosius
Kun-Yao Chang

Academia Sinica

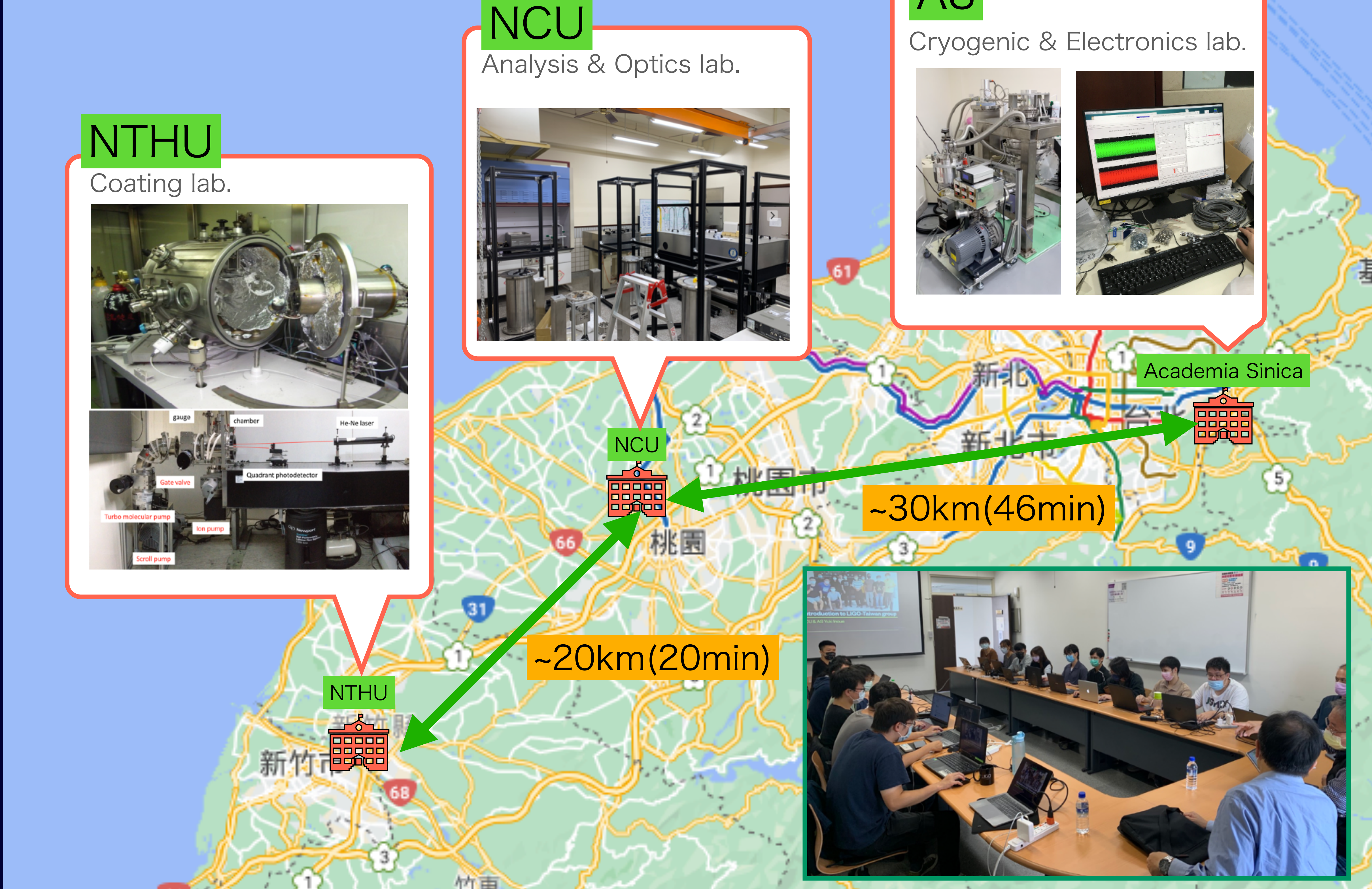
Tsz-King Wong
Feng-Kai Lin
Hsiang-Chieh Hsu
Daiki Tanabe
Debby Lin

NTHU

Chao Shiuh
Zi-Yu Wong
Tong-Yu Chen
Chung-Huan Wong

20 staffs and students join our group

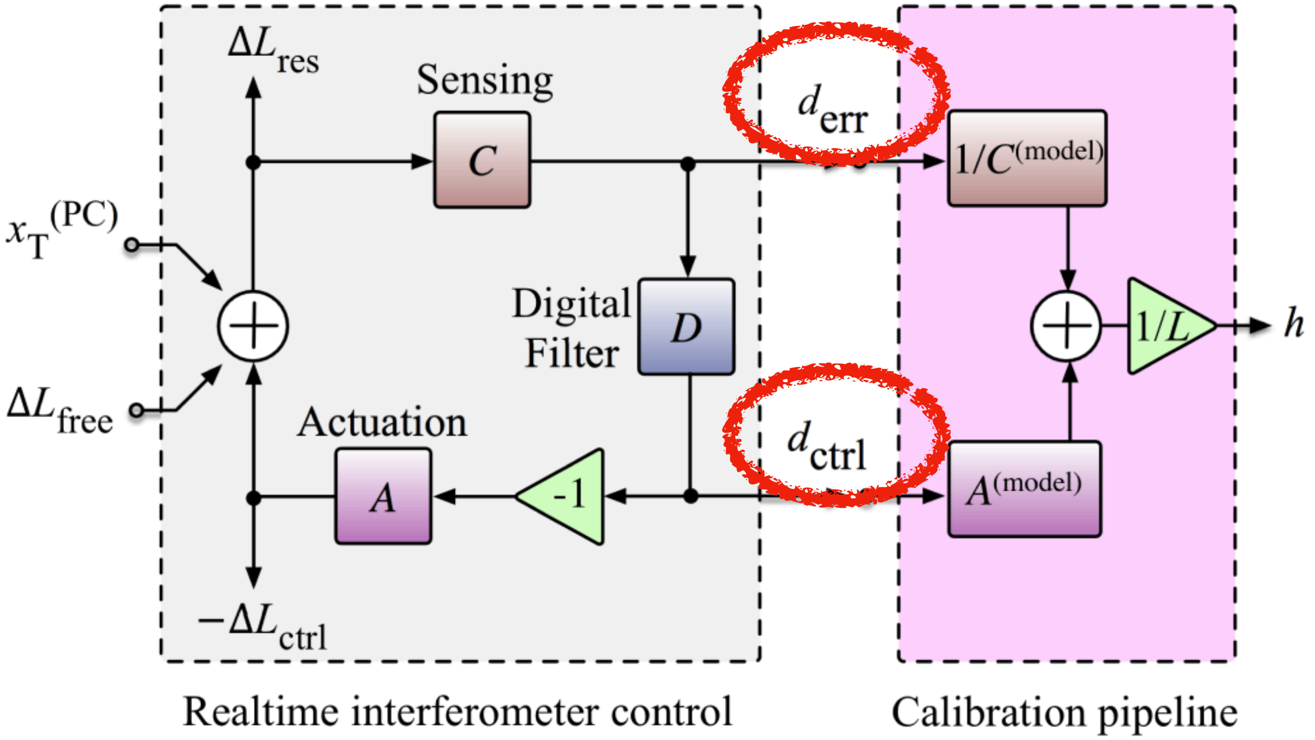
Facilities of LIGO-Taiwan



Current activity in our group

- Calibration
  - Systematic Error estimation in O4 -> Hsiang-Yu, Arif, You-Ru (3 members)
  - Calibration model with quantum effect -> Yuki, You-Ru, Avani (3 members)
  - Bulk deformation systematic error -> Daiki, Niko (2 members)
  - Generation-4 Calibration instruments -> Yuki (1 member)
- Core Optics (Coating)
  - Fabrication with LPCVD -> Kun-Huan, Debby, Prof.Chao (3 members)
  - Mechanical Loss measurement system -> Zi-Yu, Chung-Huan, Daiki (3 members)
  - Optical Loss measurement system -> Tong-Yu, Kun-Huan (2 members)
- Future technology
  - NCU interferometer-> Arif, Dennis, Jhon, Eason, Niko (5 members)
  - ASGRAF-> Daiki, Feng-Kai, Zi-Yu, Chung-Huan (4 members)

Modeling of Interferometer



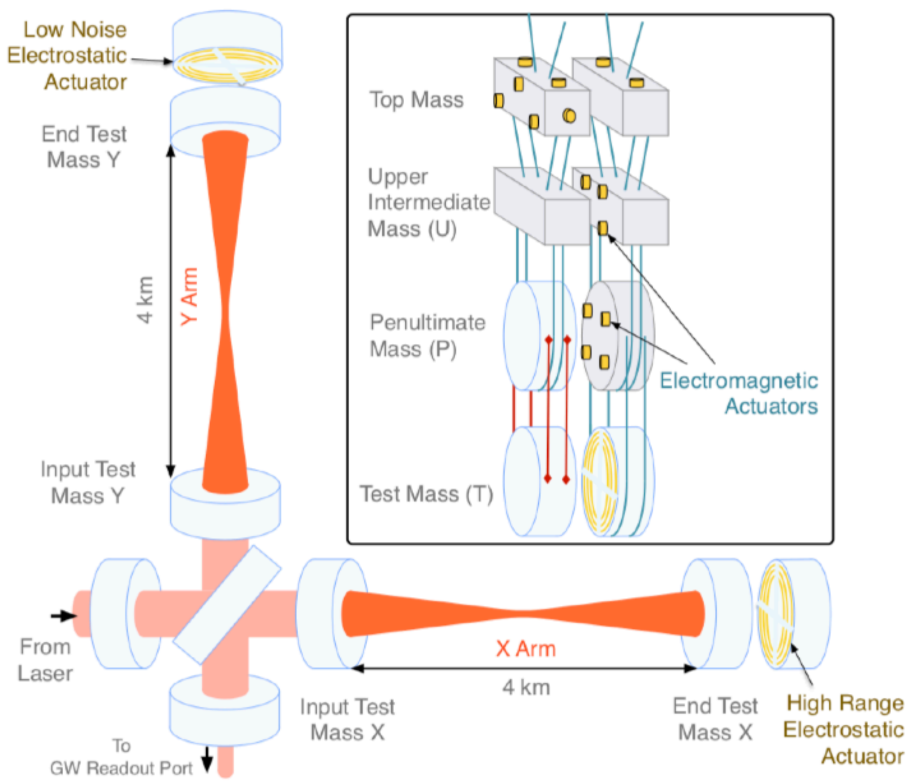
Changes of arm length are measured between Actuator and Detector

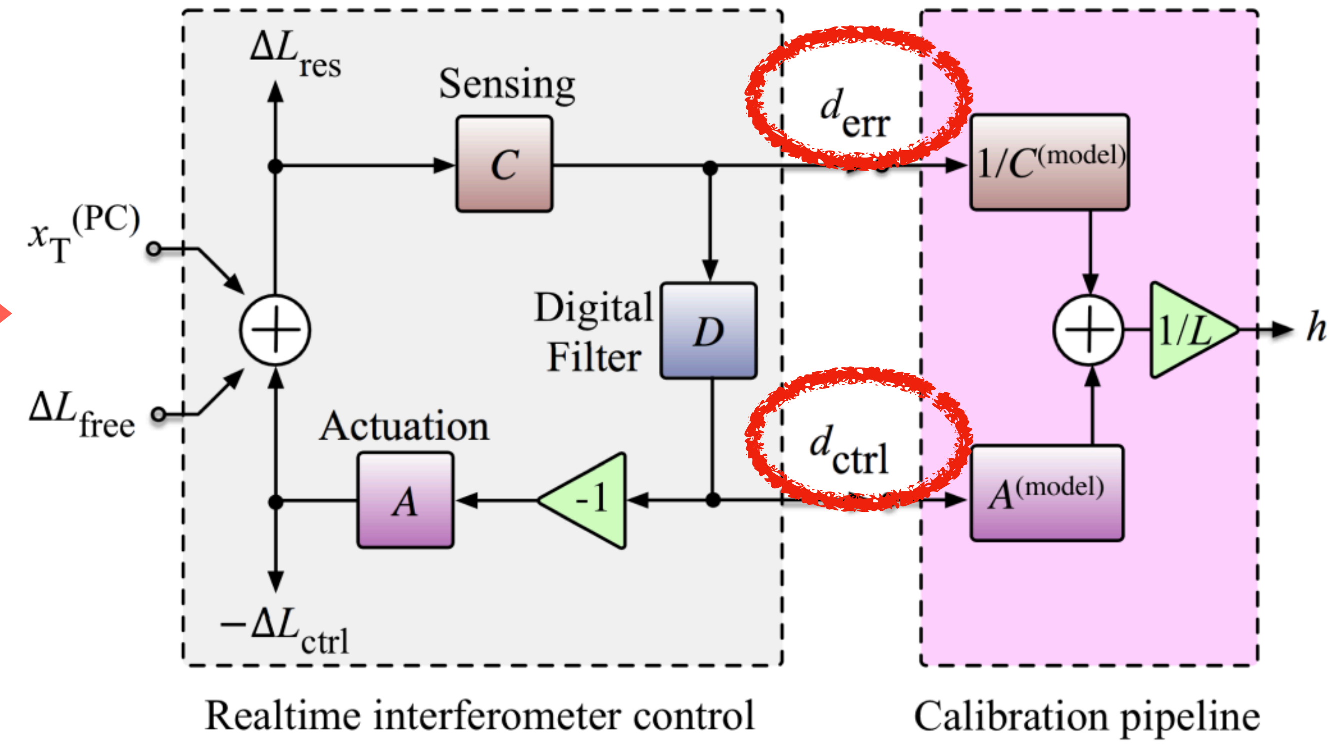
So, we can separate A and C part by estimation accurate model of A and C

→ Definition of Calibration：Parameter estimation of A and C

→ Definition of Reconstruction：Calculation from interferometer response

Modeling of Interferometer





Changes of arm length are measured between Actuator and Detector

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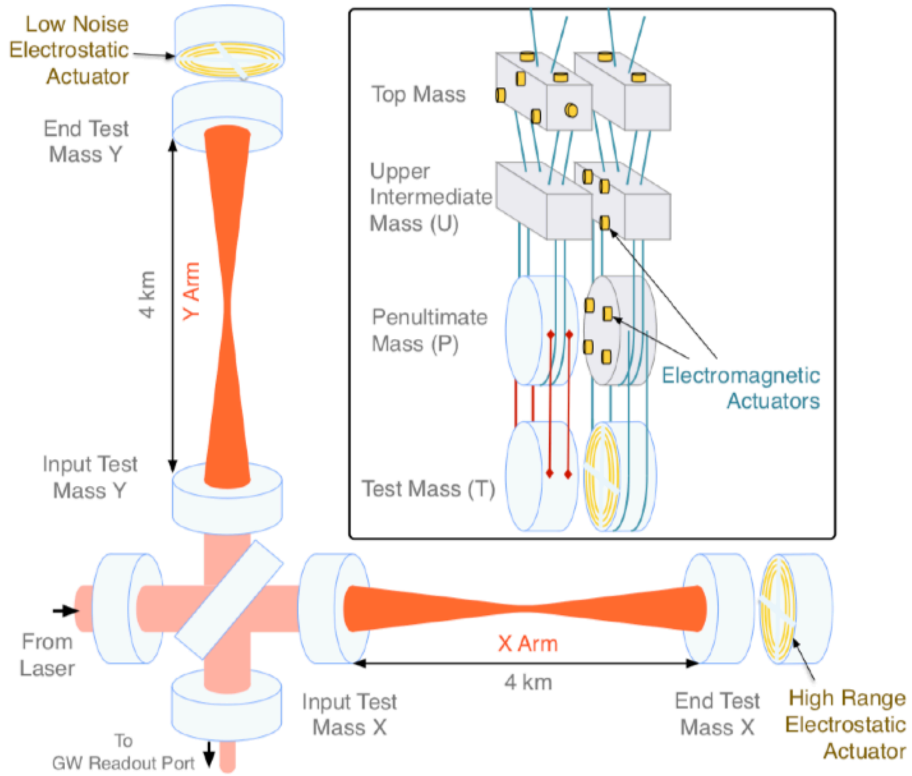
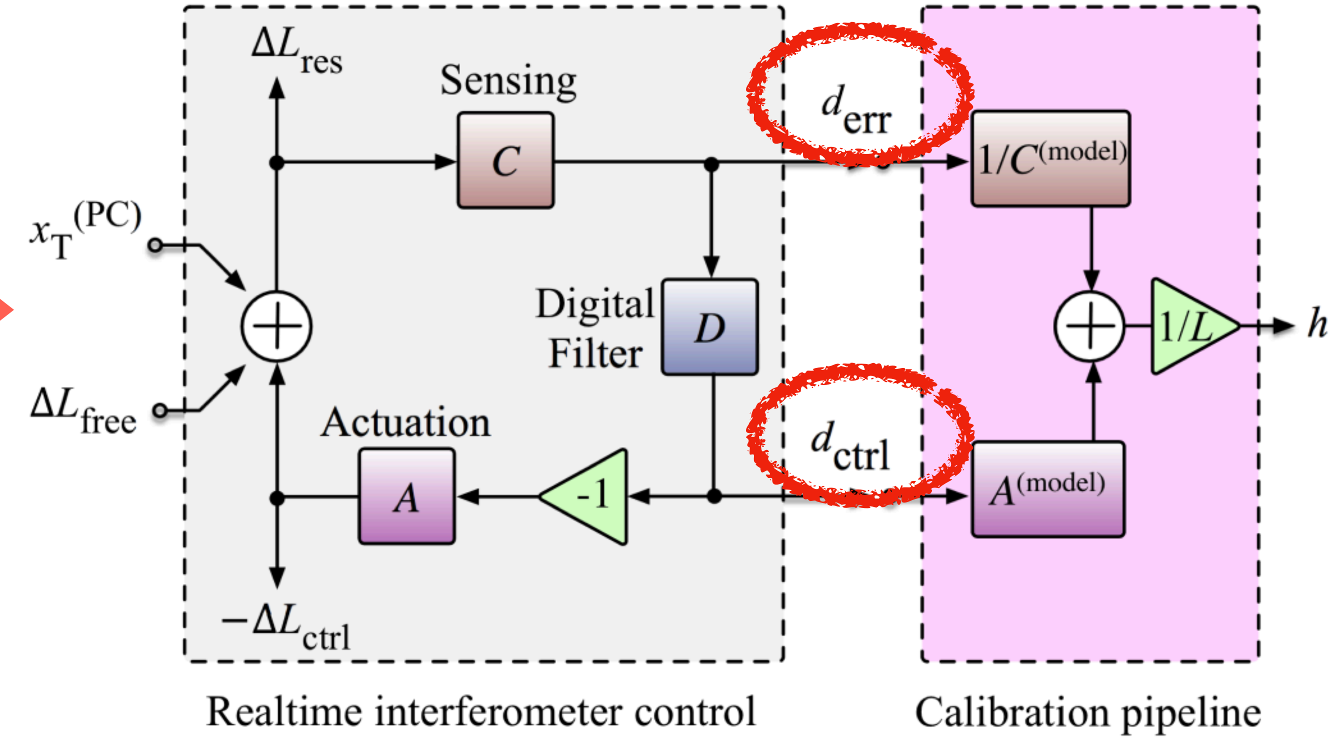
Reconstruction of LIGO





$$\mathbf{d_{err}, d_{ctrl} \not\approx h(t)}$$

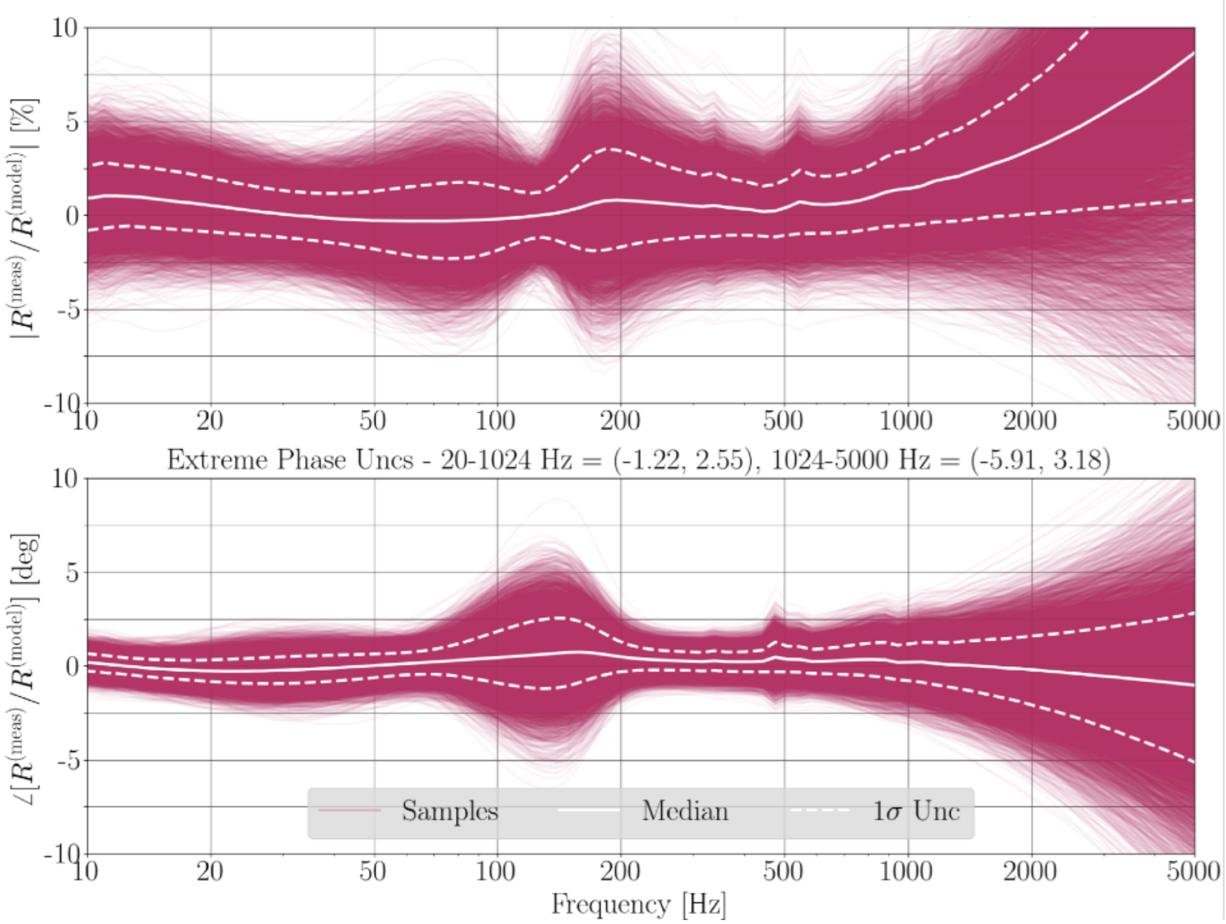
Modeling error -> Calibration error

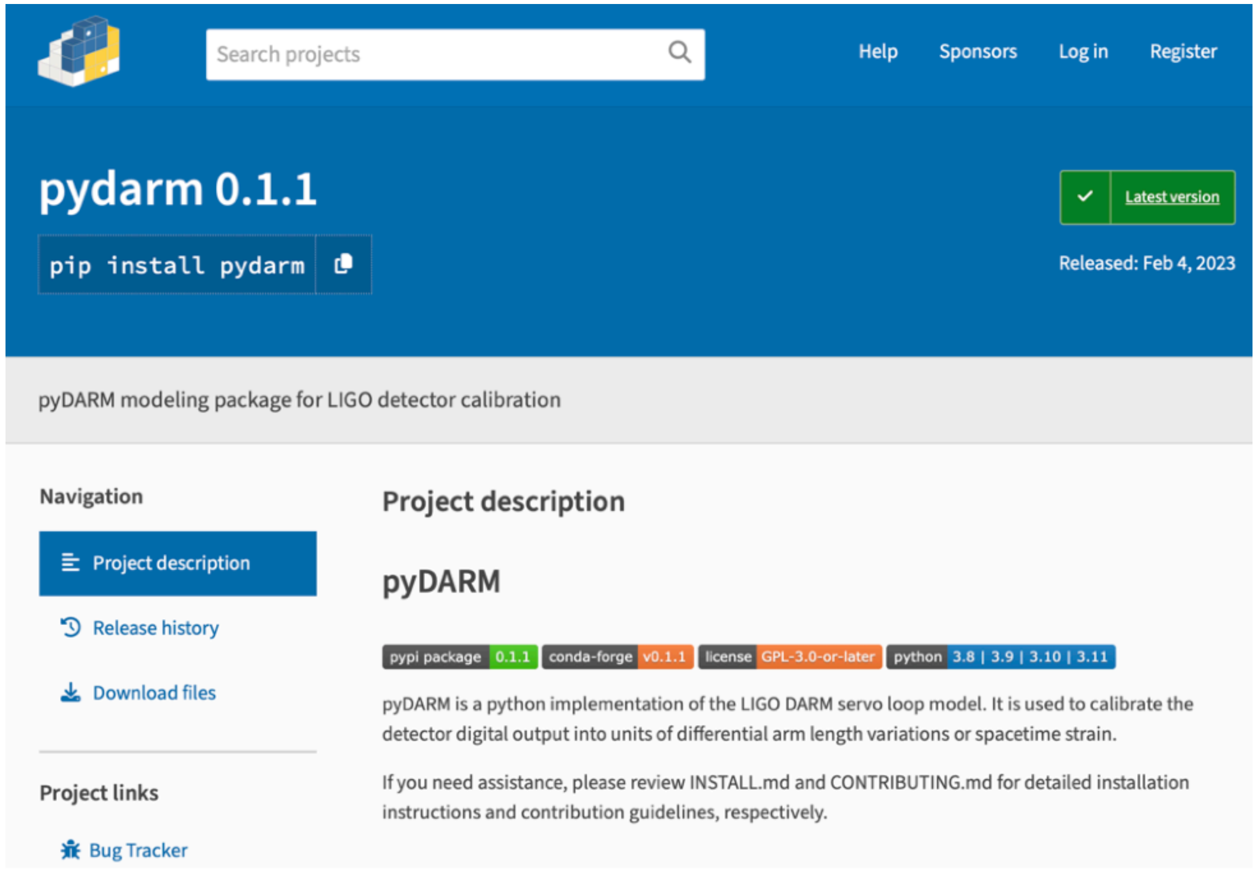
We reconstruct h(t) by modeling time-dependent Sensing and Actuation factor

$$h(t) = \frac{\Delta L_{\mathrm{ext}}(t)}{L} \quad = \quad \mathcal{C}^{-1} * d_{\mathrm{err}}(t)/L + \mathcal{A} * d_{\mathrm{ctrl}}(t)/L$$

Development of pyDARM

- python DARM model
- Interferometer modeling
- Filter generation for reconstruction
- Calibration parameter and filter
- Systematic uncertainty estimation of provided h(t)





Quick Progress of O5 model project

$$h(t) = \frac{\Delta L_{\mathrm{ext}}(t)}{L} = \mathcal{C}^{-1} * d_{\mathrm{err}}(t)/L + \mathcal{A} * d_{\mathrm{ctrl}}(t)/L$$

Requirement of O5 model

- **Including Homodyne detection angle**
- **Including Detuning angle**

Non-zero ϕ and ζ model is required!

Our approaches

Yuki Inoue: Development of analytical model

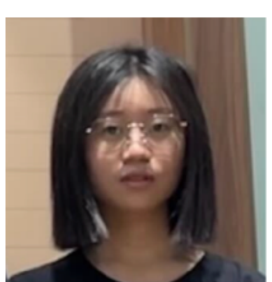
You-Ru Lee: Comparing the accuracy of analytical model with Finesse3

Yuki's contribution

Input parameter

Transmissivity of ETM	T_e	5 ppm
Transmissivity of ITM	T_i	1.4%
Transmissivity of SRC	T_s	37 %
Arm Length	L	4000 m
Mass of Test mass	M	40kg
laser wave length	λ_0	1064nm
Input laser power	P_{in}	125W

You-Ru's contribution



Analytical model

Calculate C function from creation/annihilation operator under liner perturbation theory

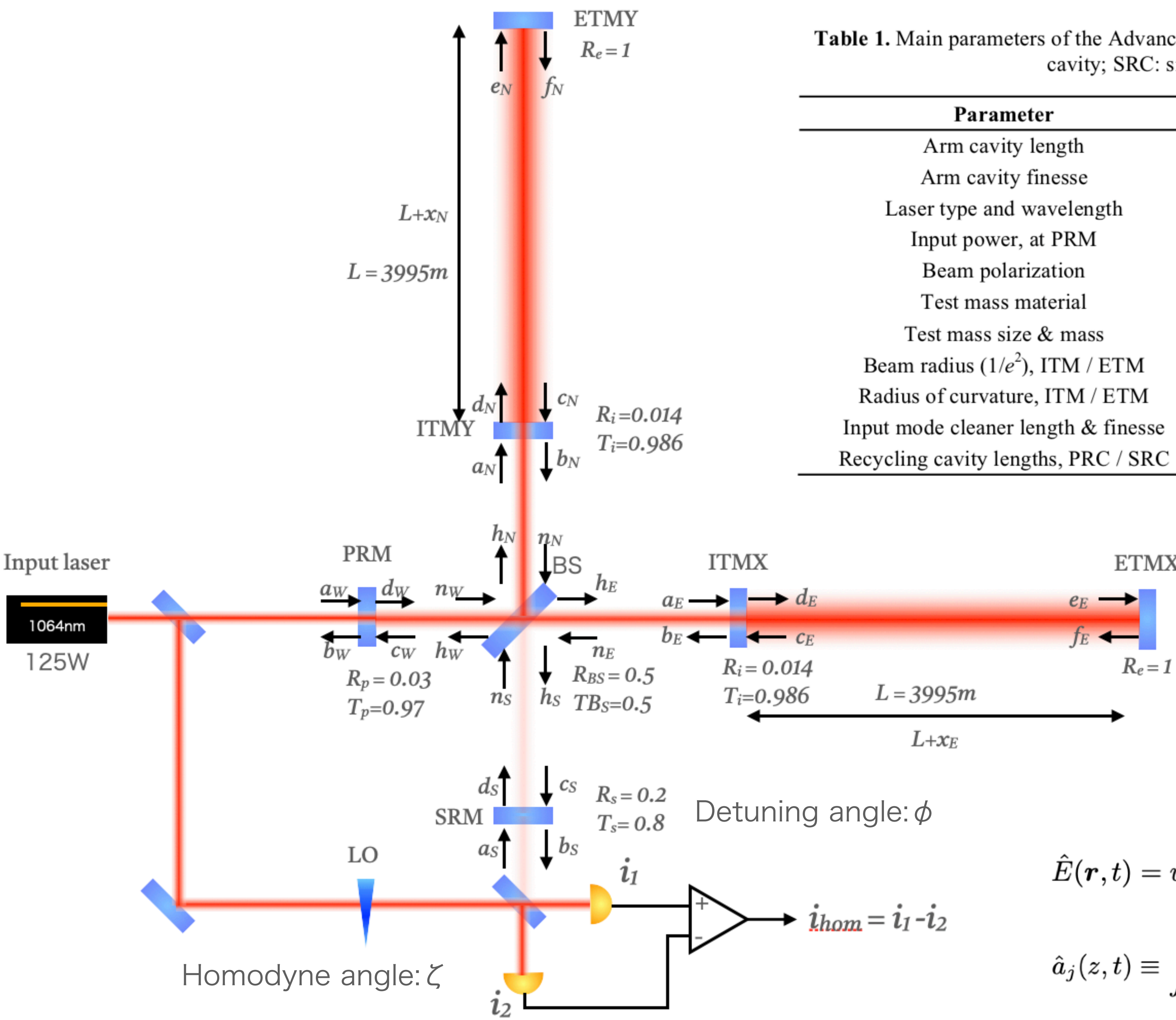
Comparison!

New approaches!

Simulate C function with Optical simulation software

Finesse3 simulation

Interferometer Model



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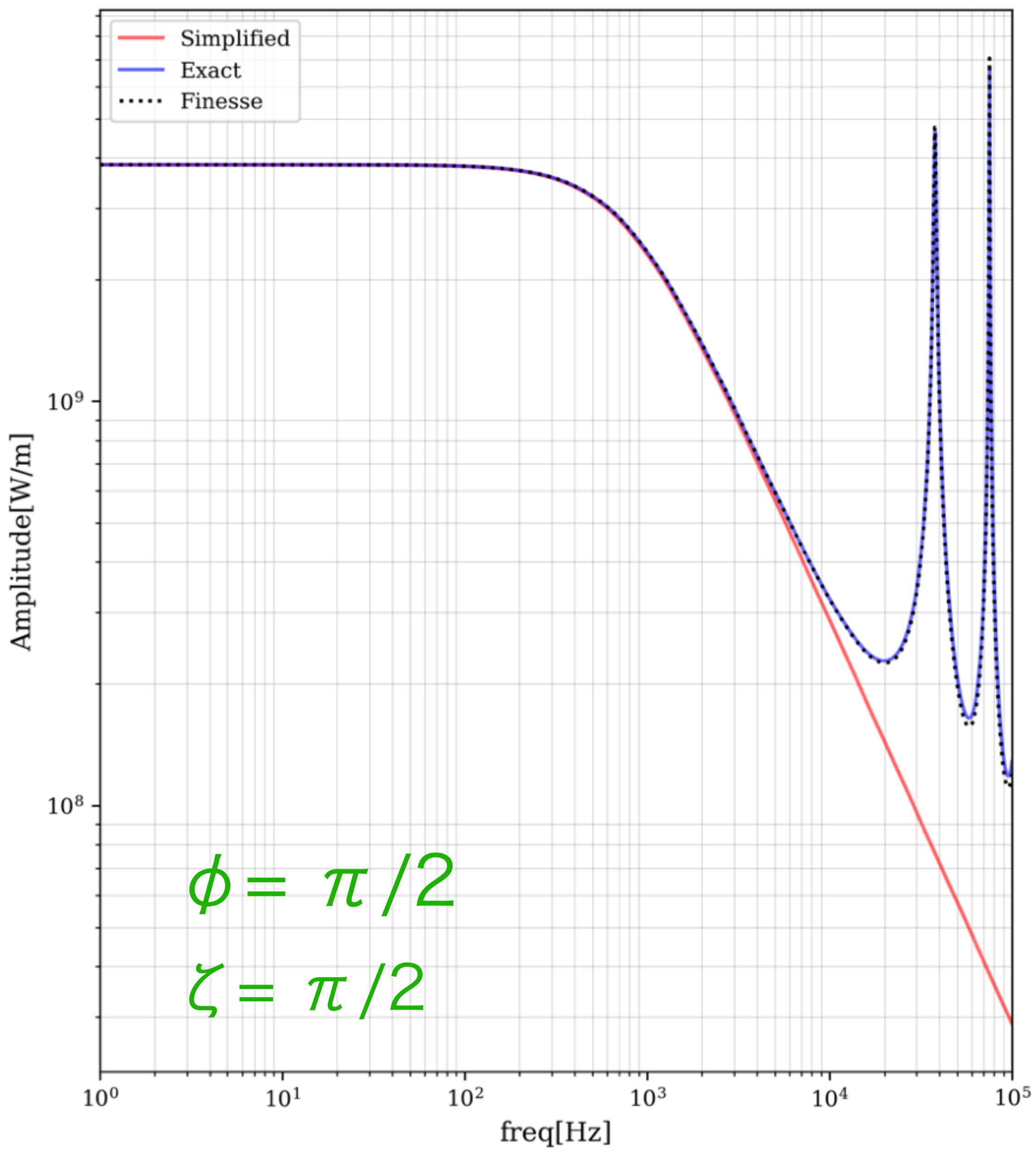
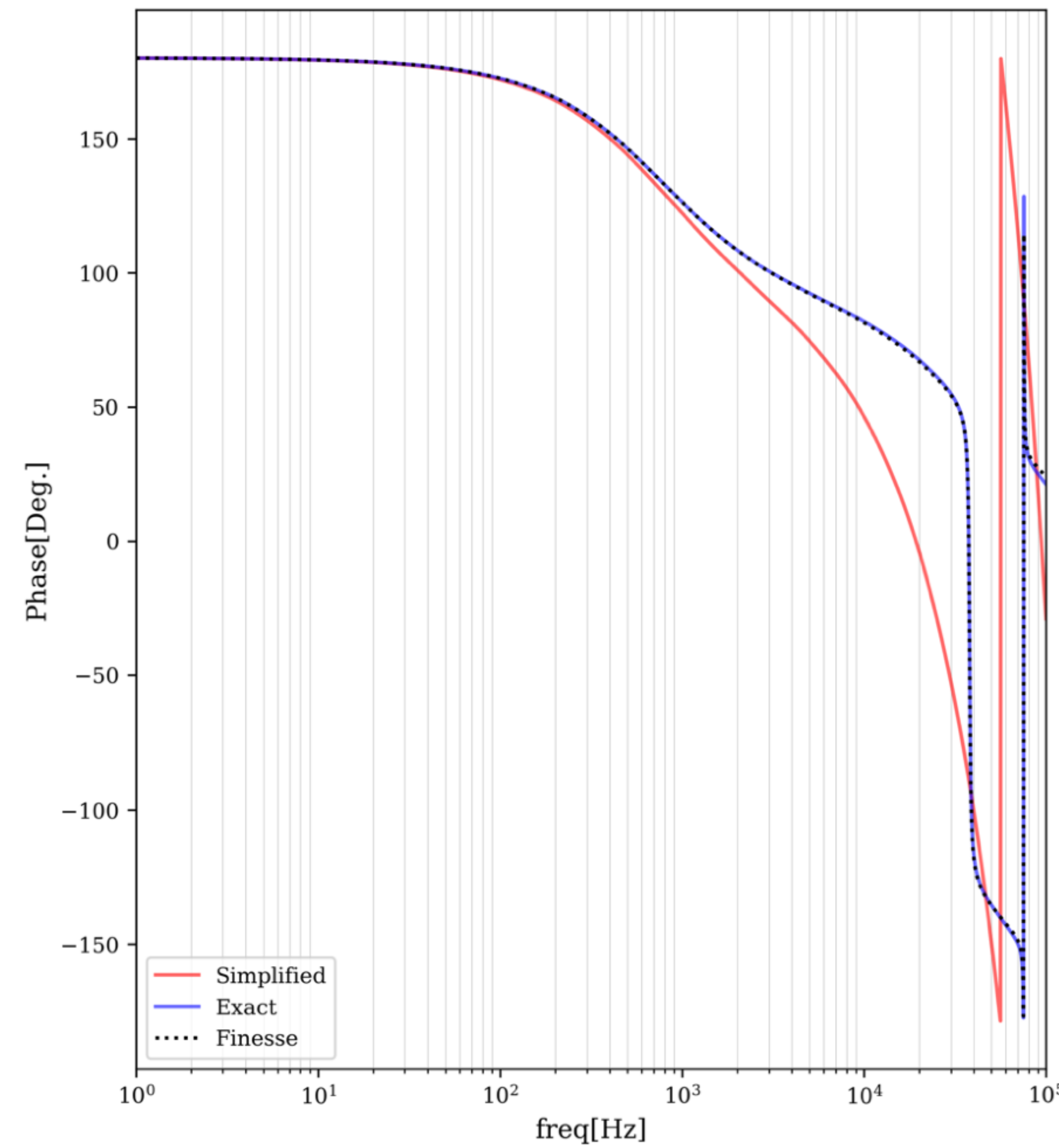
$$\hat{E}(\boldsymbol{r}, t) = u(\boldsymbol{r})\sqrt{\frac{4\pi\hbar\omega_1}{\mathcal{A}c}}\left[\hat{a}_1(z,t)\cos\omega_1 t + \hat{a}_2(z,t)\sin\omega_1 t\right]$$

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

Comparison with simulation





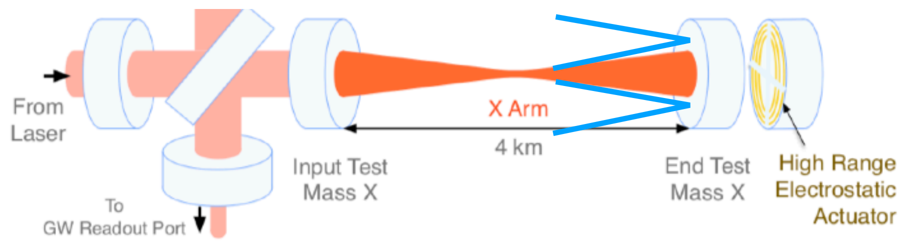
$$C(f) = \frac{g\,\mathrm{e}^{-2\pi\mathrm{i}fL/c} \times (1 + \mathrm{i}f/z)}{1 + \mathrm{i}f/|p|Q_p - f^2/|p|^2 - \xi^2/f^2},$$

Consistent with simulation!

$$C(f) = g\frac{(\cos(\beta+\Phi_s) + if_a\sin(\beta+\Phi_s)/z)}{(\cos(\beta+\Phi_s) + if_a\sin(\beta+\Phi_s)/p)(\cos(\beta+\Phi_s) + if_a\sin(\beta+\Phi_s)/p^*) - \xi^2/f^2}\frac{(1-r_i)}{\sqrt{1-2r_i\cos 2\Phi + r_i^2}}$$

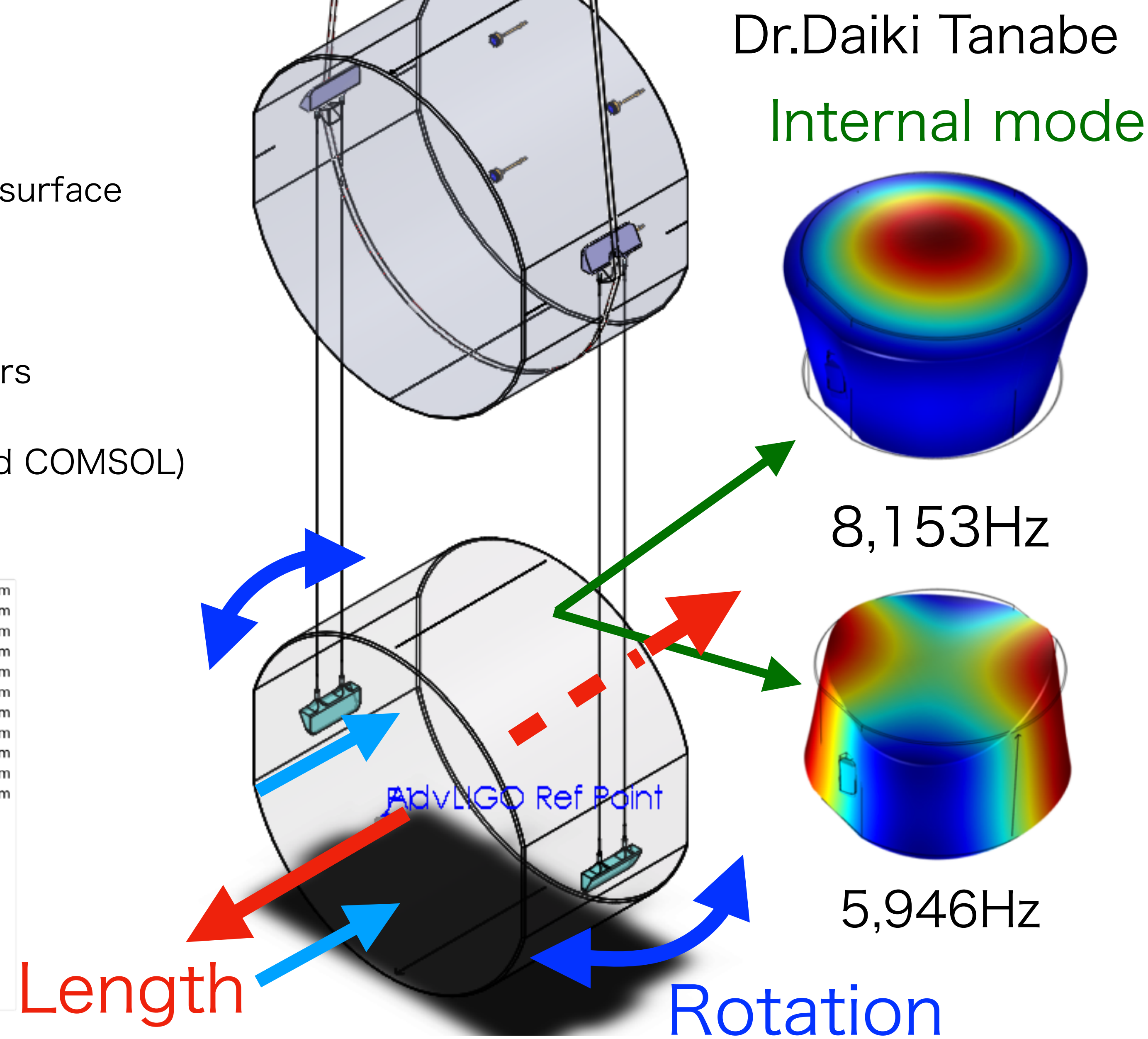
Bulk deformation of LVK

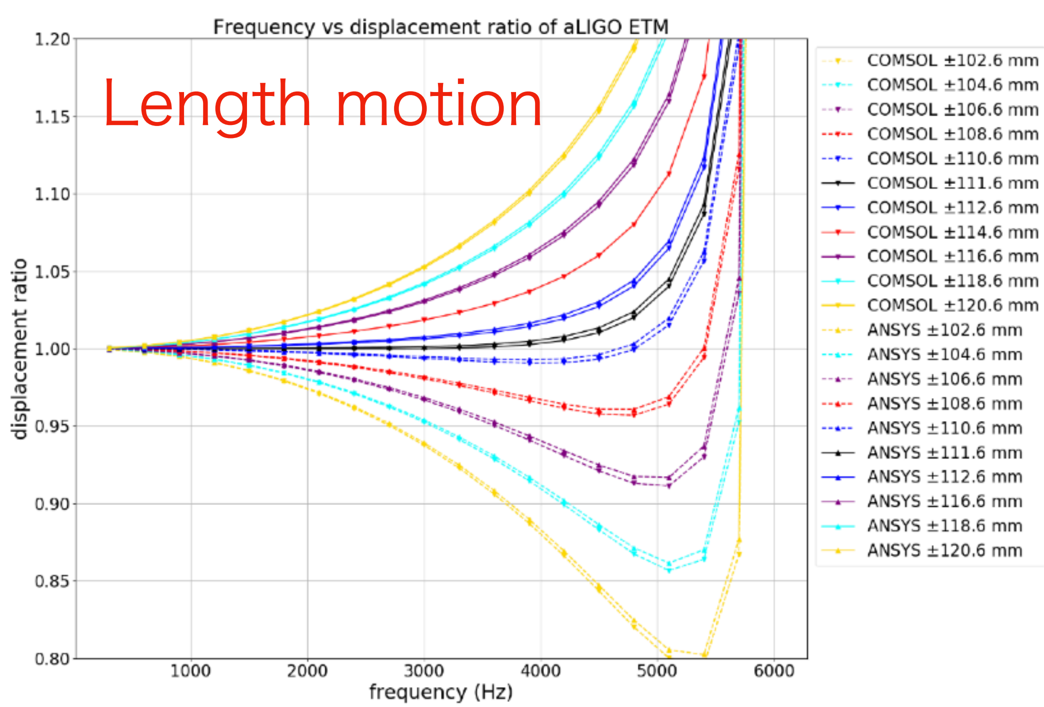
Photon Calibrator



Dr.Daiki Tanabe

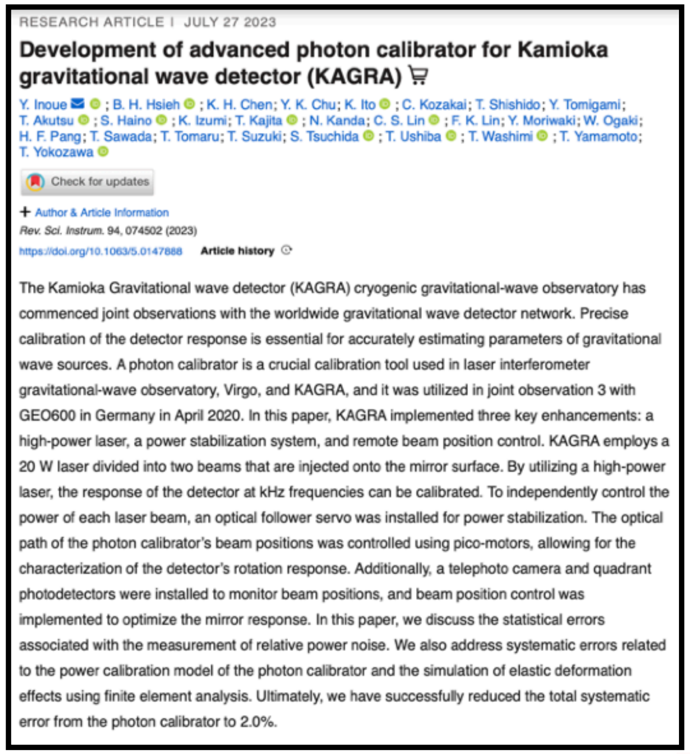
- Calibration instruments to measure C and A
- Inject independent laser beam for pushing mirror surface
- We can separate 3 components
- Rotation error is one of the major systematic errors
- Estimate the effect by FEM simulations (Ansys and COMSOL)





Taiwan calculate all LVK systematic error

4G Calibration instruments



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

+ Author & Article Information
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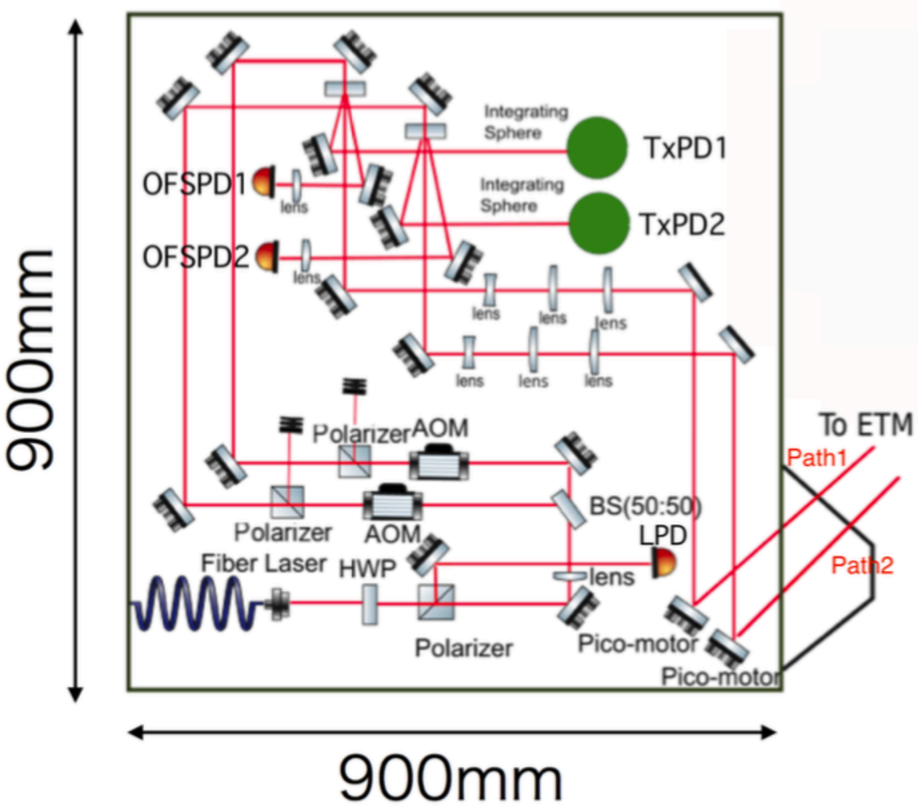
https://doi.org/10.1063/5.0147888 Article history

The Kamioka Gravitational wave detector (KAGRA) cryogenic gravitational-wave observatory has commenced joint observations with the worldwide gravitational wave detector network. Precise calibration of the detector response is essential for accurately estimating parameters of gravitational wave sources. A photon calibrator is a crucial calibration tool used in laser interferometer gravitational-wave observatory, Virgo, and KAGRA, and it was utilized in joint observation 3 with GEO600 in Germany in April 2020. In this paper, KAGRA implemented three key enhancements: a high-power laser, a power stabilization system, and remote beam position control. KAGRA employs a 20 W laser divided into two beams that are injected onto the mirror surface. By utilizing a high-power laser, the response of the detector at kHz frequencies can be calibrated. To independently control the power of each laser beam, an optical follower servo was installed for power stabilization. The optical path of the photon calibrator's beam positions was controlled using pico-motors, allowing for the characterization of the detector's rotation response. Additionally, a telephoto camera and quadrant photodetectors were installed to monitor beam positions, and beam position control was implemented to optimize the mirror response. In this paper, we discuss the statistical errors associated with the measurement of relative power noise. We also address systematic errors related to the power calibration model of the photon calibrator and the simulation of elastic deformation effects using finite element analysis. Ultimately, we have successfully reduced the total systematic error from the photon calibrator to 2.0%.

Based on the experience of 3G Calibration instruments development in KAGRA. We are designing future LIGO Calibration instruments around 2029.

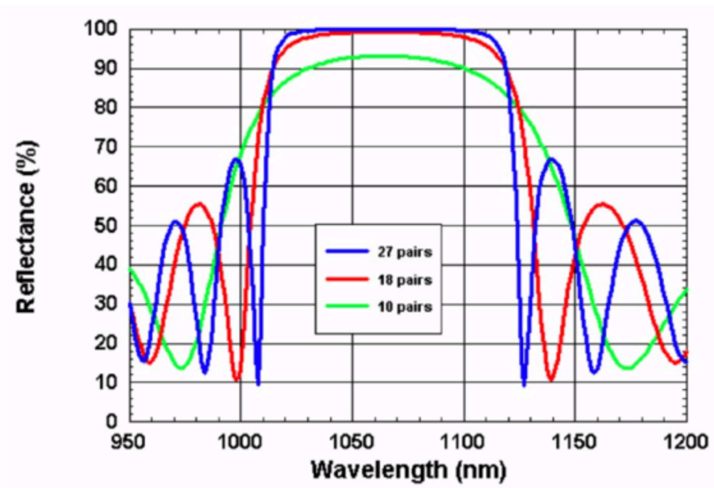


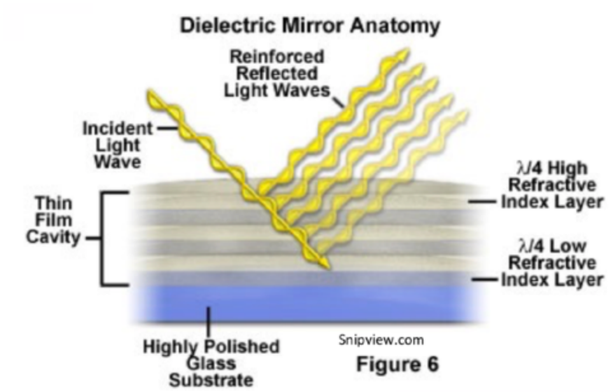
	Post-O5 Upgrade	Voyager Upgrade
Laser	Yb fiber laser 1-20W 1047nm KEO-CTFL-TERA (Keopsys) (Demonstrated in 3G-PCAL)	Thulium doped CW fiber laser 1-30W, 1900-2050um KEO-CTFL-TERA (Keopsys)
OFS	Same design, double OFS (Demonstrated in 3G-PCAL)	Same design, double OFS (Demonstrated in 3G-PCAL)
AOM	High power AOM: M1080-T80L-M (Demonstrated in 3G-PCAL)	AOM: M1099(M)-T40L-2 1.9-2,1um, 100W
Integrating Sphere	Same design: >99% b/w 400-1500nm (Demonstrated in LIGO)	Same design: >95% b/w 250-2500nm
Periscope	Improvement is needed	Development is needed
Calibration in NIST	Same design (Demonstrated in LIGO)	New setup need to be installed in NIST (2027~)

Optics(Coating)

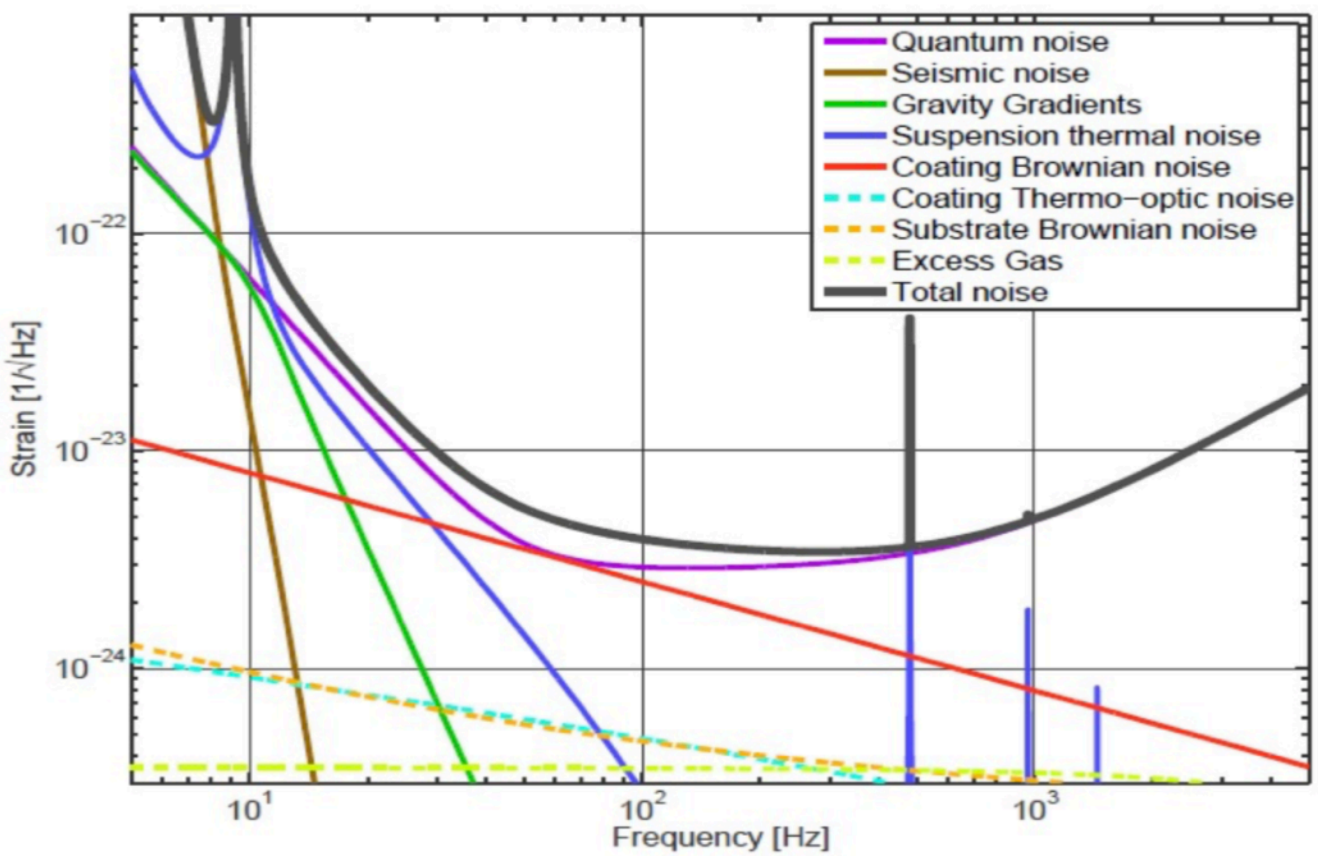
Contribution of LIGO 2 (Coating)

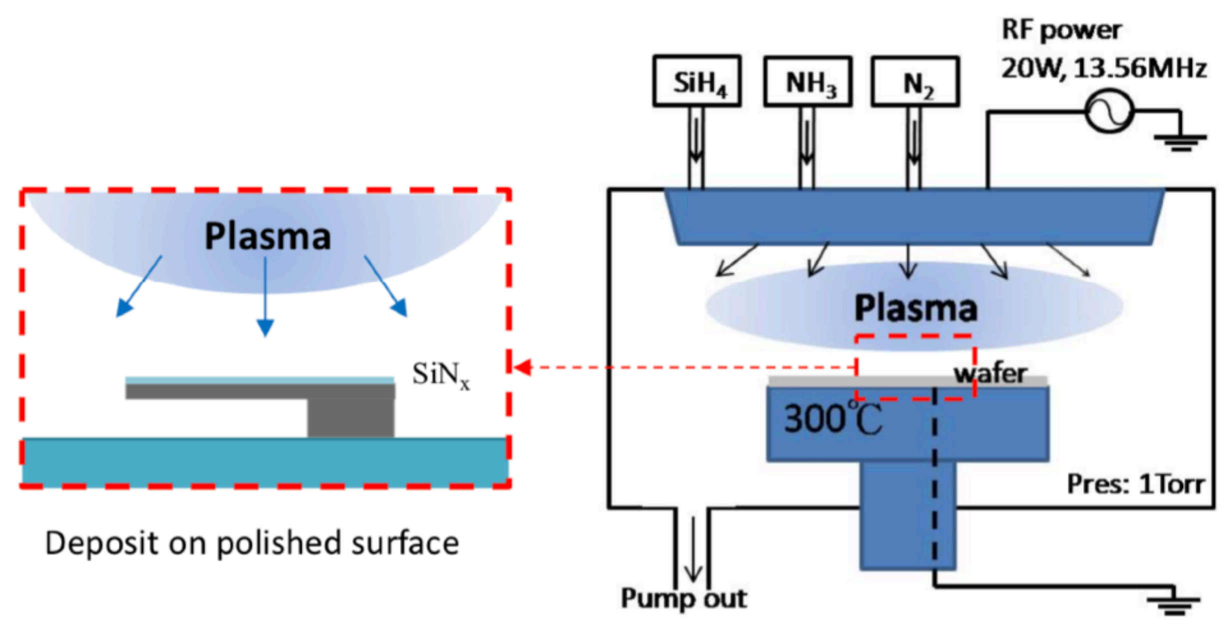
Development of High quality coating technique with Chemical Vapor Deposition method



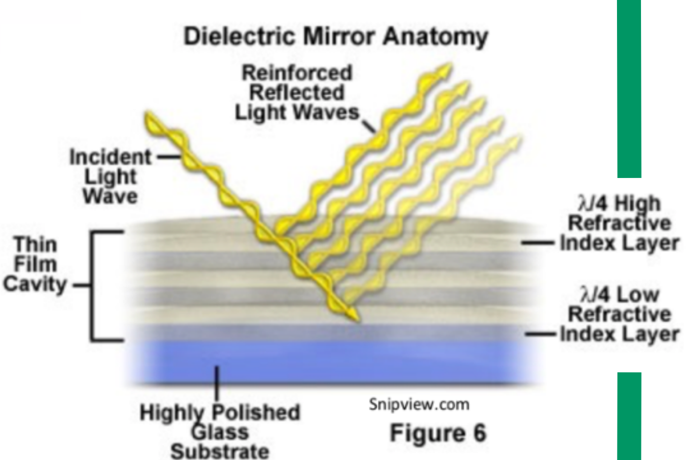


- LIGO employs Ion Beam Spattering Coating
- Large area coating technique
- Taiwan has high quality semiconductor technique
- Development of new coating method

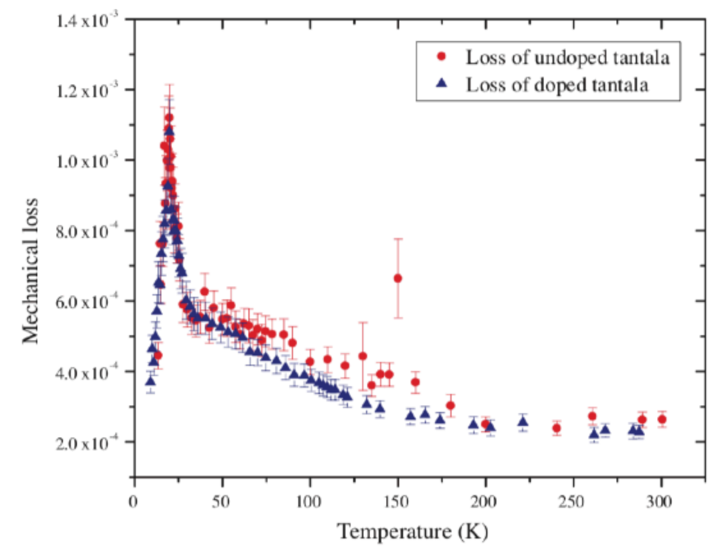




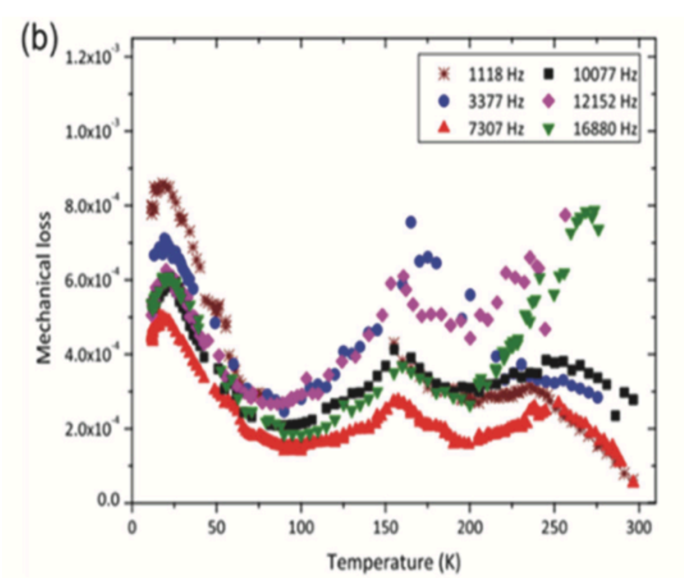
Current problem and approaches



High index material (Ti:Ta2O2)



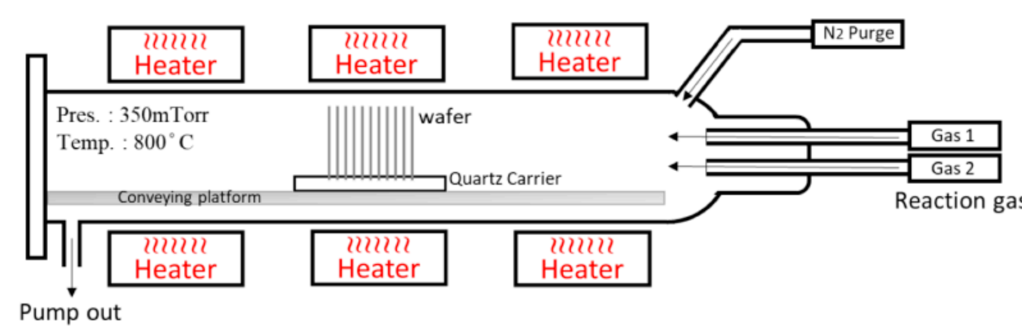
Low index material (SiO2)



I.W.Martin et. al.(2009)

There are low temperature mechanical loss peak for both materials.

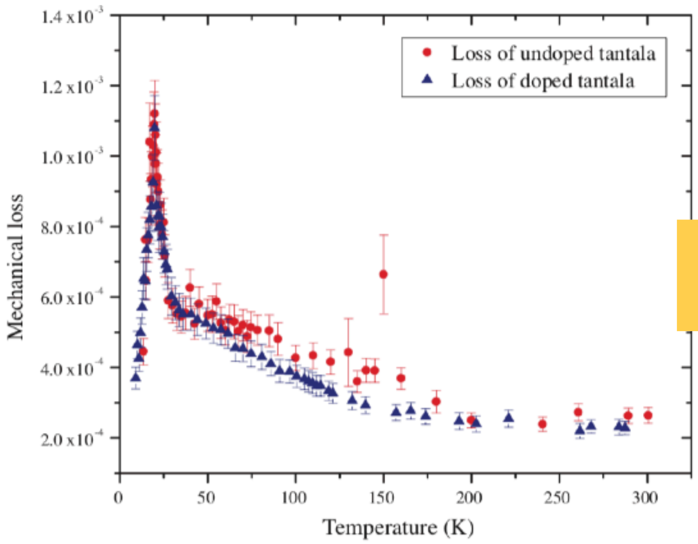
By using LPCVD method, we will reduce the cryogenic peaks and optical absorption



Approaches

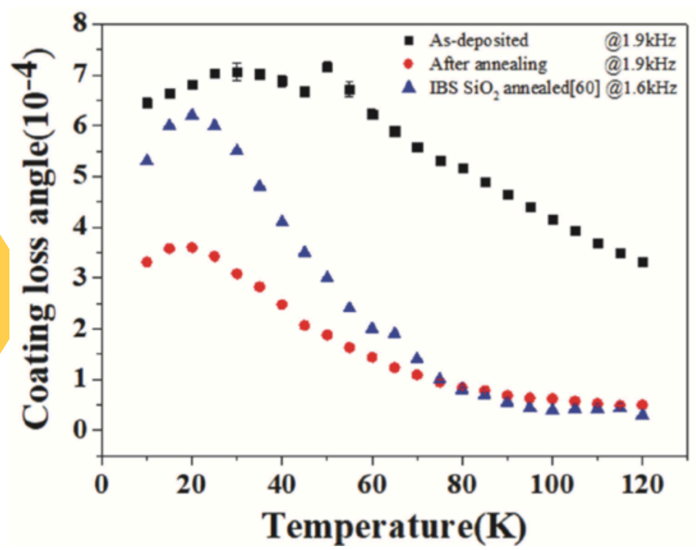
High index material

Ti:Ta2O2



Plasma enhanced CVD method

SiNX



Optical absorption: 1.4e-5 @1550nm

Low pressure CVD method

SiNX

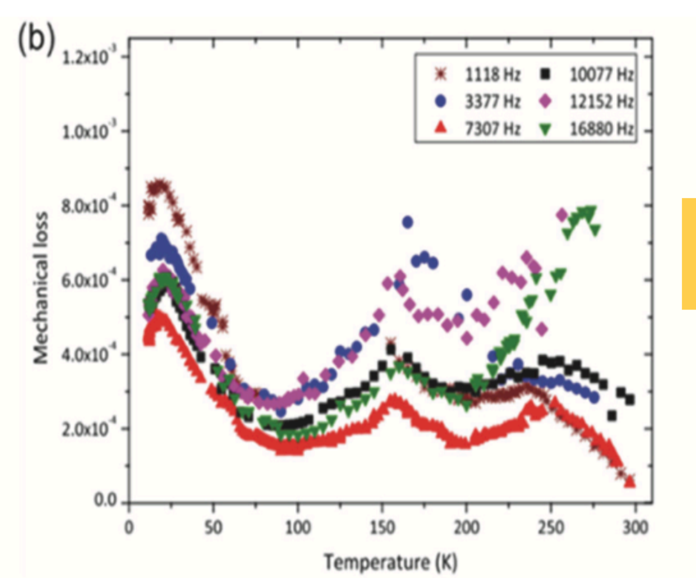
Fabrication: Done!!

Developing GNS system

Optical absorption:5.8e-6@1550nm

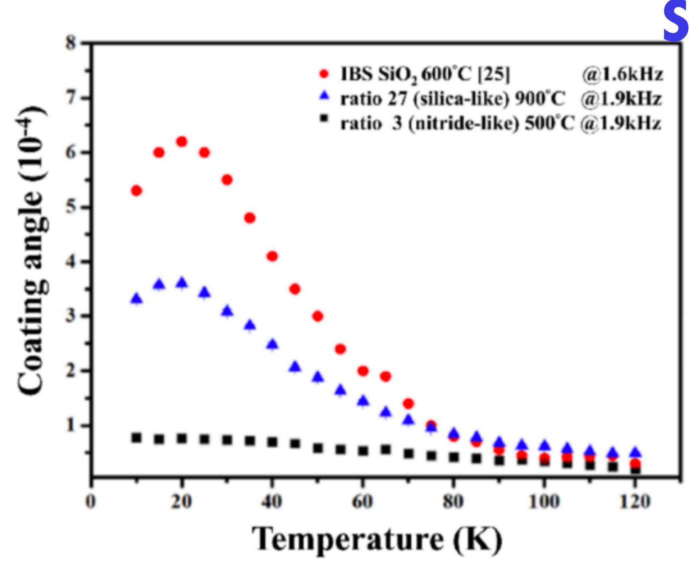
Low index material

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

Fabrication

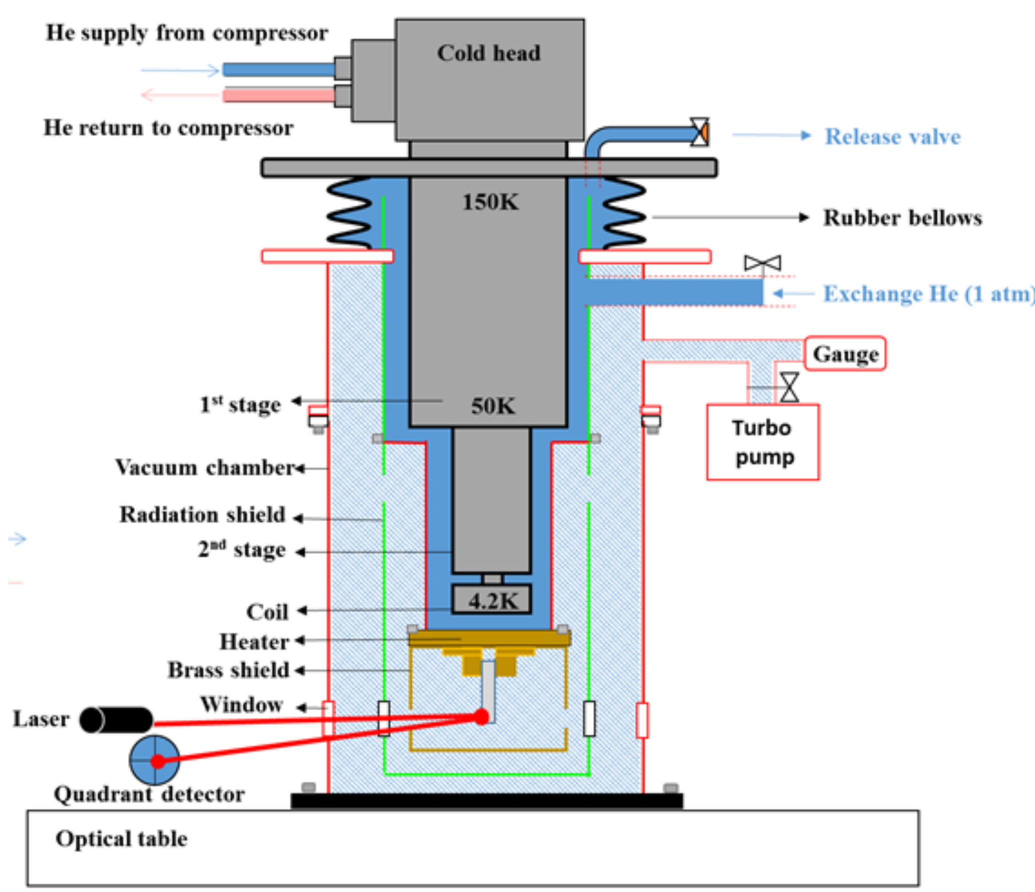
- Taiwan-LIGO instrumentation group (NCU-AS-NTHU) have developed coating with chemical vapor deposition (CVD) method. By using Taiwan Semiconductor Research Institute (TSRI), we test this idea.

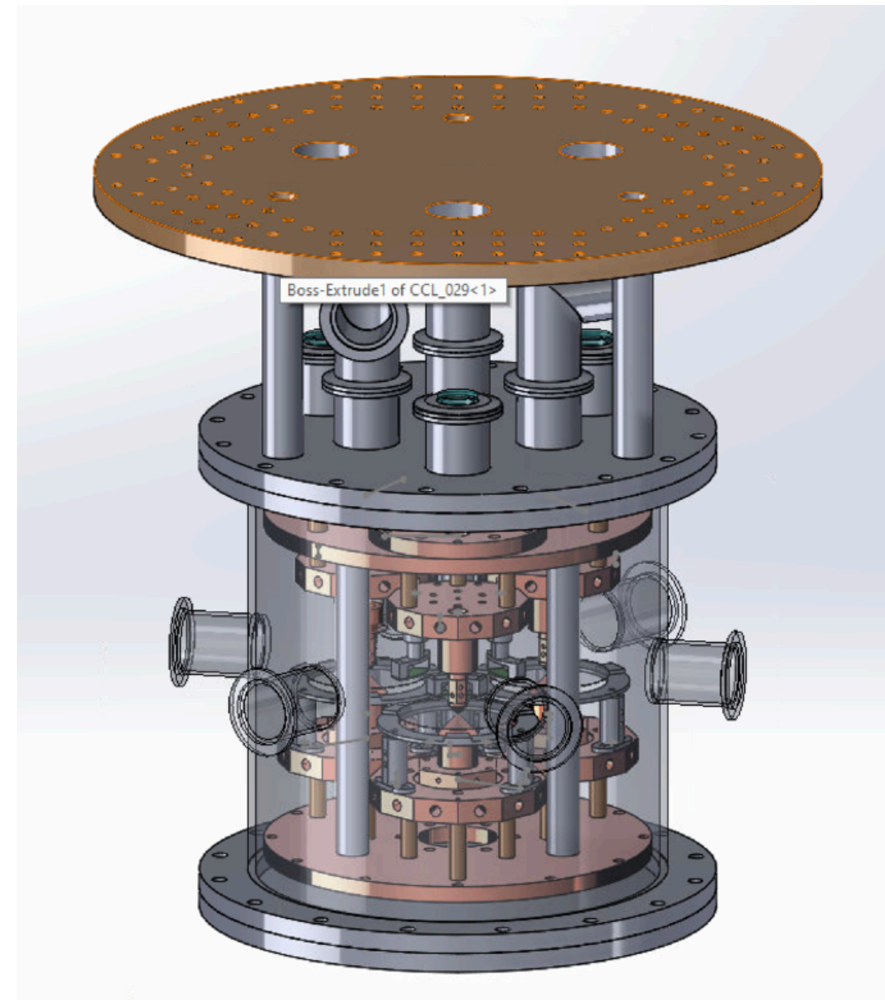
- In his study, we need to reduce the optical absorption with low pressure CVD method. The sample of high index material was developed. So, we focus on the development of low index material. However, we need to add N20 gas line to LPCVD system in TSRI.

- The proposal of gas line was approved in TSRI. The gas line will be prepared in April 2024.

Measurement system

Cryogenic Cantilever system

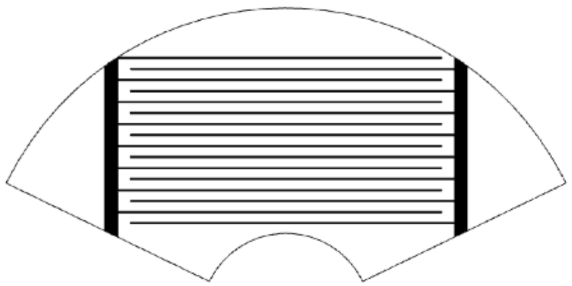


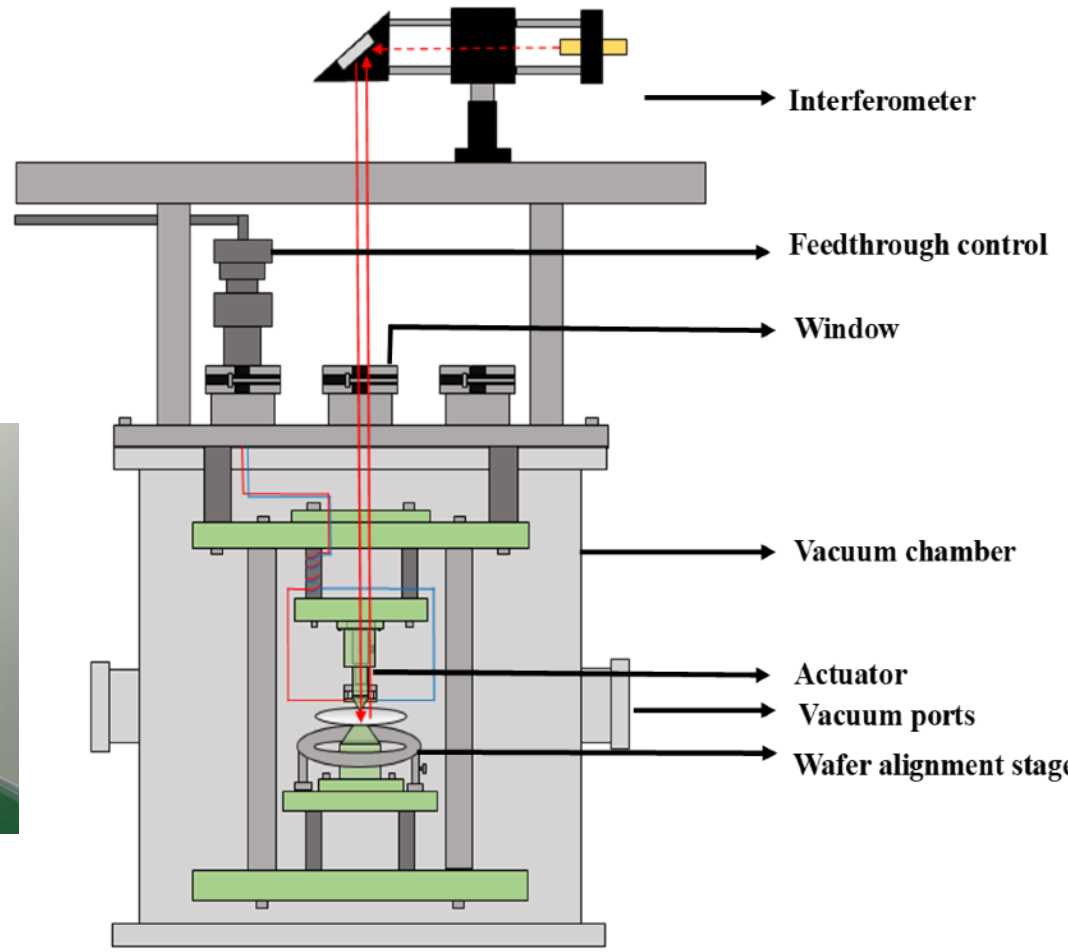


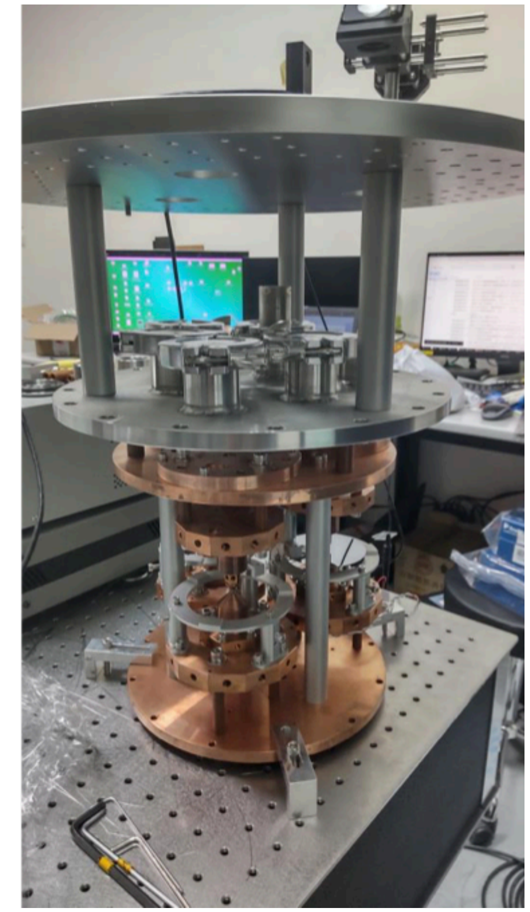
- To make a sample of Cryogenic Cantilever method, we need to consider the KOH edging method. But, because of pollution of system, we cannot use the it in LPCVD method.
- We decided to develop new cryogenic mechanical loss measurement system with GNS system

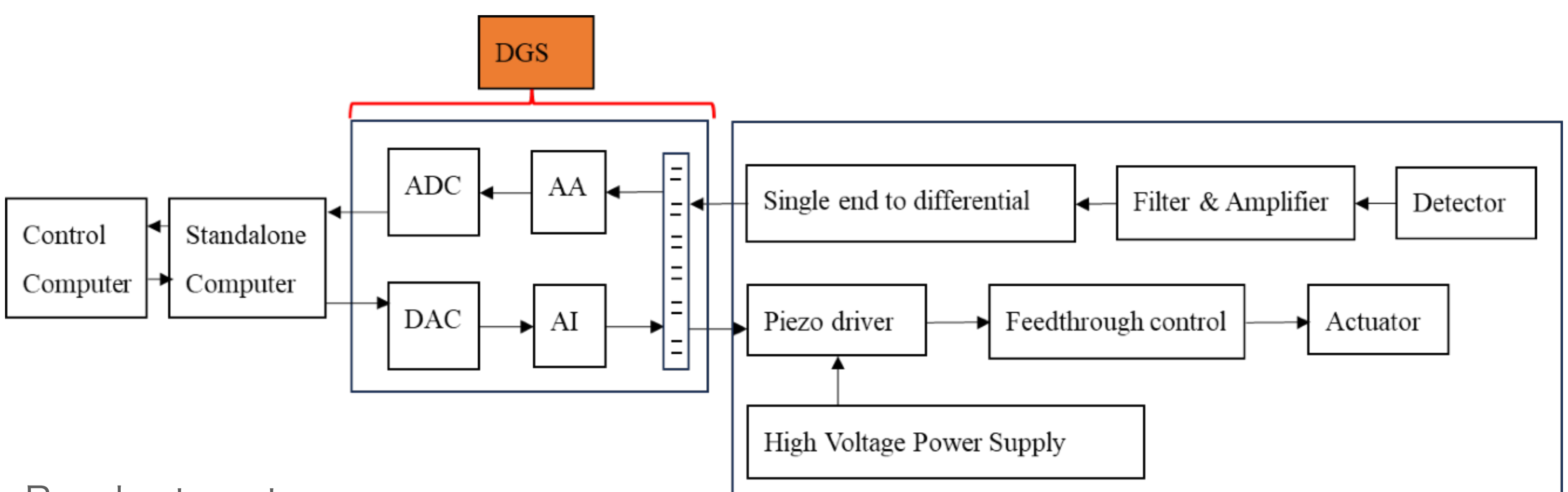
GNS system in Academia Sinica

Electric static actuator

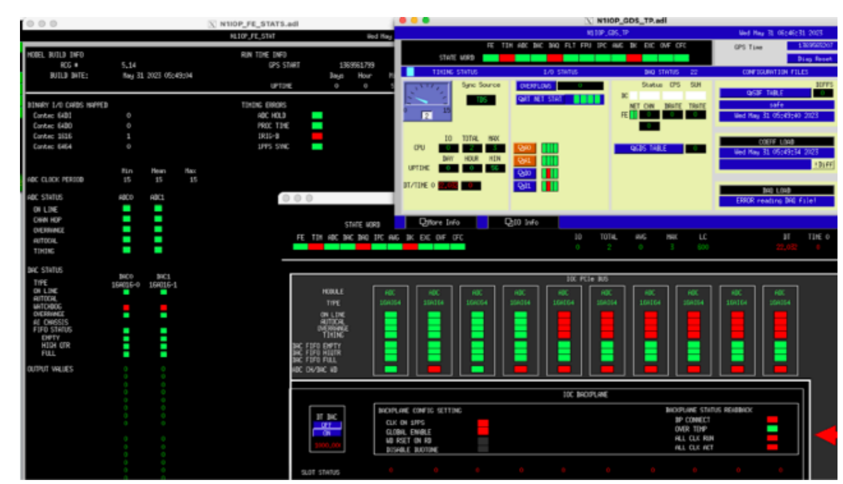








Readout system



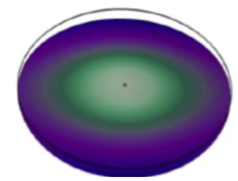
Digital System (Debian 11)

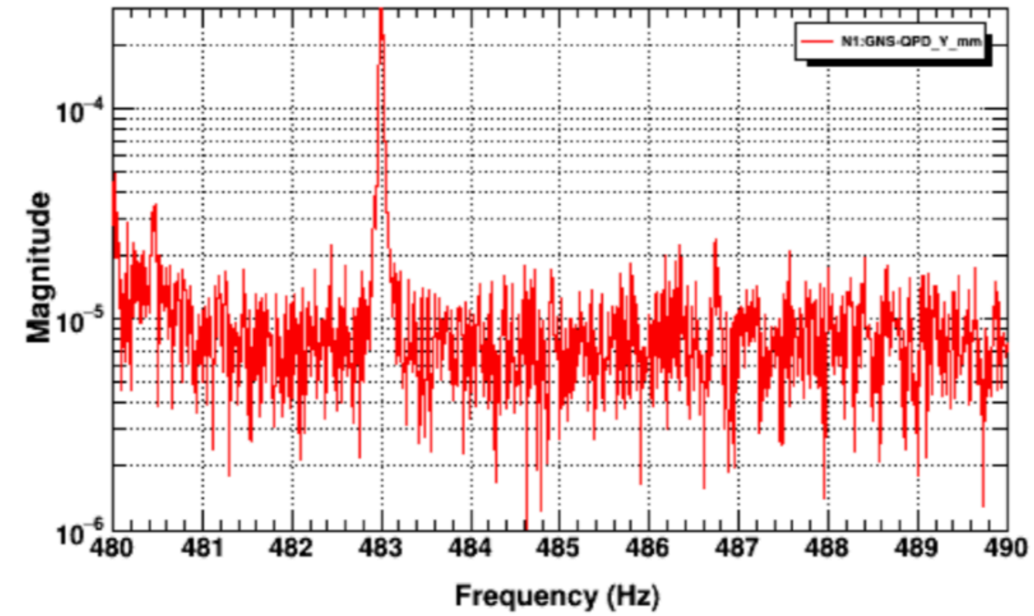
Test is ongoing

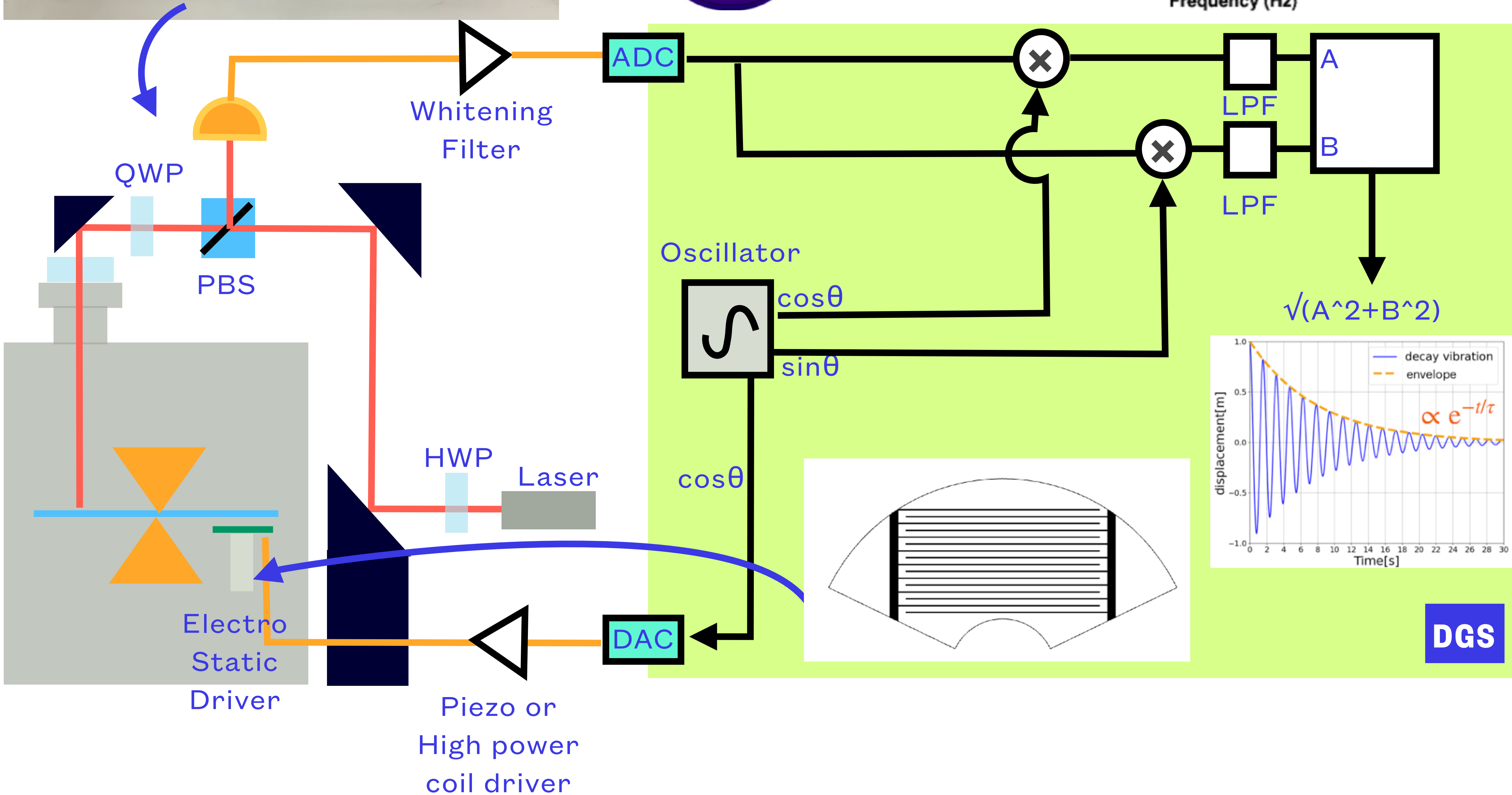
QPD/Interferometer Optional

Modal analysis with COMSOL

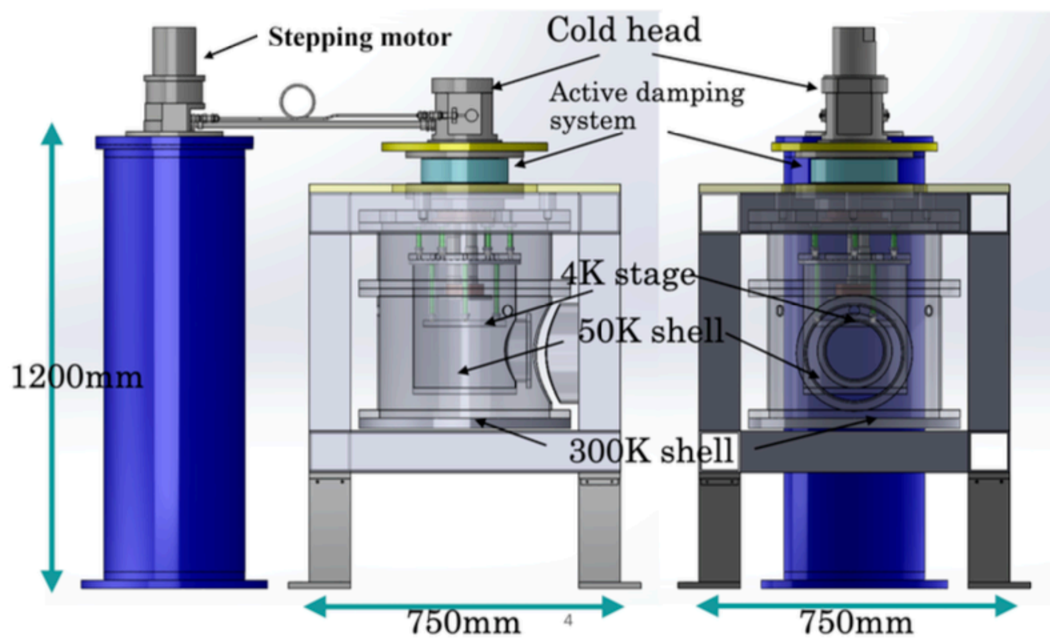
Mode 3 489.32Hz



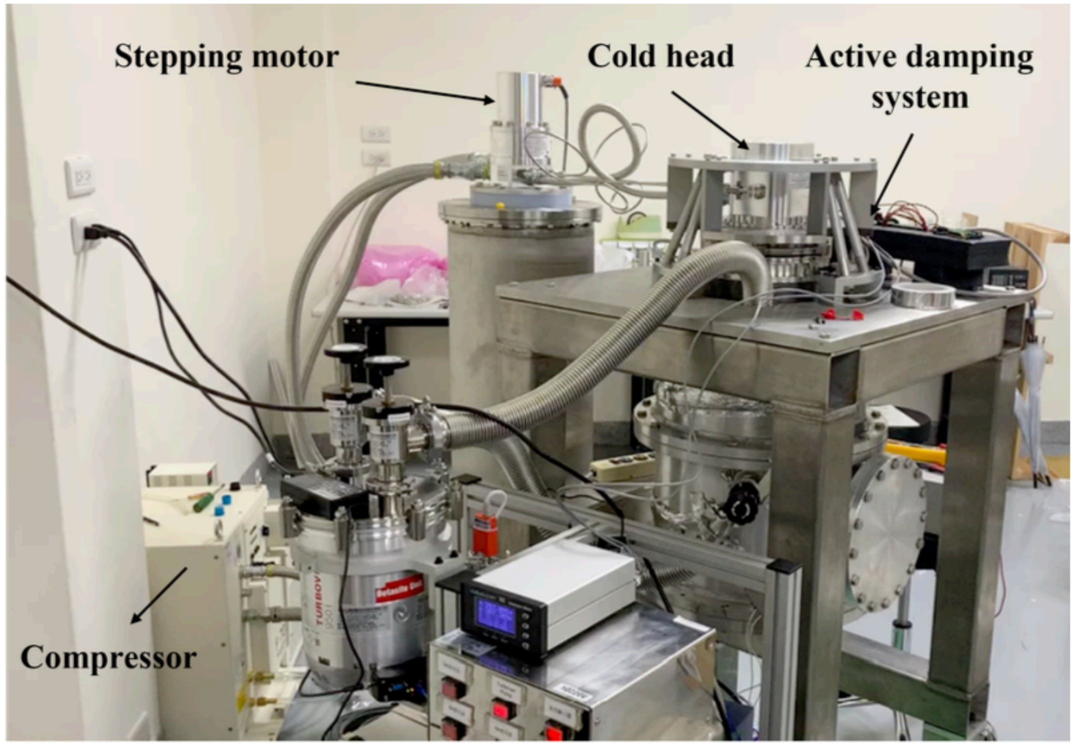




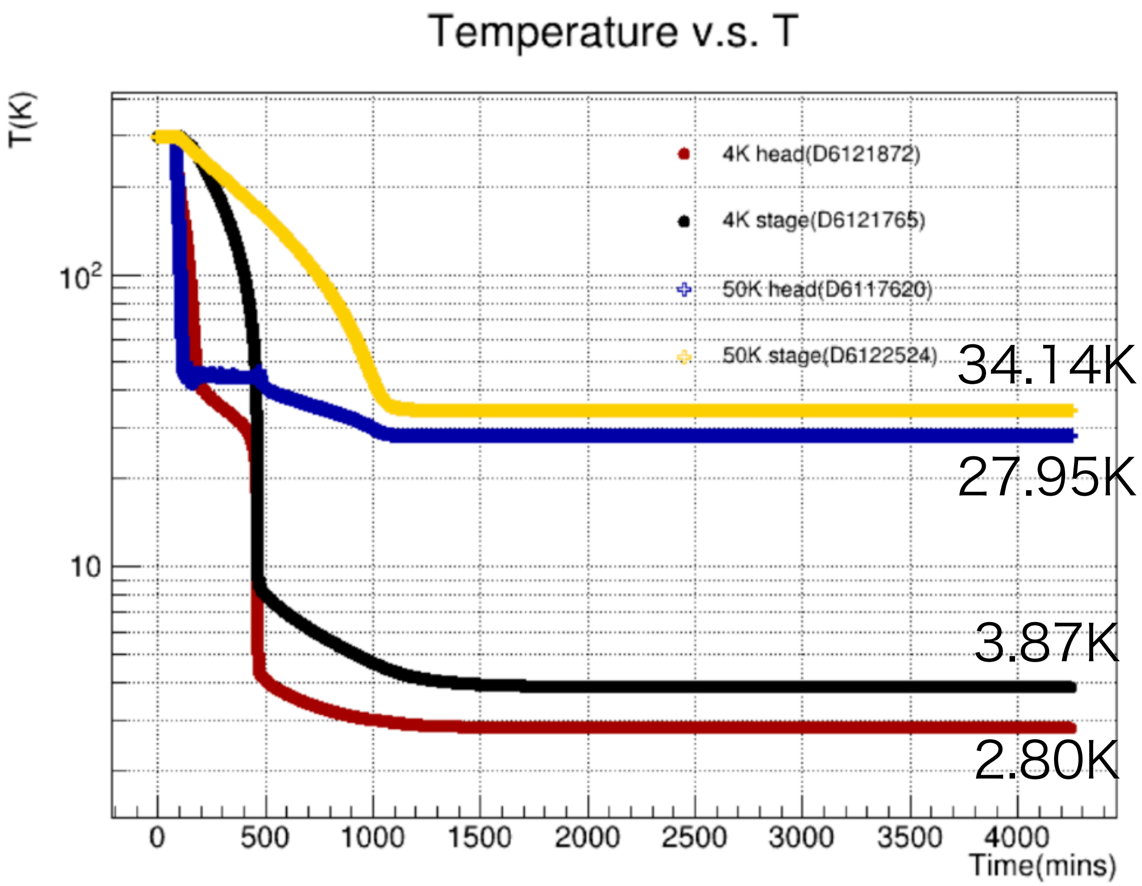
Cryogenic performance

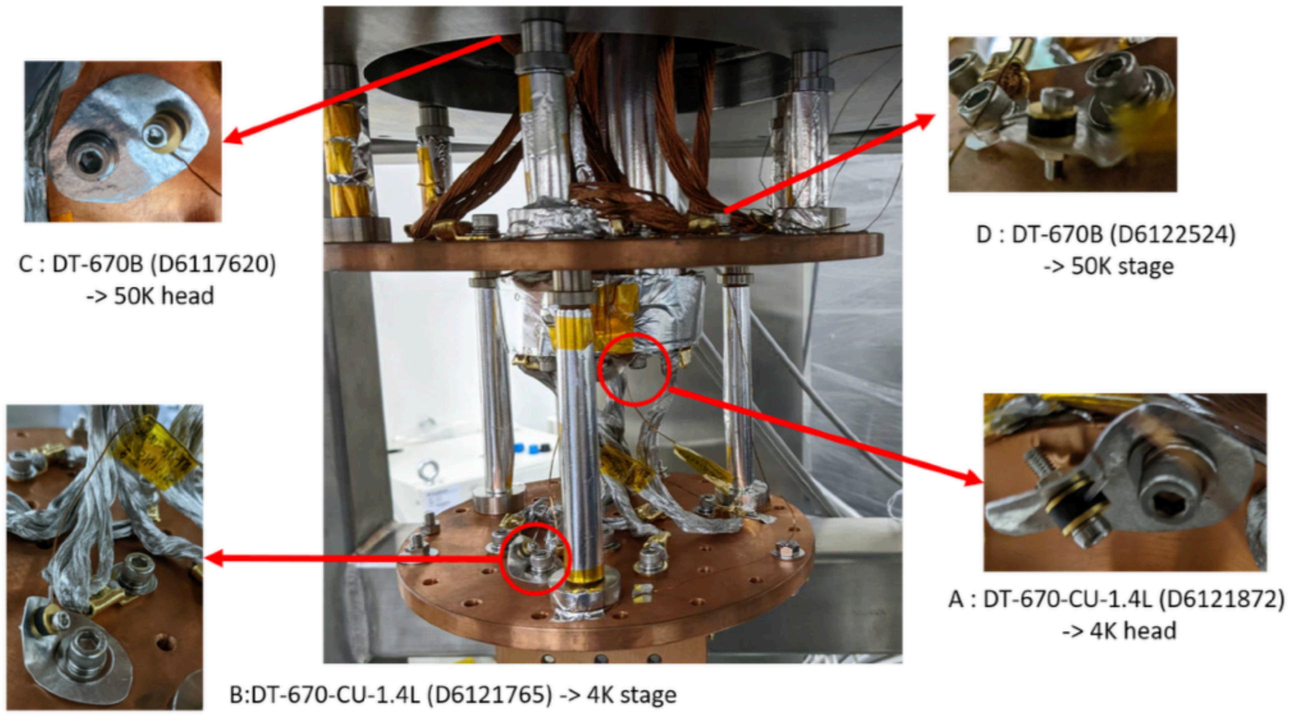


(a) The CAD rendering of the cryogenic

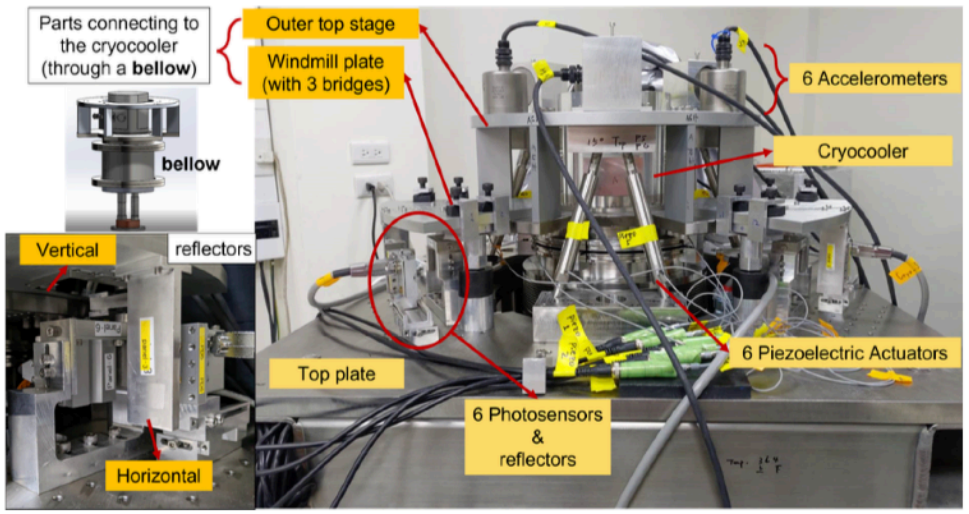


(b) The picture of the cryogenic chamber.

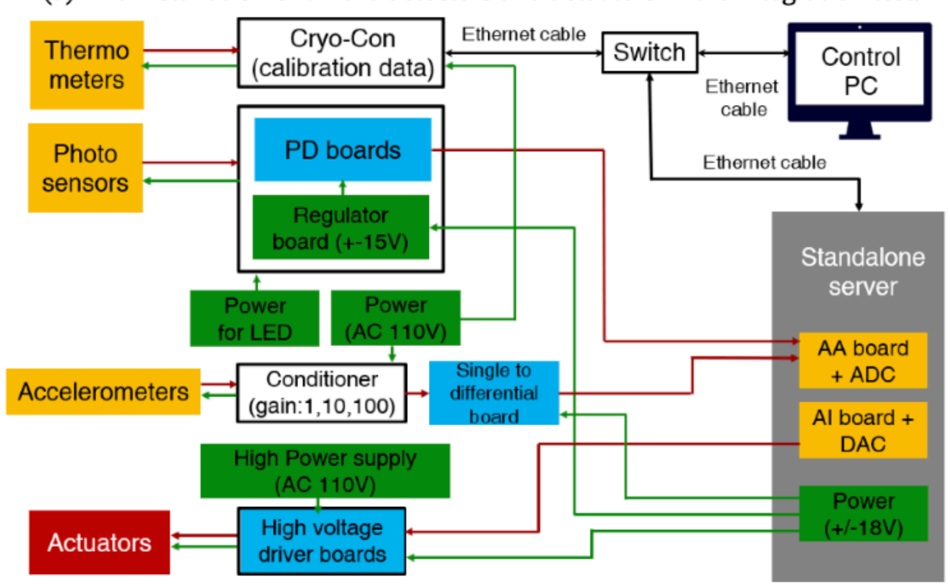




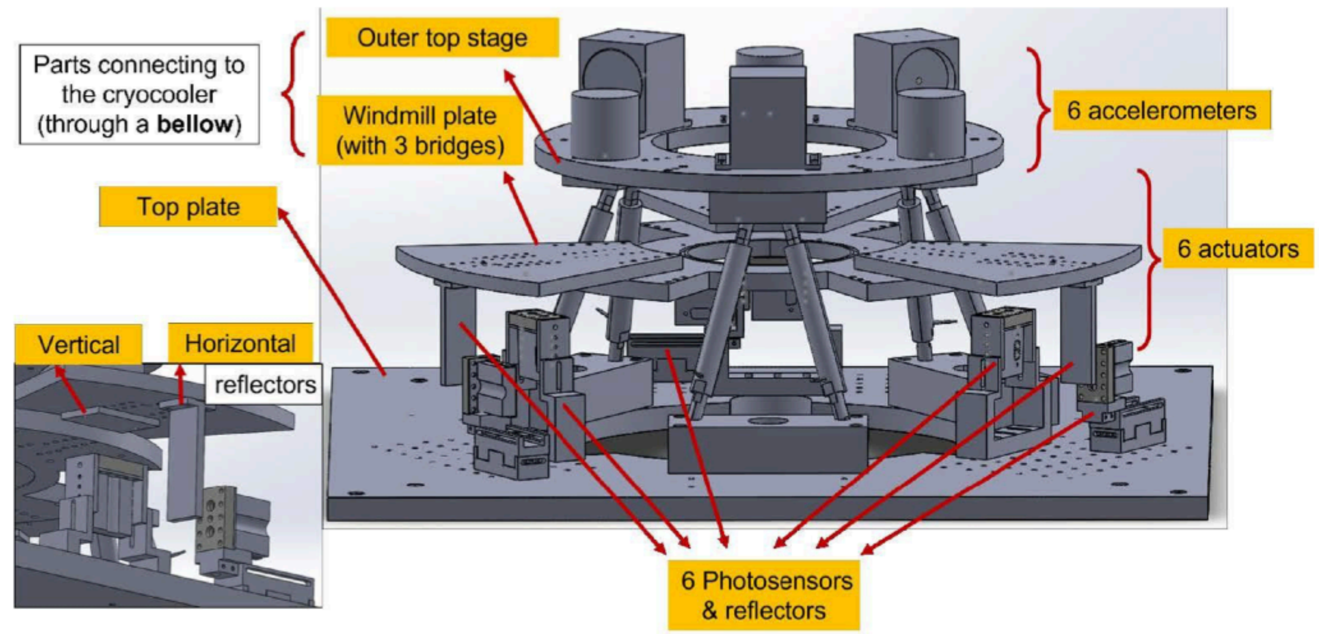
Active vibration isolation system

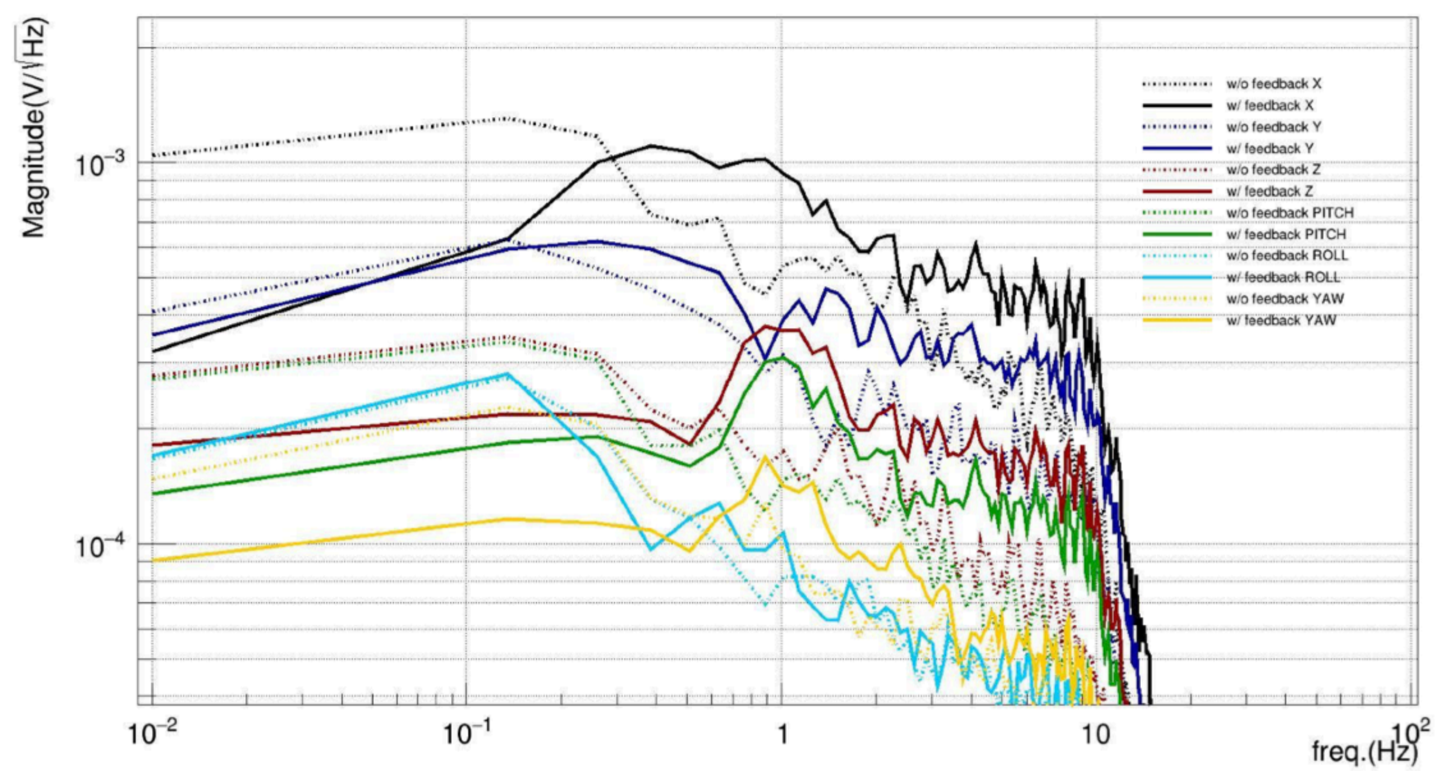


(a) The installation of all the detectors and actuators in the integration test.



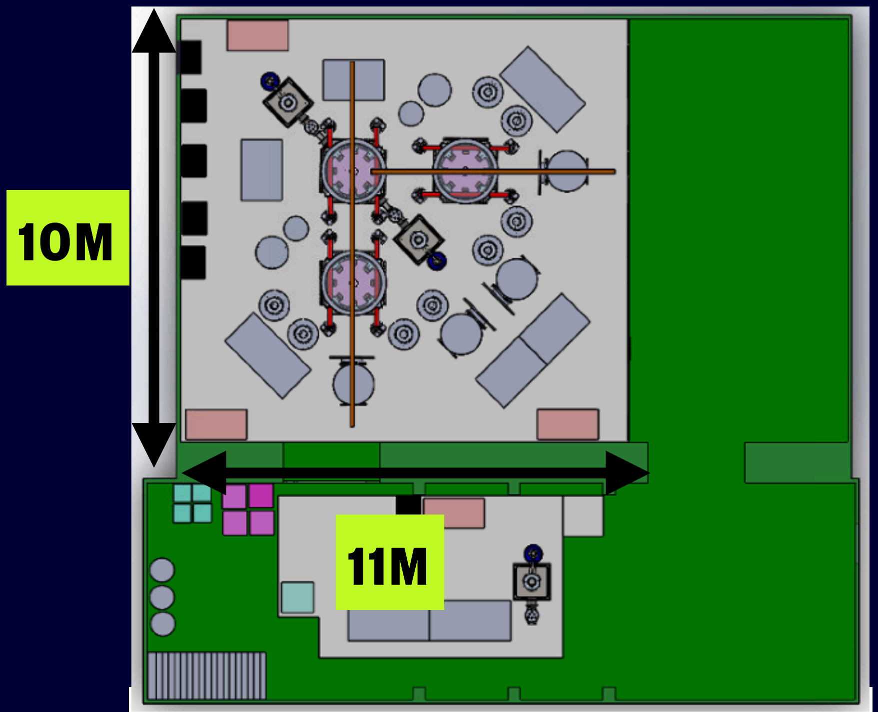
(b) An overview of the connection.

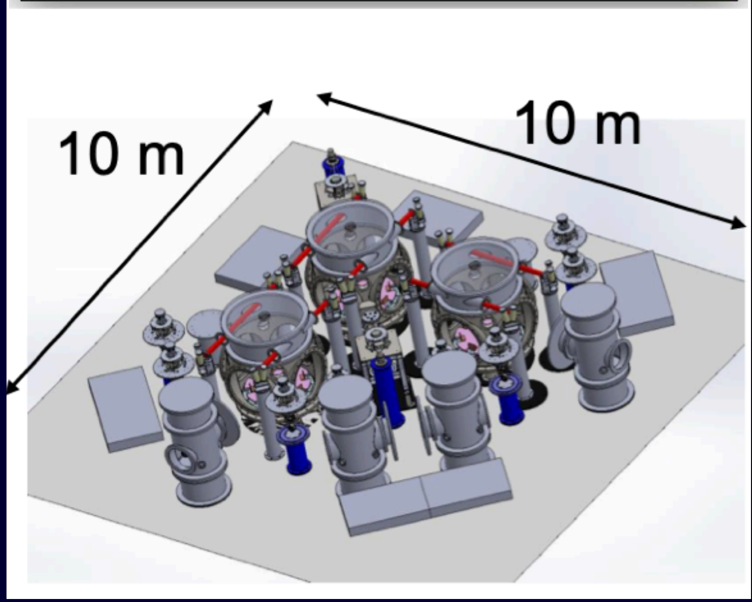




Future technologies

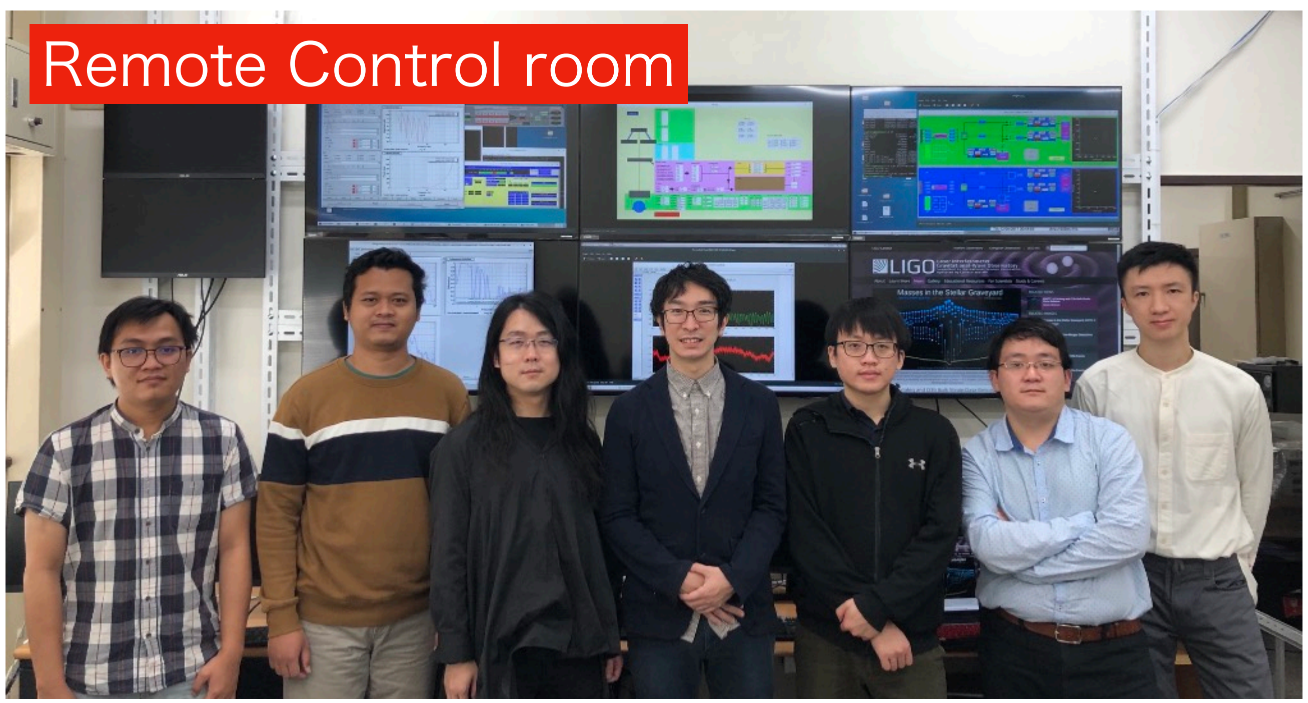
Academia Sinica Gravitational physics Research Facility (*ASGRAF*)

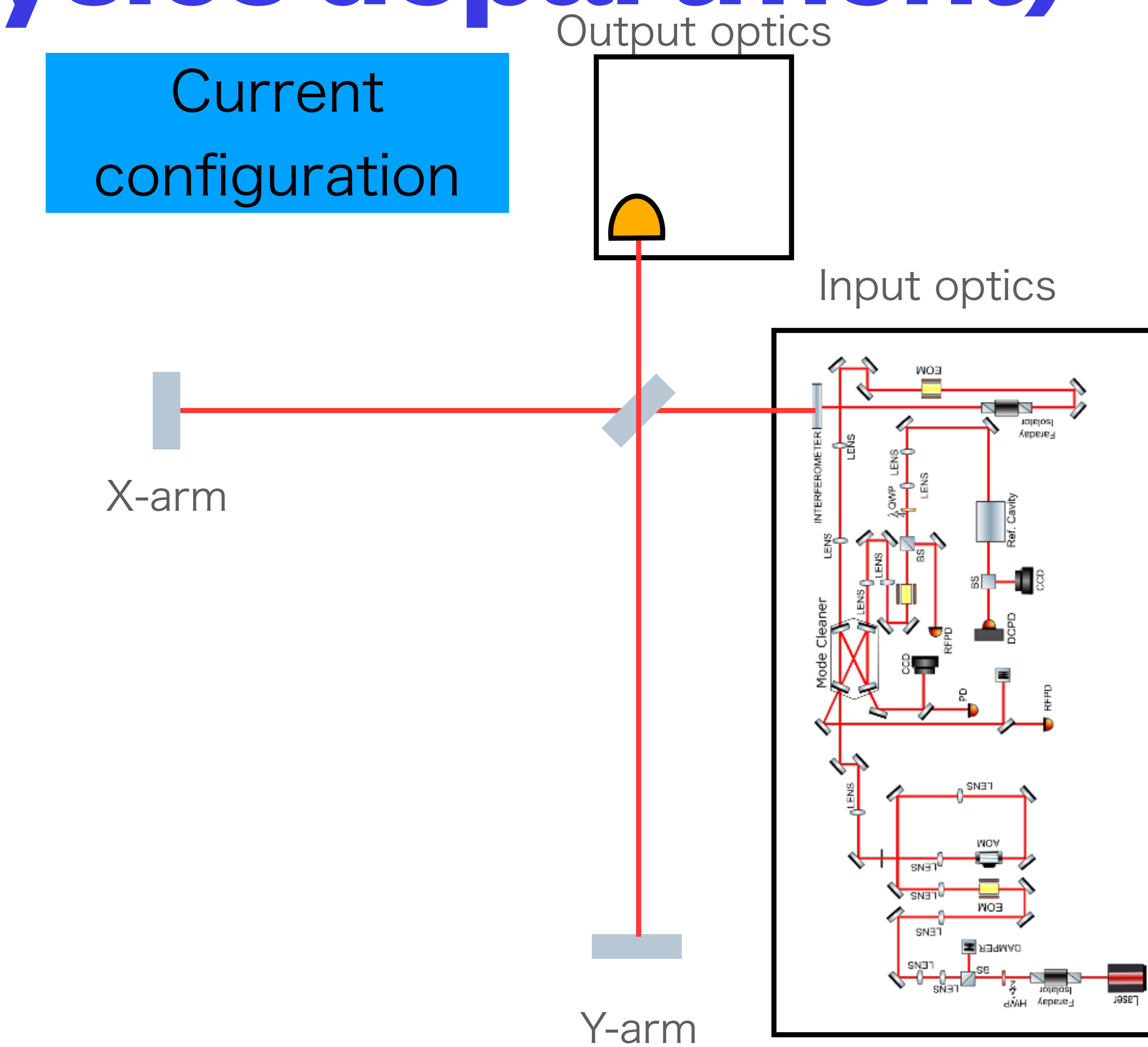




- Test facility for LIGO
- Controlled by Digital Control System
- Class 1000 clean room

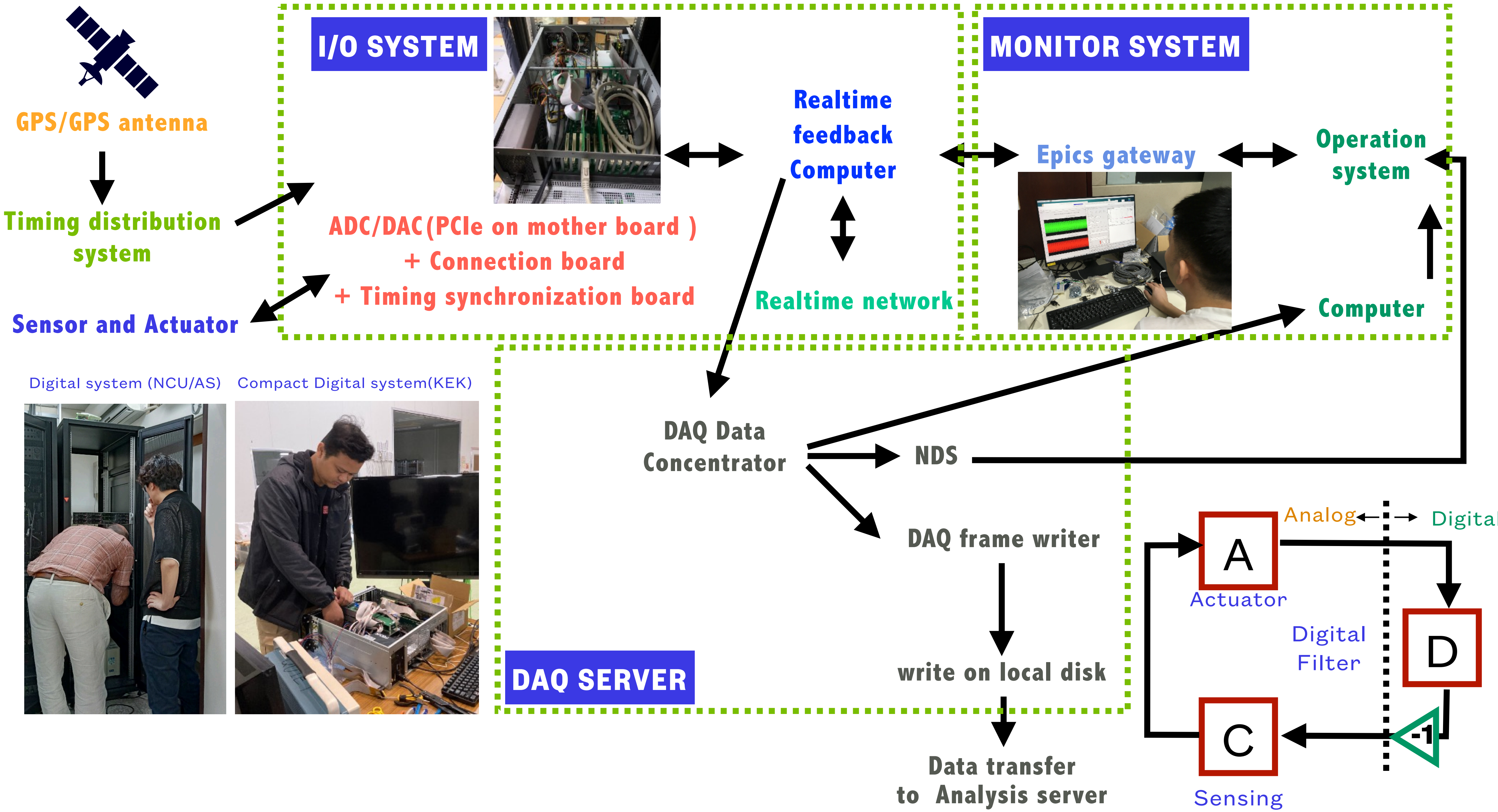
NCU observatory (Physics department)





New students are joining R&D project of IFO. System will be integrated into future ASGRAF.

Digital feedback system



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

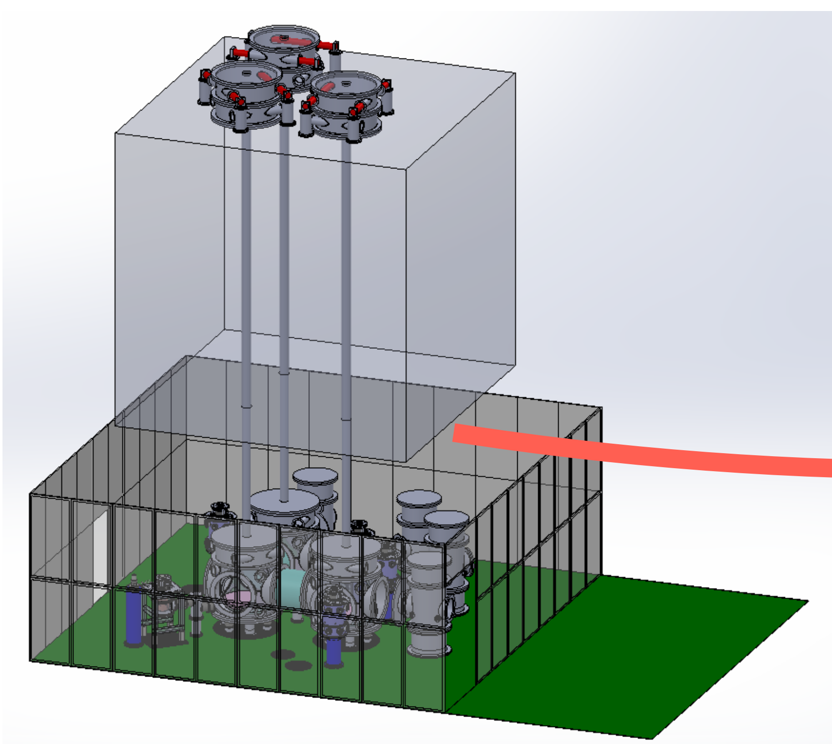
TORSION BAR

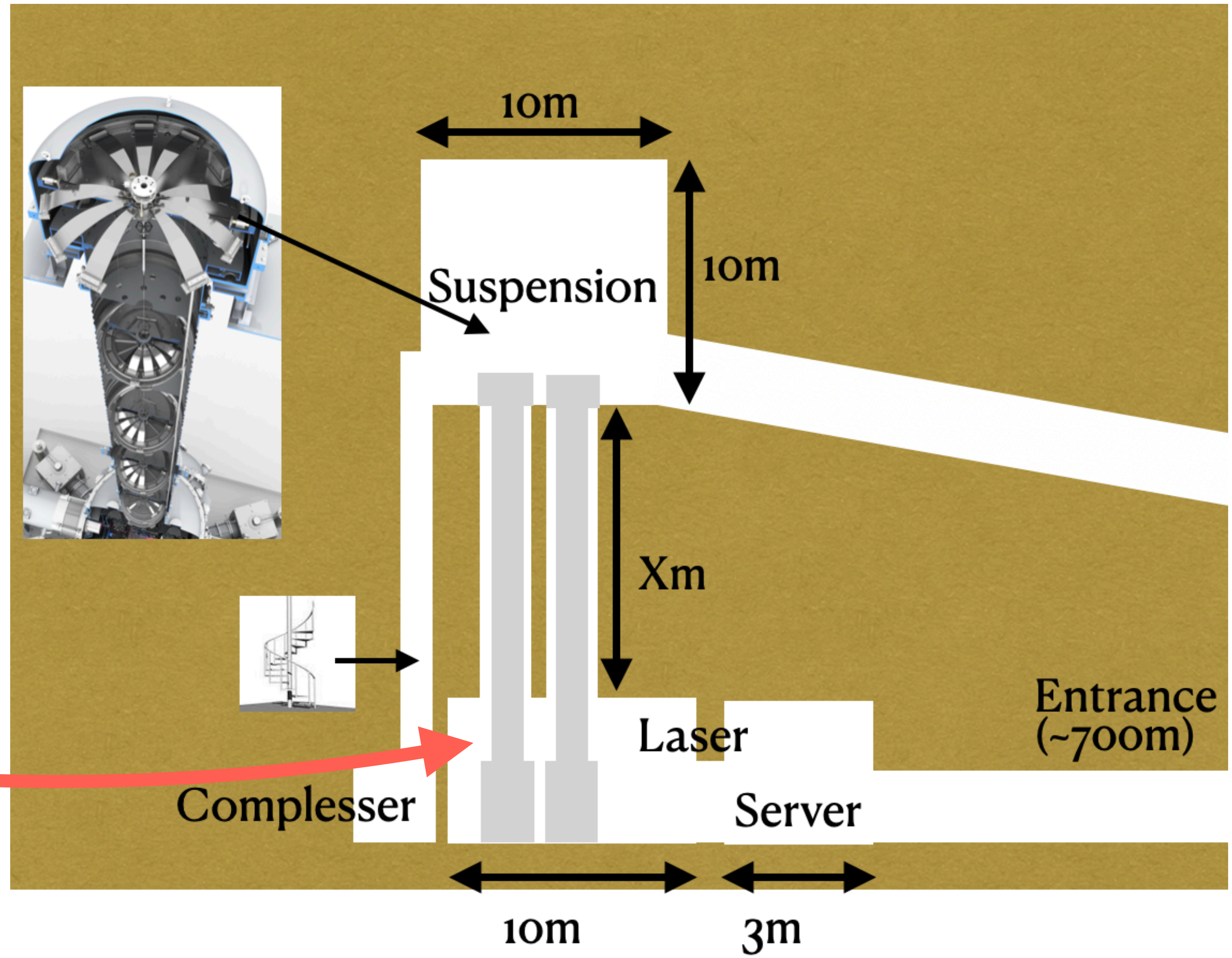
CHRONOS Overview

- Location: Underground site in Taiwan
- R&D is ongoing
- Phase 1: R&D for Key technologies (2020-2024)
- Phase 2: Integration test in ASGRAF (2024-2027)
- Phase 3: Insulation and Commissioning of CHRONOS in Underground lab (2027-2030)

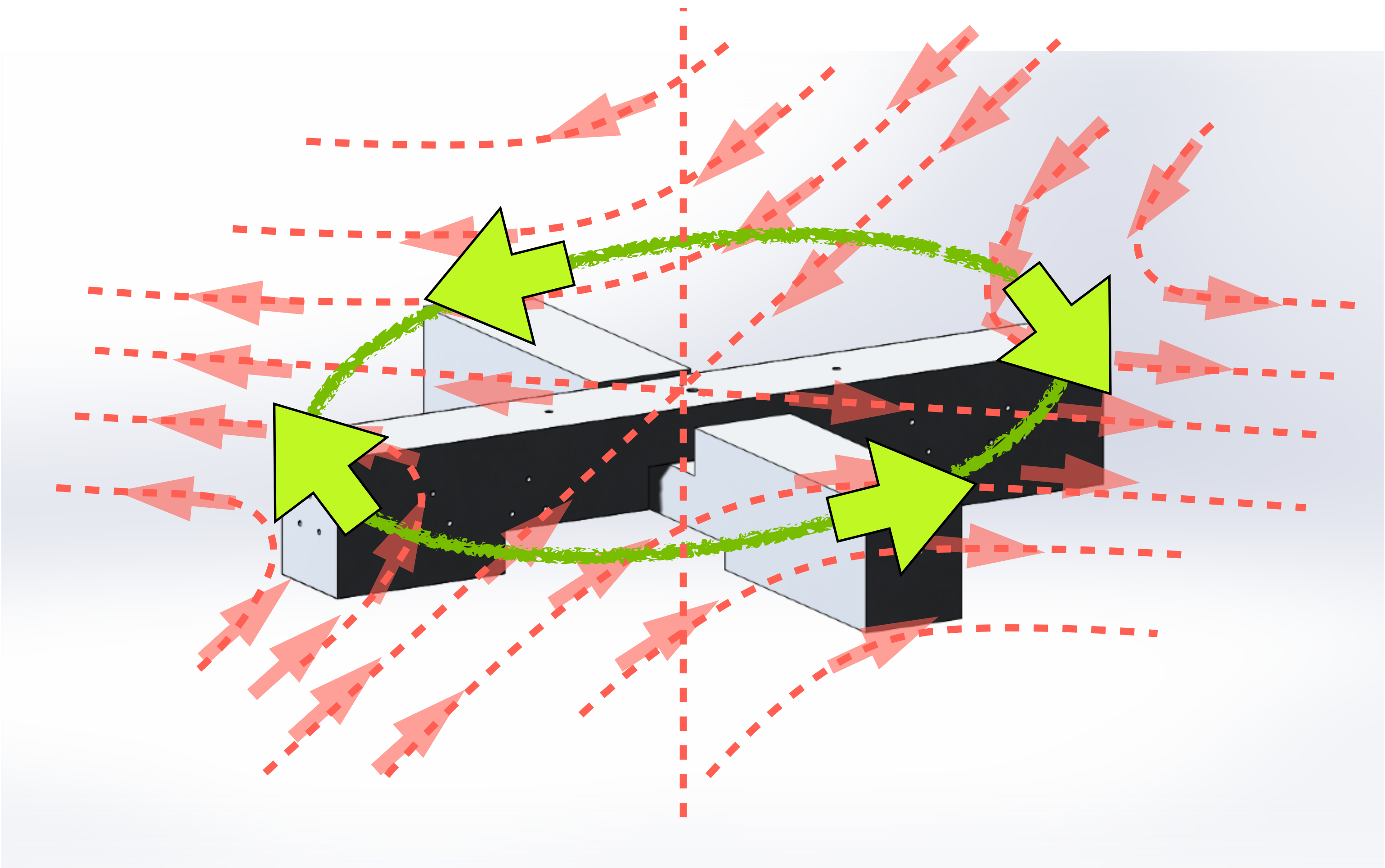
CHRONOS's target observation year = 2030

Cross section of CHRONOS observatory



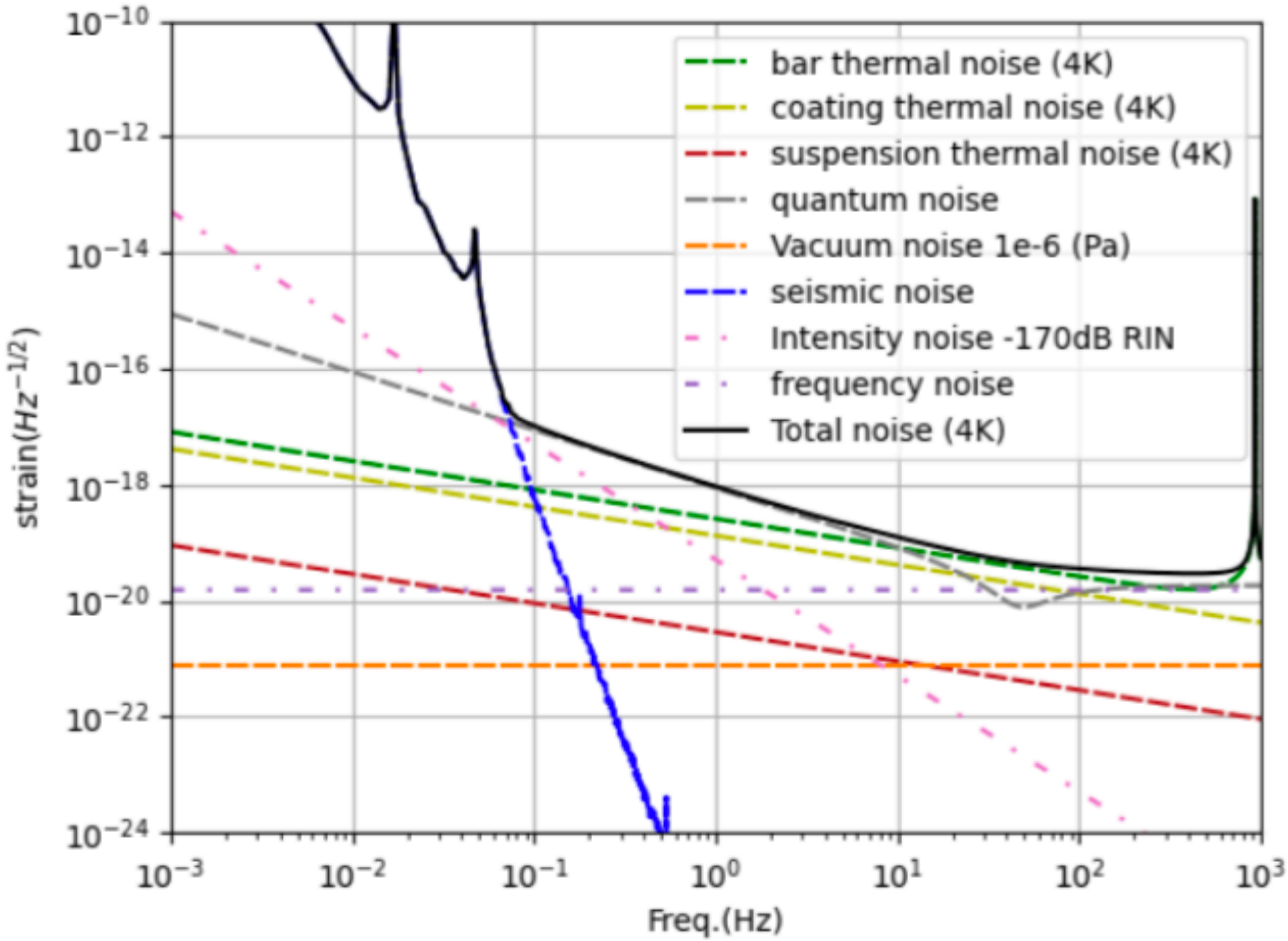


Torsion bar in Gravitational Wave



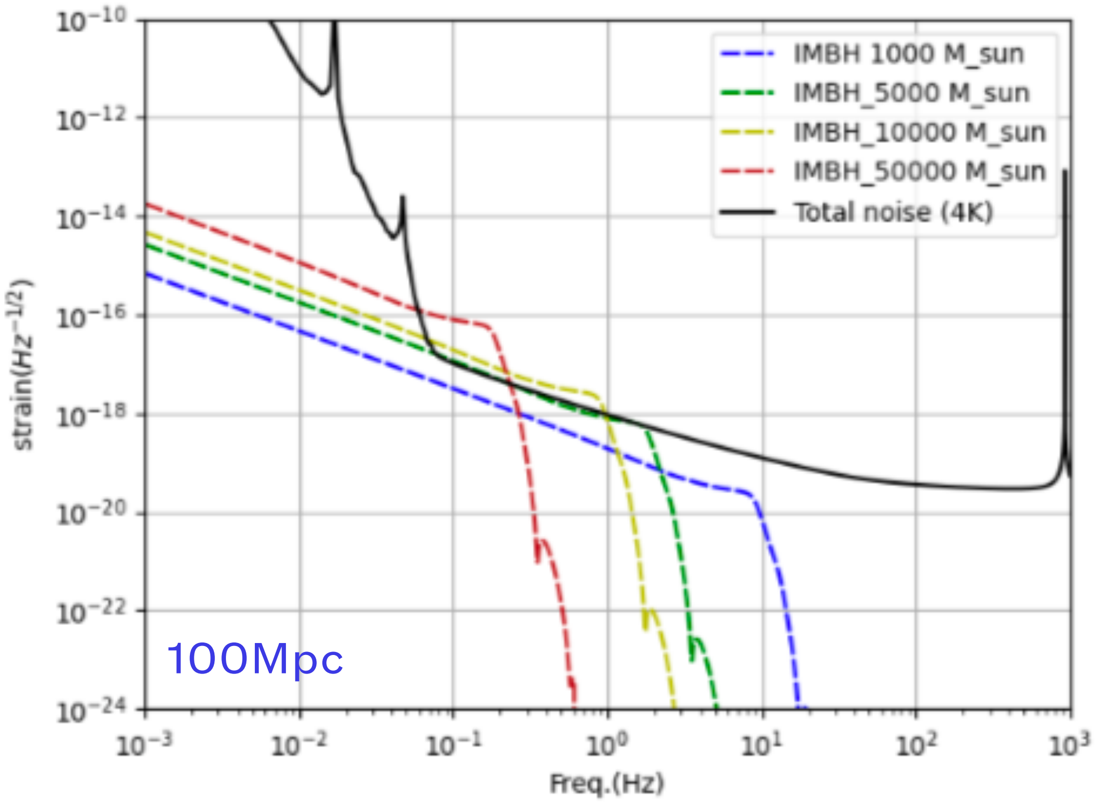
- Torsion bars keep staying through the metric
- Tensor mode metric perturbation (= Gravitational wave) change the relative angle of cross bars
- By measuring relative angle, we can reconstruct the gravitational wave foam, h(t).

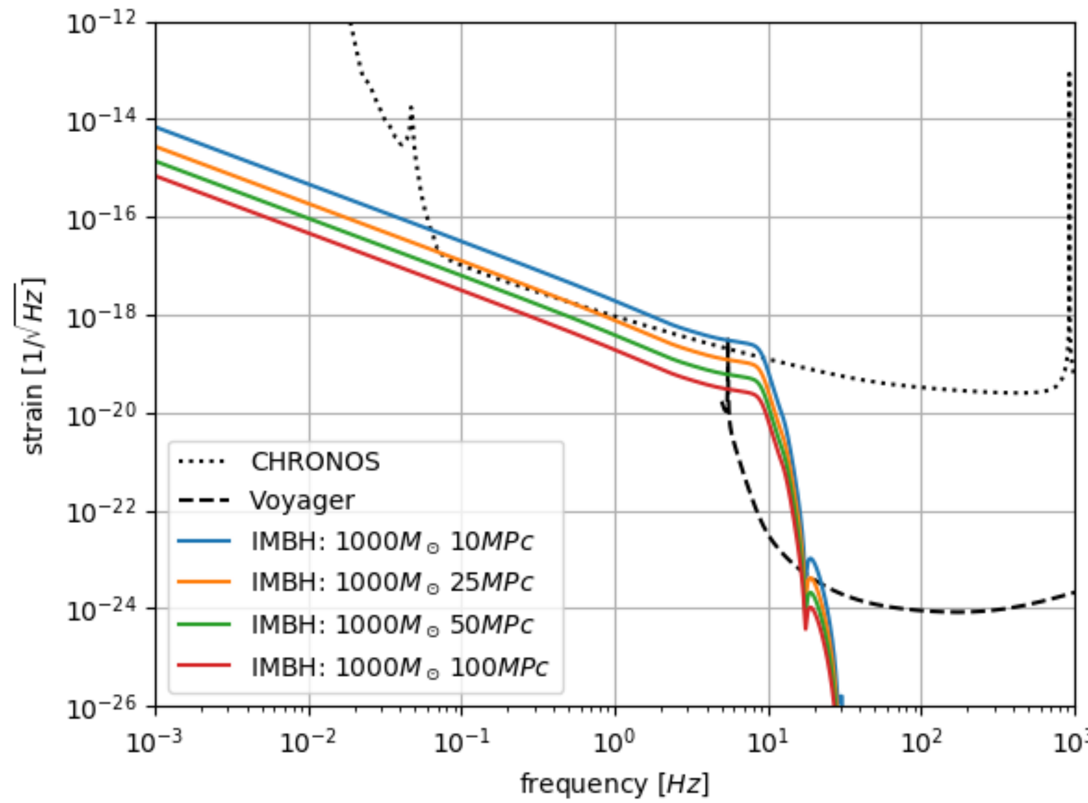
Sensitivity



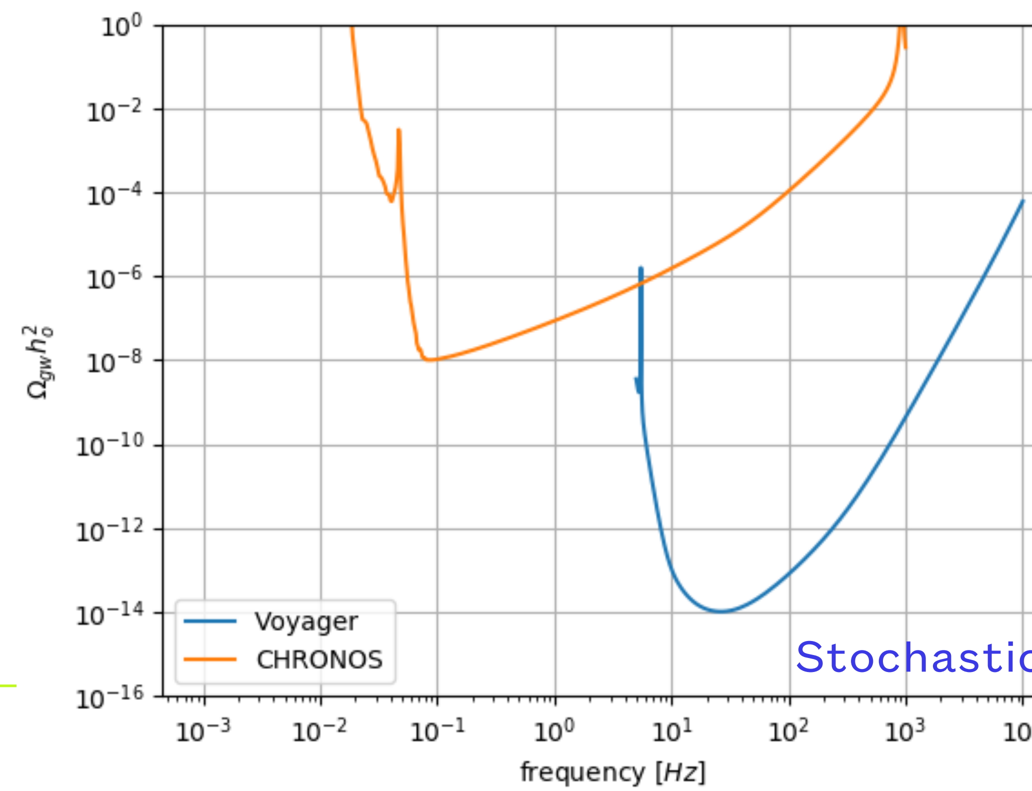
CHRONOS

Expected Science





- O($10^4 M_\odot$) Black hole marger
- Stochastic background
- Newtonian Noise



Summary

- NCU is one of the institute of LIGO scientific collaborations. O4 is ongoing (From Mar.25 2023). Detection rate is 1 event par 3 days in O4.
- Data releases of O4a and O4b is planed at middle 2024 and 2026.
- Taiwan-LIGO instrumentation group is contributing Calibration and Coating. We are discussing the extension of MOU2024 for contributing these technique.
- ASGRAF is constructed and installation work is ongoing. ASGRAF will be used for LIGO and CHRONOS R&D.