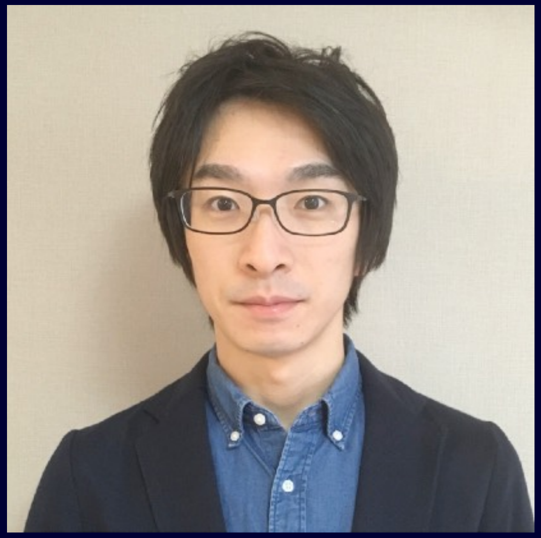
Progress of observation in LIGO and challenge with Taiwanese gravitational physics research facility for future R&D

National Central University & Academia Sinica
Yuki Inoue

LSC

Introduce myself



Yuki Inoue

Assistant professor in National Central University

Adjunct Assistant research fellow in Academia Sinica

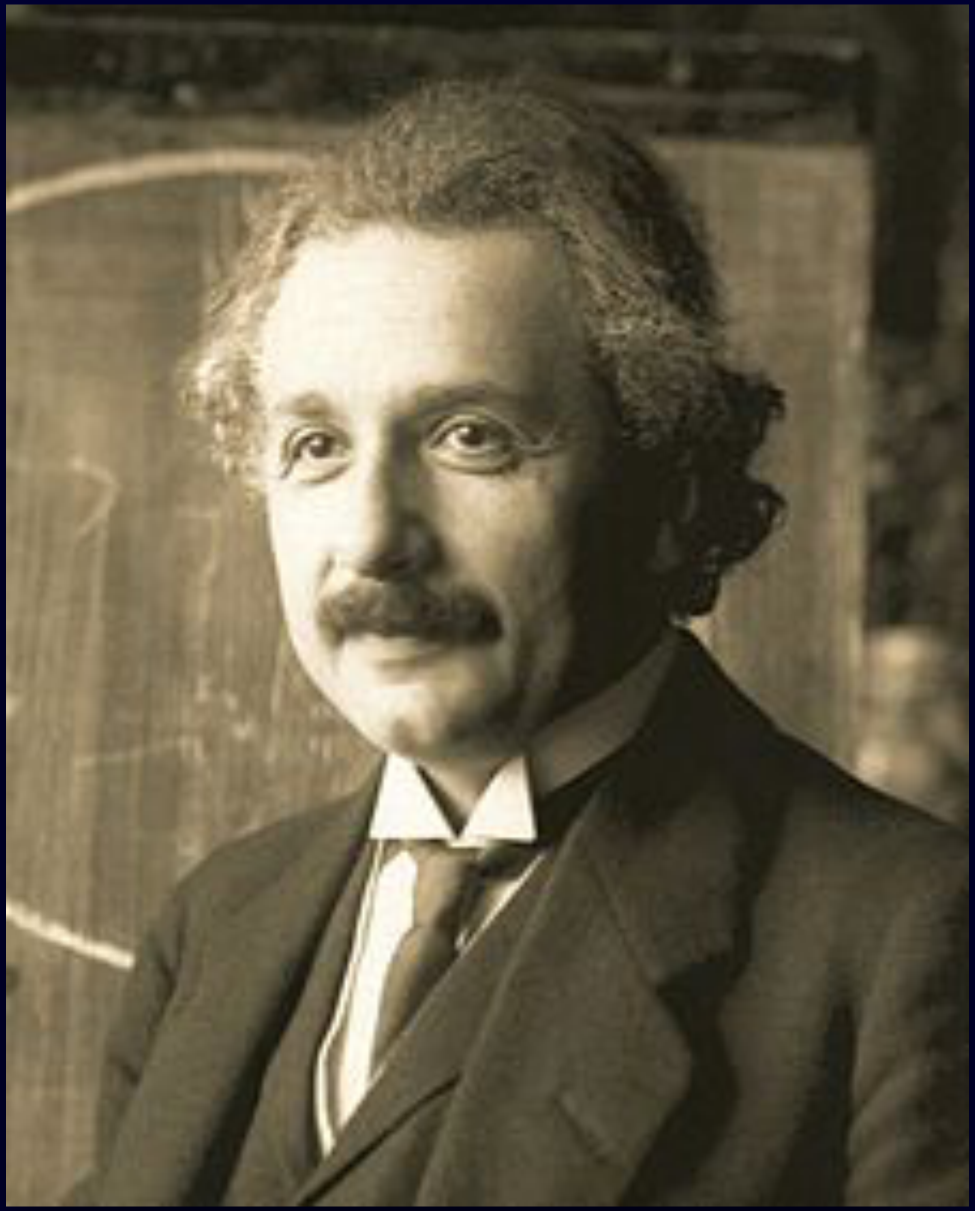
- Research history:
  - 2011-2016: POLARBEAR/Simons Array (Cosmic Microwave Background)
  - 2016-2021: KAGRA (Gravitational Wave experiment in Japan)
    - Calibration and Reconstruction
  - 2021-: LIGO(Gravitational Wave experiment in US) + Future R&D

Outline

- Introduction
- LIGO
- Contribution of Taiwan
- ASGRAF and CHRONOS
- Progress of ASGRAF construction
- Summary

Introduction

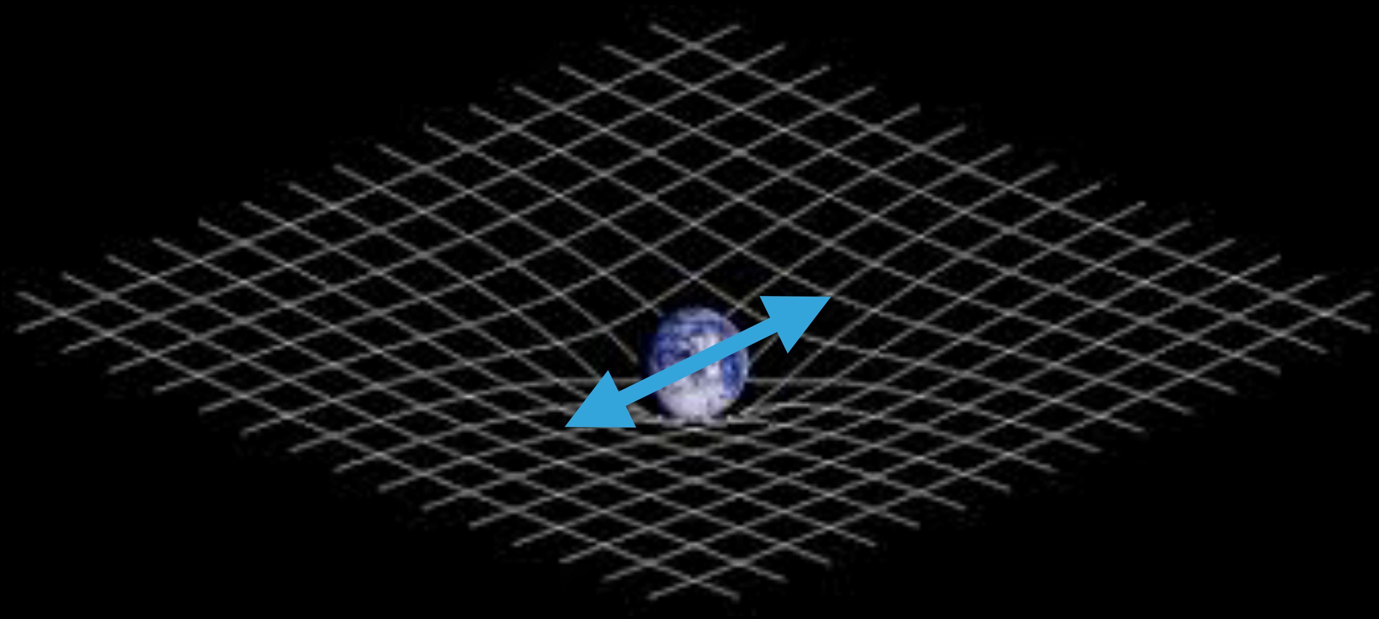
Introduction

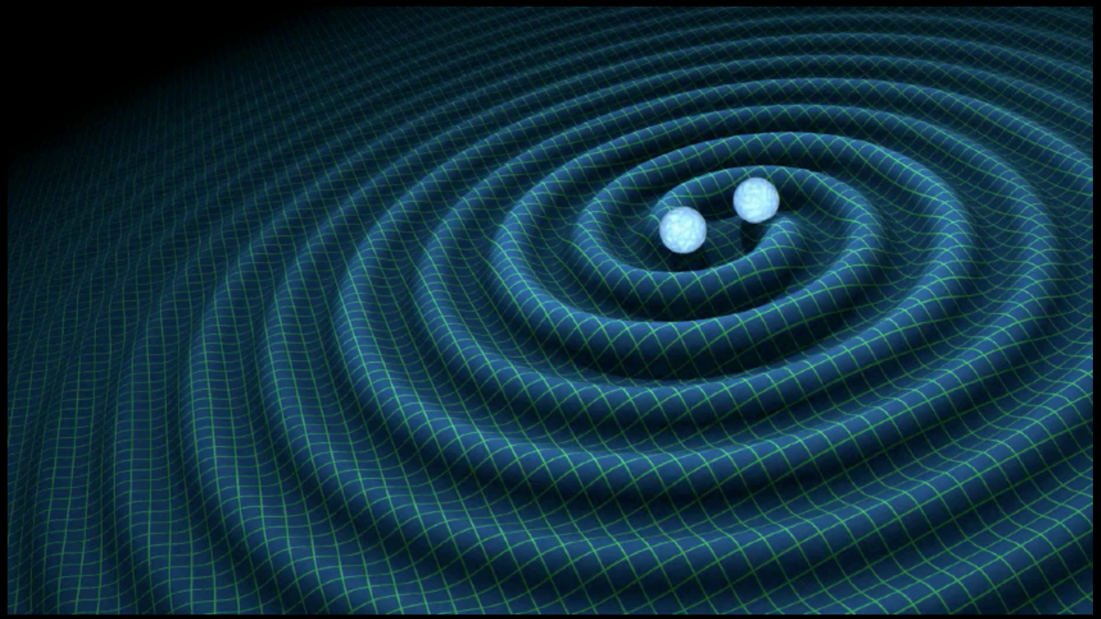


- Albert Einstein
- 1916 General Relativity
  - ‘Distortion of Space and Time’
- One of the most important predictions:

Gravitational Wave!

How to generate Gravitational Waves





- GW is generated by the oscillation of the massive object.
- Binary system is one of the candidate of it.

Metric

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

Metric

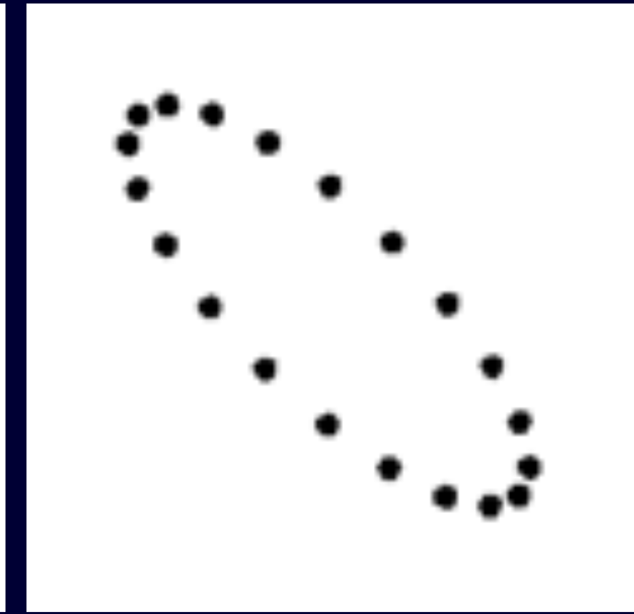
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Perturbation

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

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

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



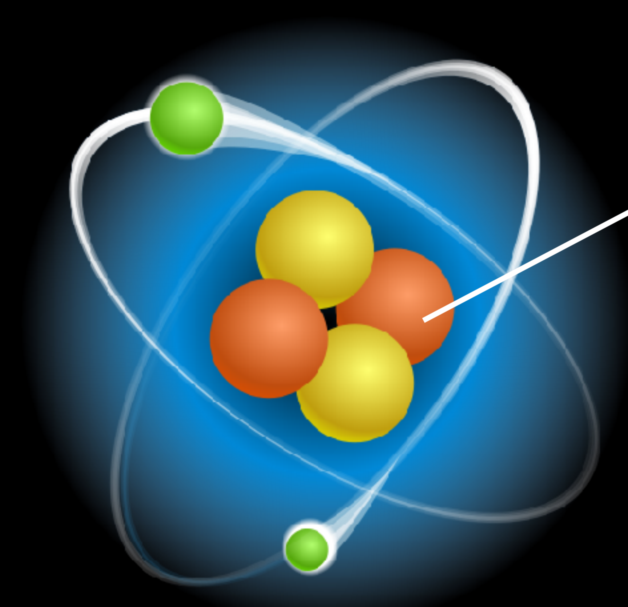
Typical gravitational wave strain sensitivity

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

Solar mass NS-NS: r_g~3km
Typical distance: 100Mpc

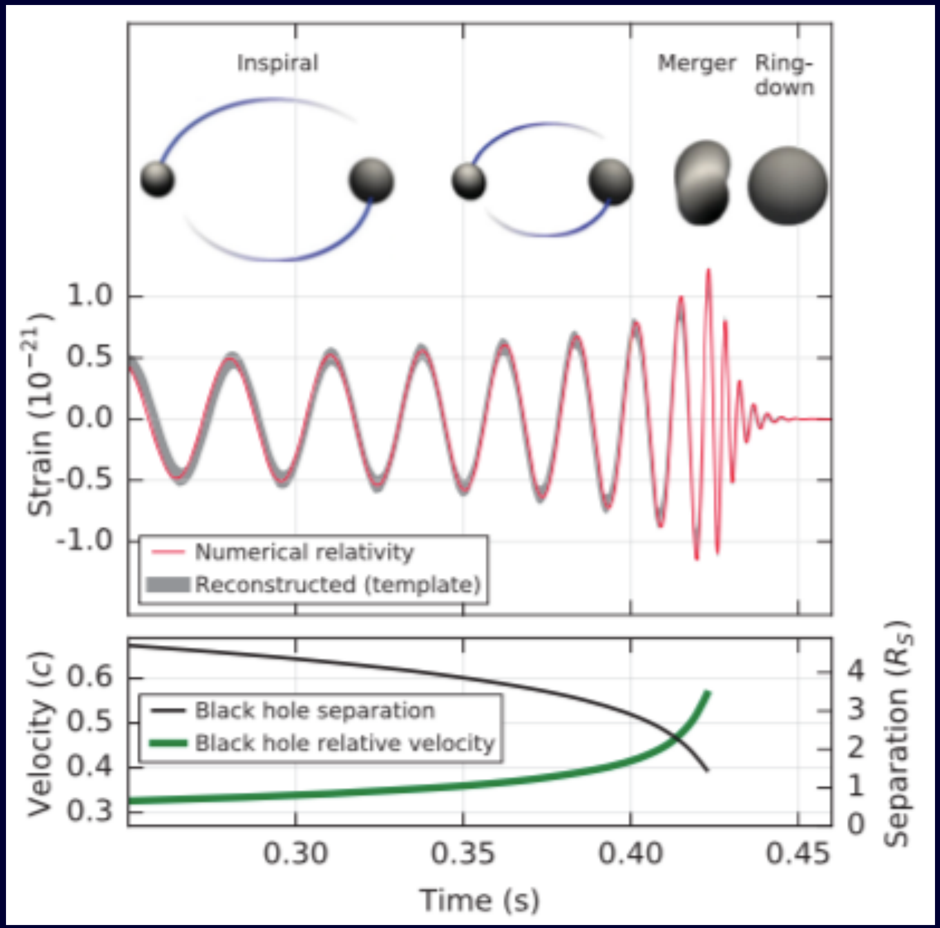
→ $h \sim \delta L/L \sim 10^{-21}$

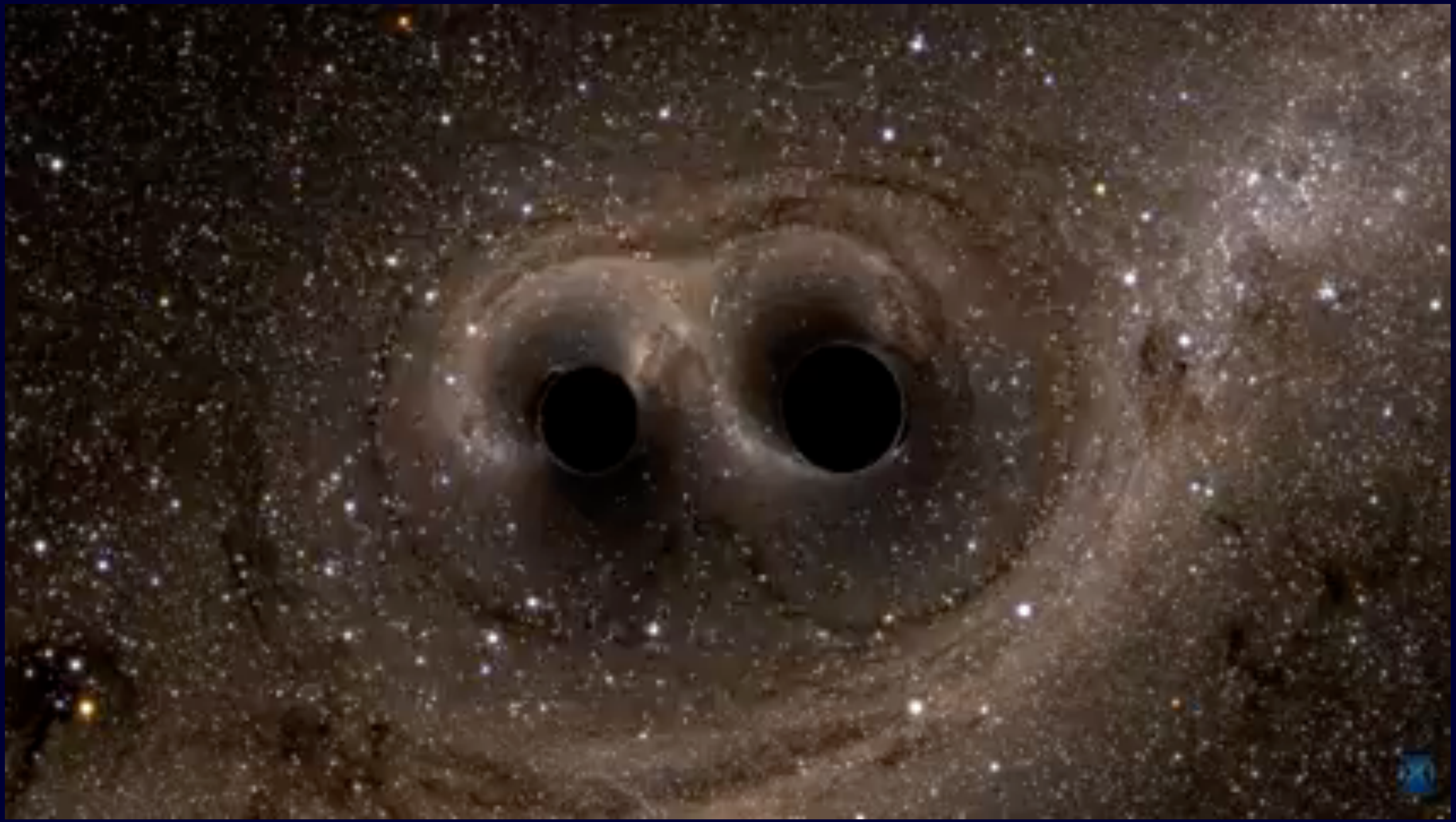
$\delta L \sim 2000\text{km} \times 10^{-21}$
$\sim 10^{-15}\text{m} \sim 1\text{fm}$



Amplitude of GW is very tiny

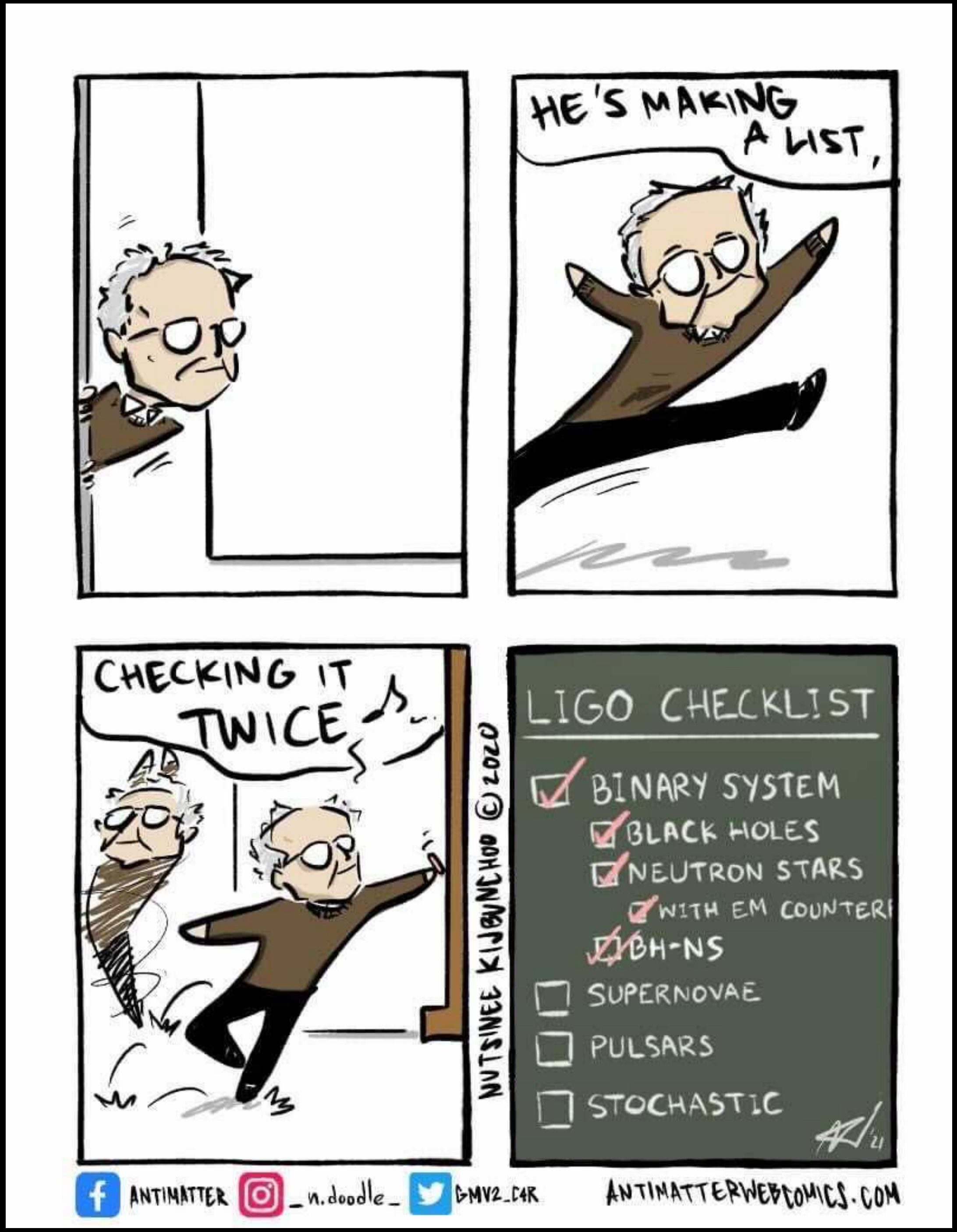
Compact Binary Coalescence



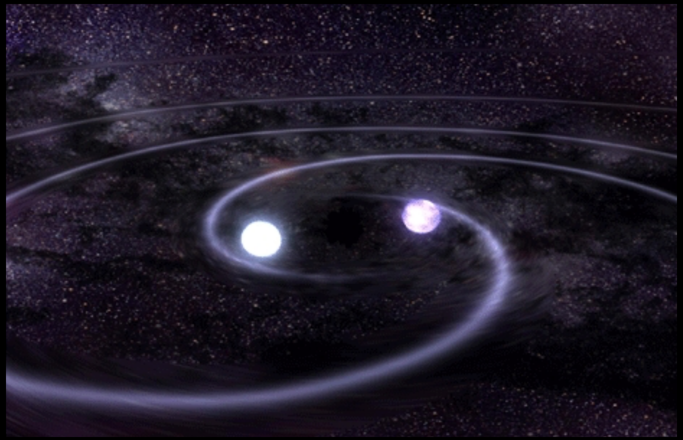


- BH-BH, BH-NS, and NS-NS (BH= Black hole, NS= Neutron Star)
- Observed as Unique Chirp signal
- LIGO and Virgo can observe it every 10 days

Gravitational wave source

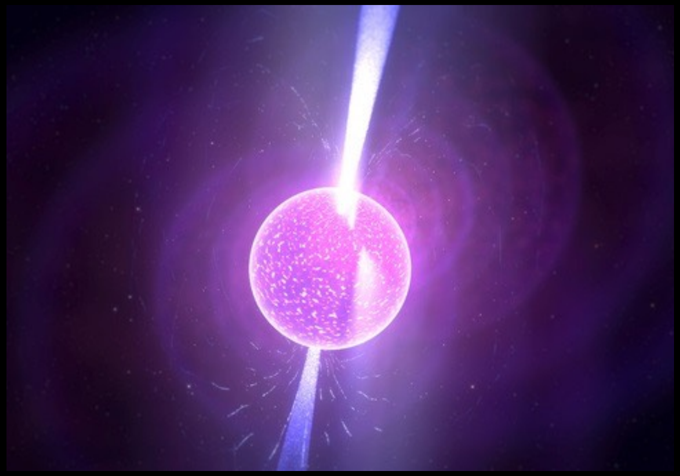


BINARY SYSTEMS

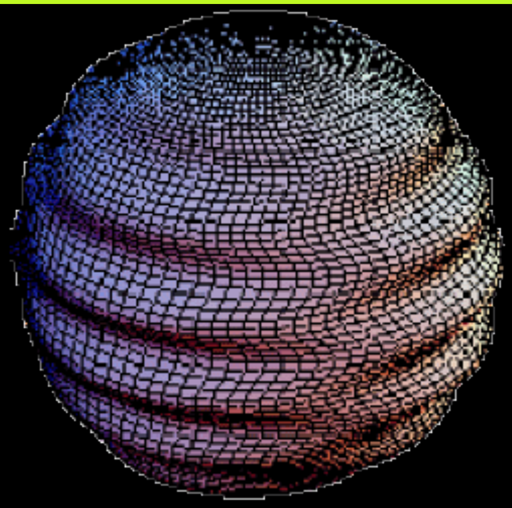


SUPER NOVA

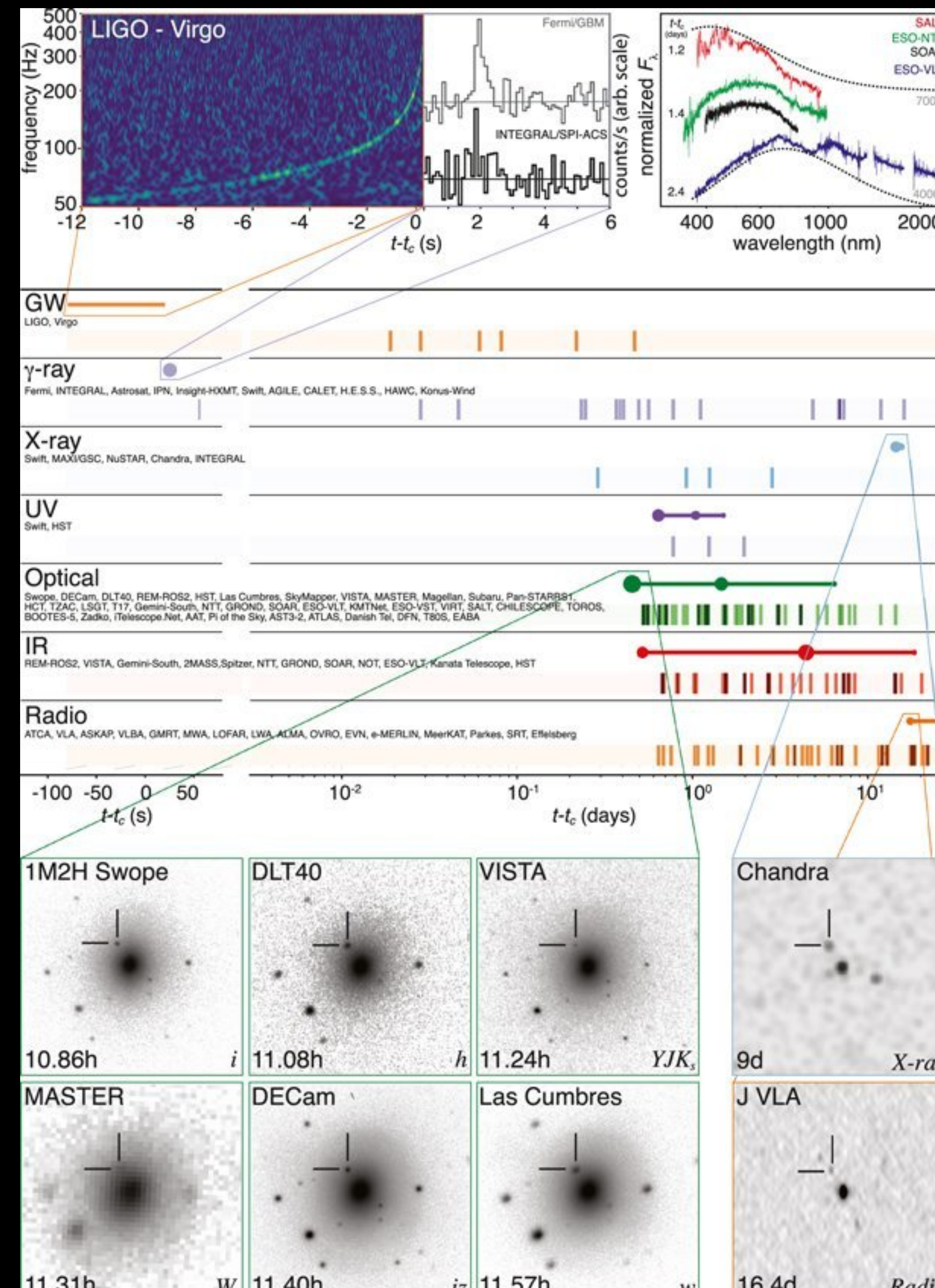
PULSER



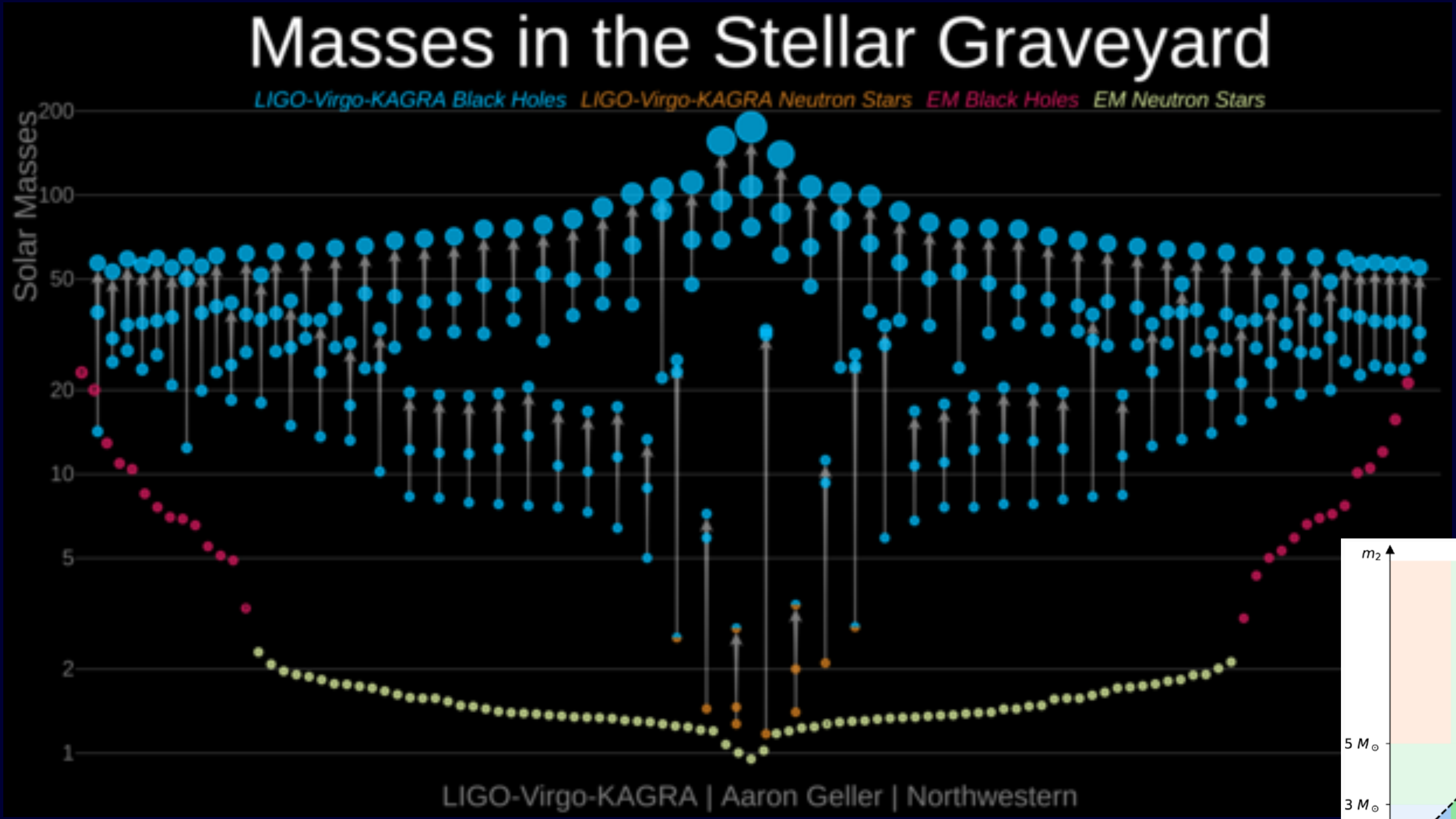
STOCHASTIC BACKGROUND

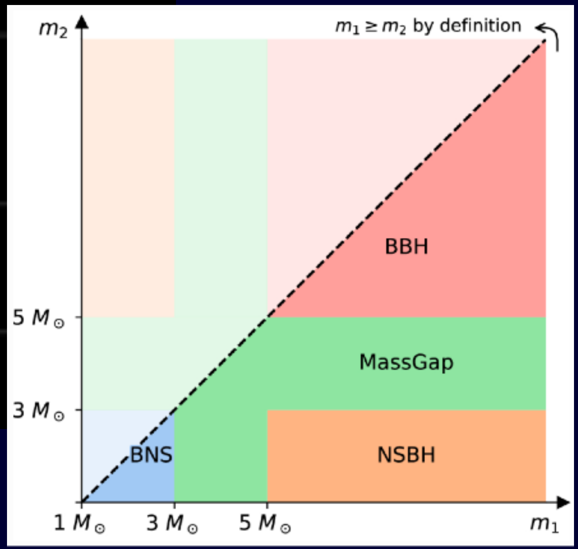


Multimessenger astronomy



Observation 3 result

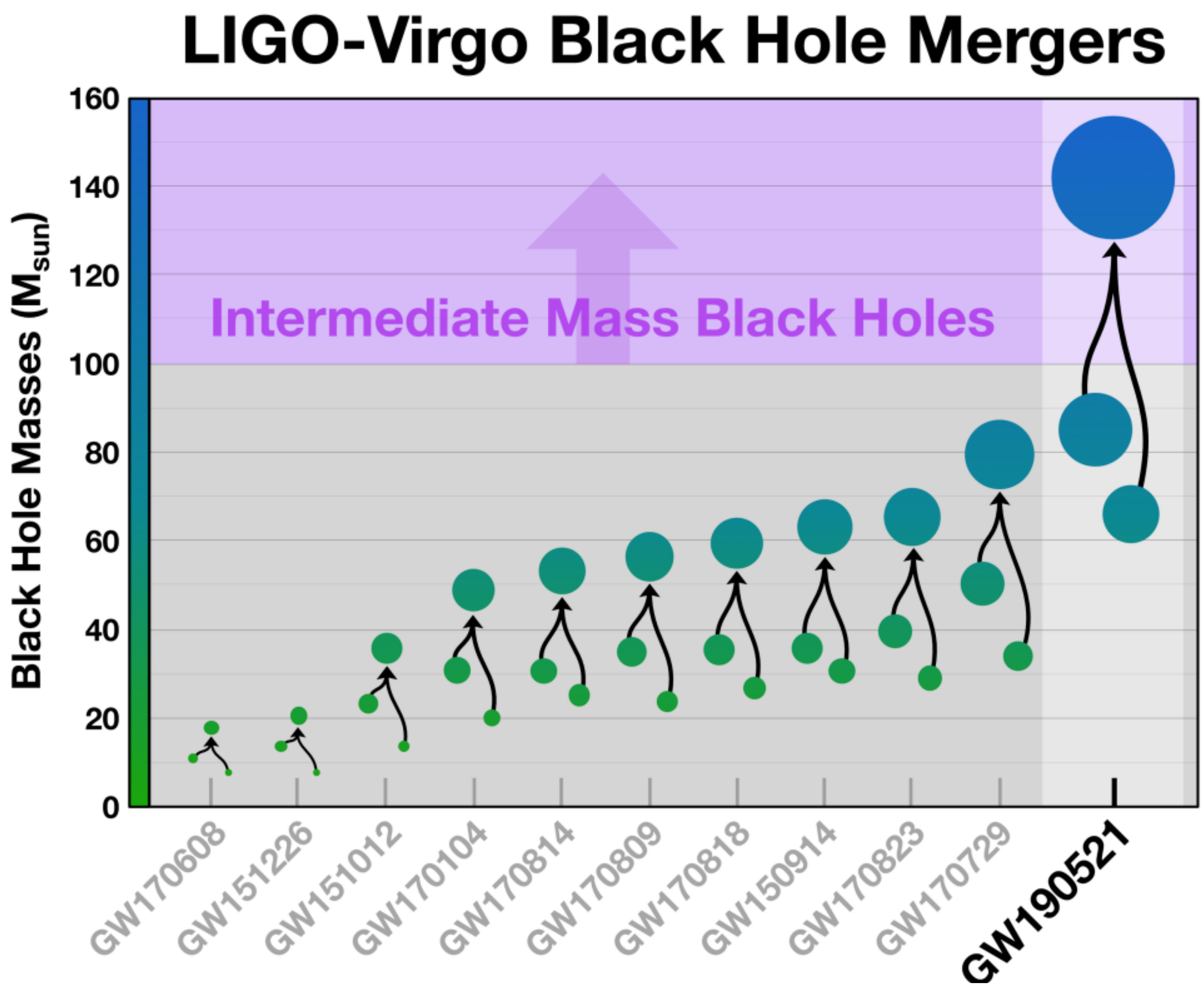




Observed IMBHs

NGC No.	distance (kpc) [63]	vel. disp. σ (km/s) [111]	BH mass ($M_\odot$)
104	4.5	10.0	794.7
362	8.5	6.2	116.3
1851	12.1	11.3	1299
1904	12.9	3.9	18.04
5272	10.4	4.8	41.57
5286	11.0	8.6	433.4
5694	34.7	6.1	108.9
5824	32.0	11.1	1209
5904	7.5	6.5	140.6
5946	10.6	4.0	19.97
6093	10.0	14.5	3539
6266	6.9	15.4	4508
6284	15.3	6.8	168.6
6293	8.8	8.2	357.9
6325	8.0	6.4	132.4
6342	8.6	5.2	57.35
6441	11.7	19.5	11645
6522	7.8	7.3	224.3
6558	7.4	3.5	11.68
6681	9.0	10.0	794.7
7099	8.0	5.8	88.96

Yagi, CQG 29 075005 (2012)

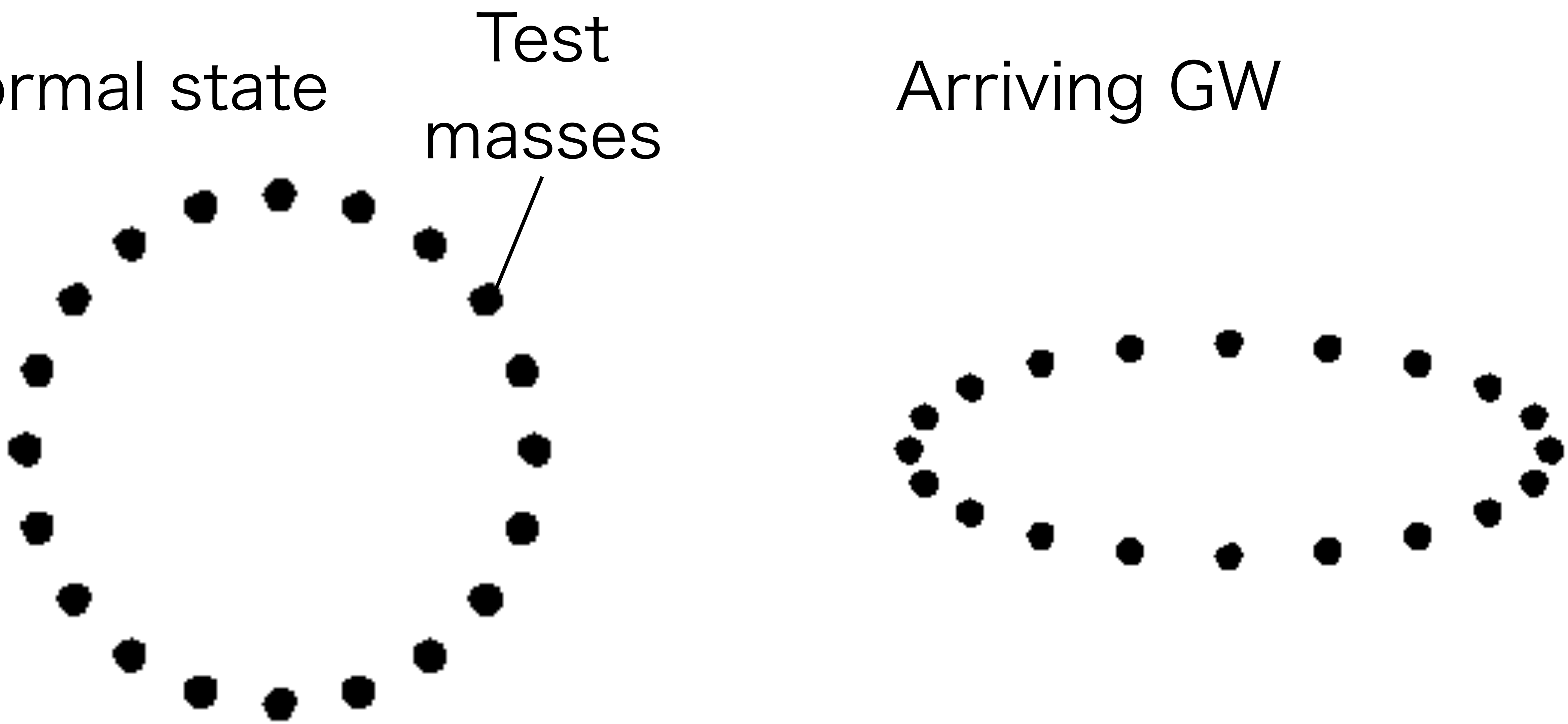


LIGO

Overview of LIGO

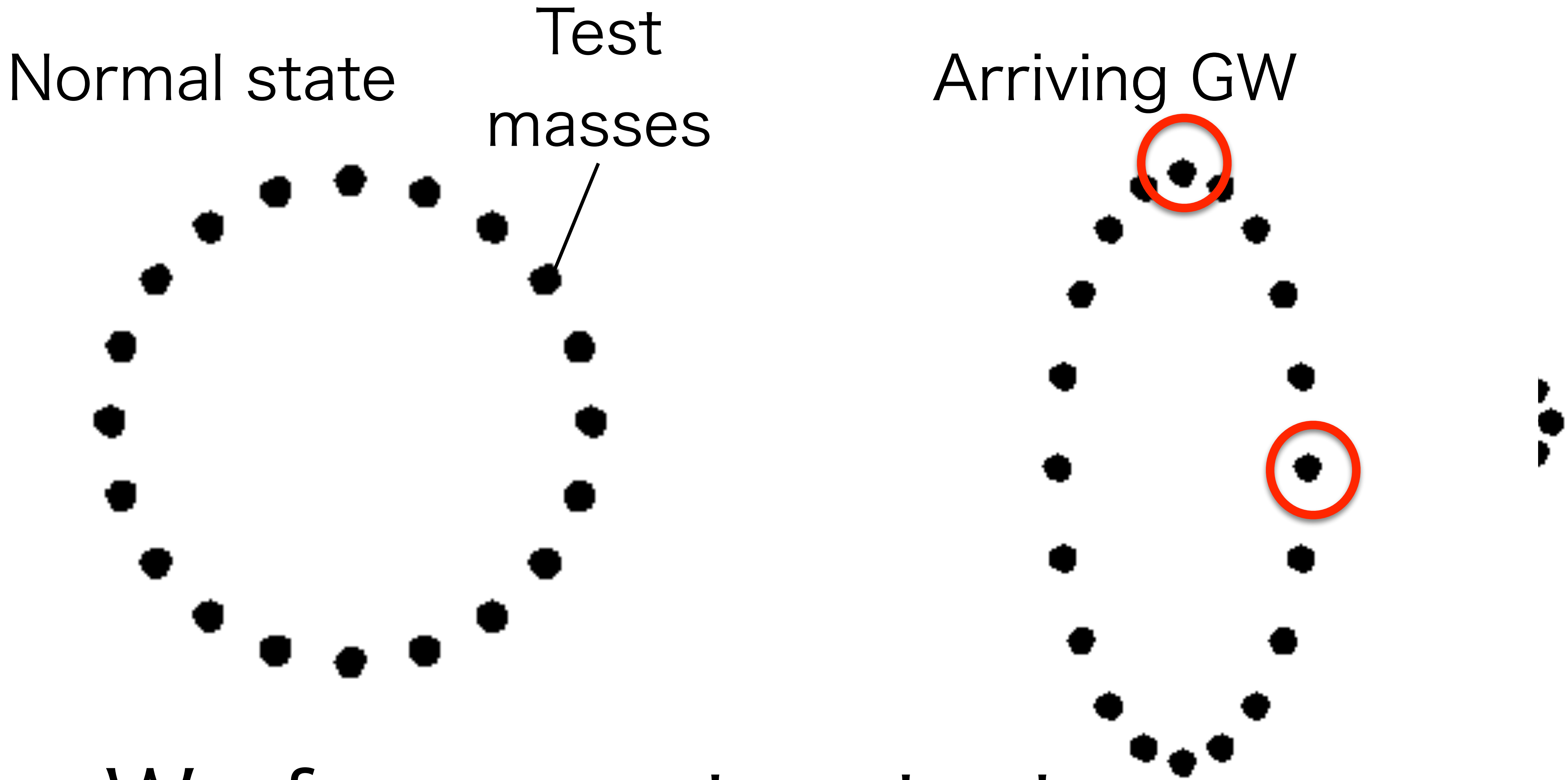
- LIGO is 2nd generation gravitational wave detector.
- They have two detector systems in Hanford and Livingston.
- 4km arm length interferometer

Principle of Observation



Test masses are moved by GWs.

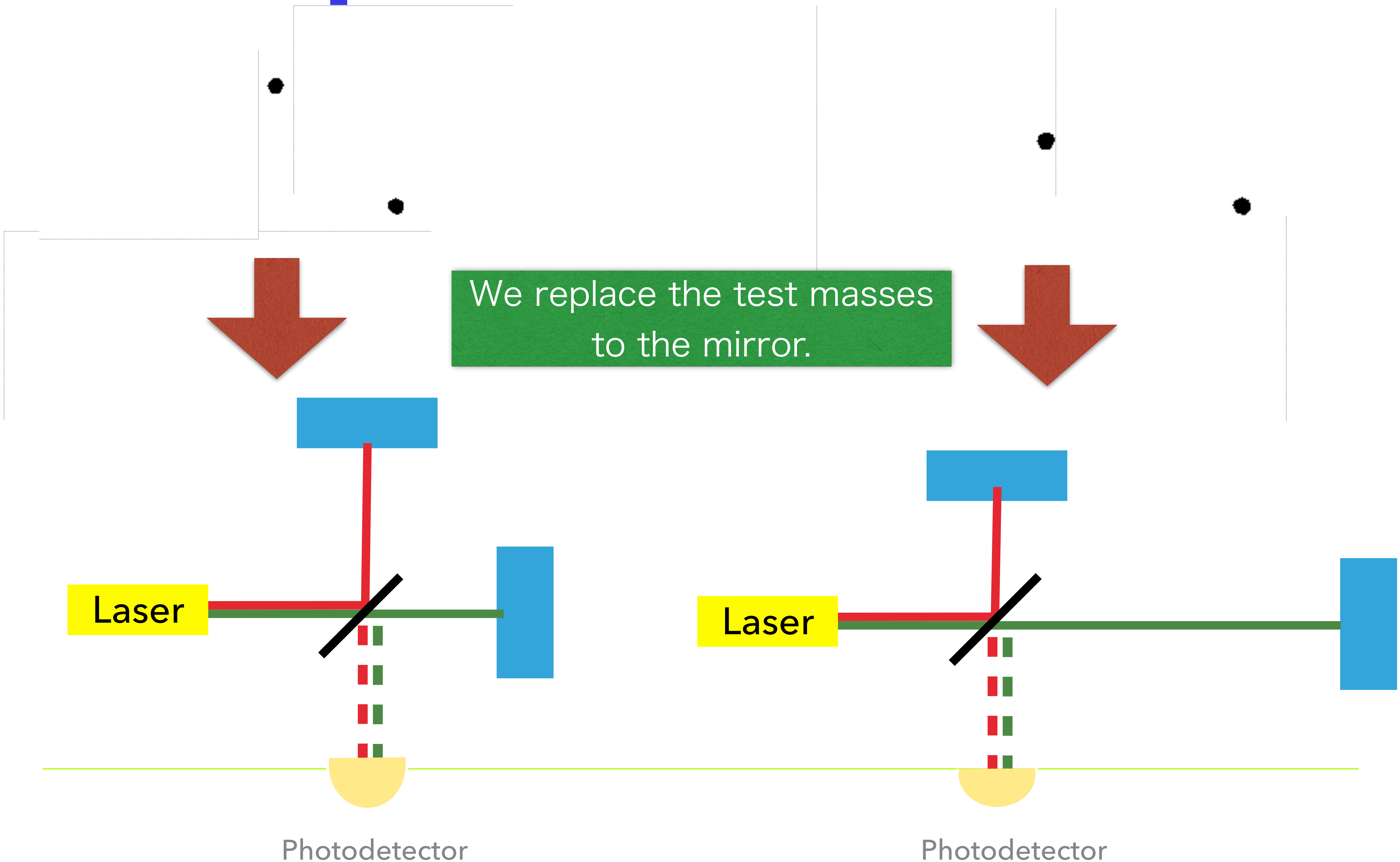
Principle of Observation



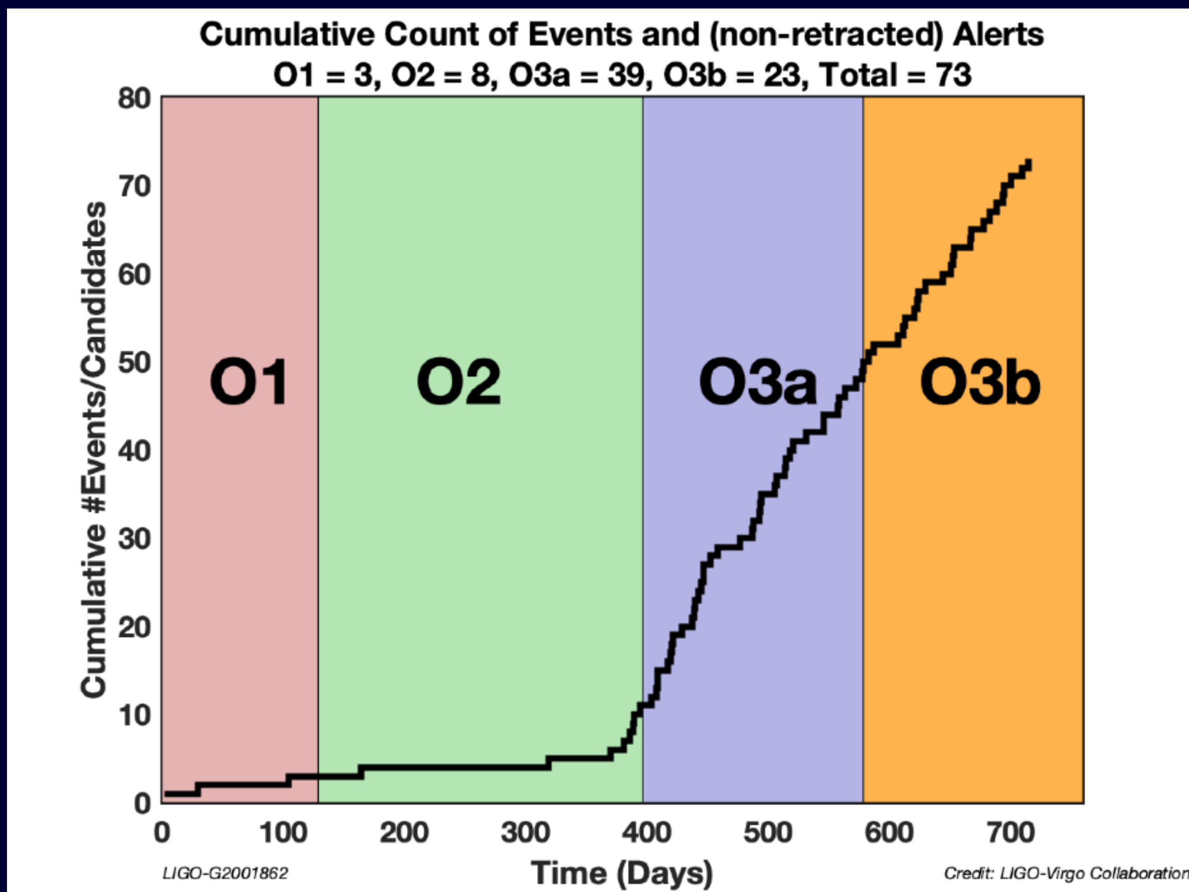
We focus on two test masses.

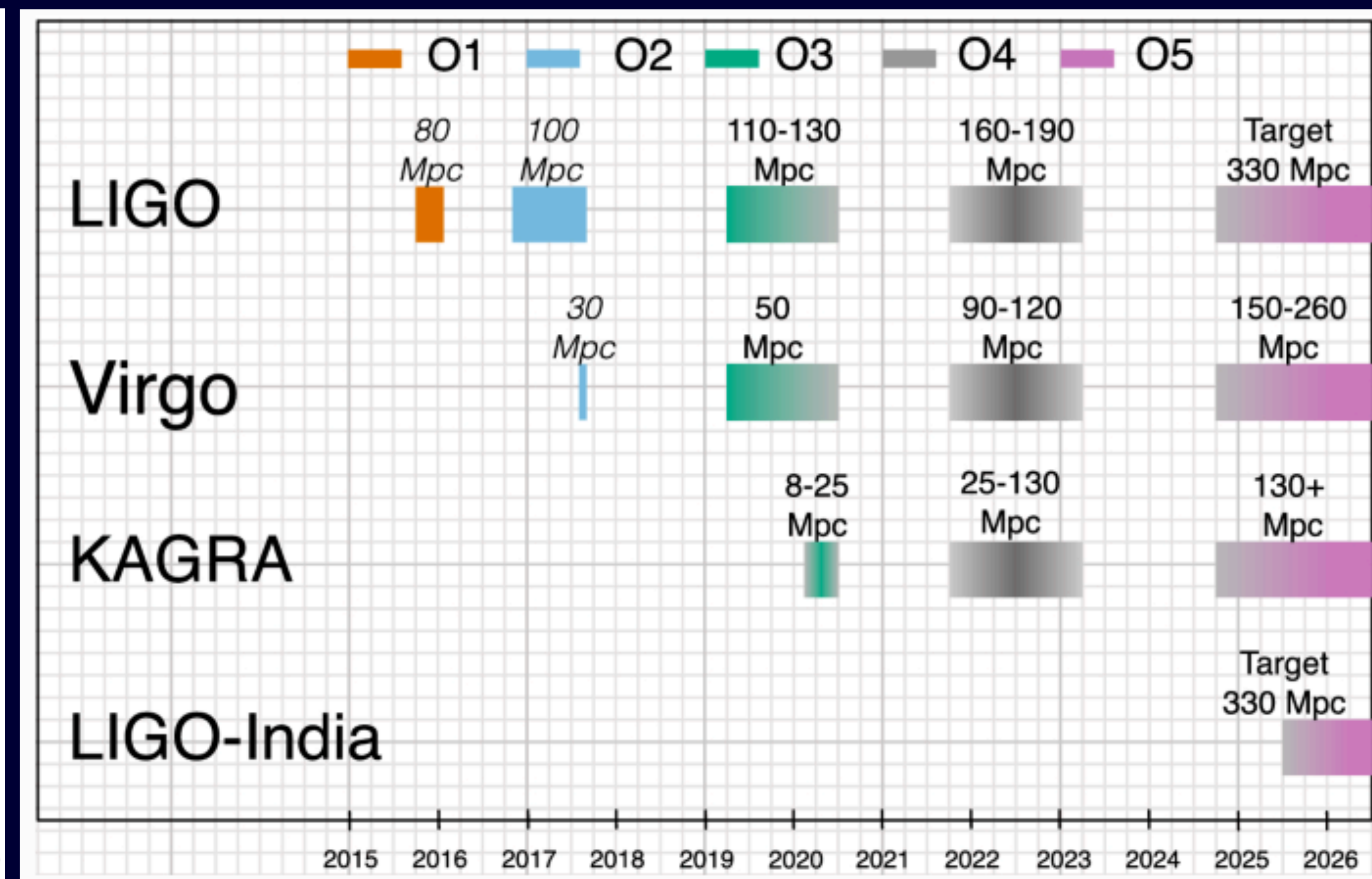
Principle of Observation

We replace the test masses to the mirror.



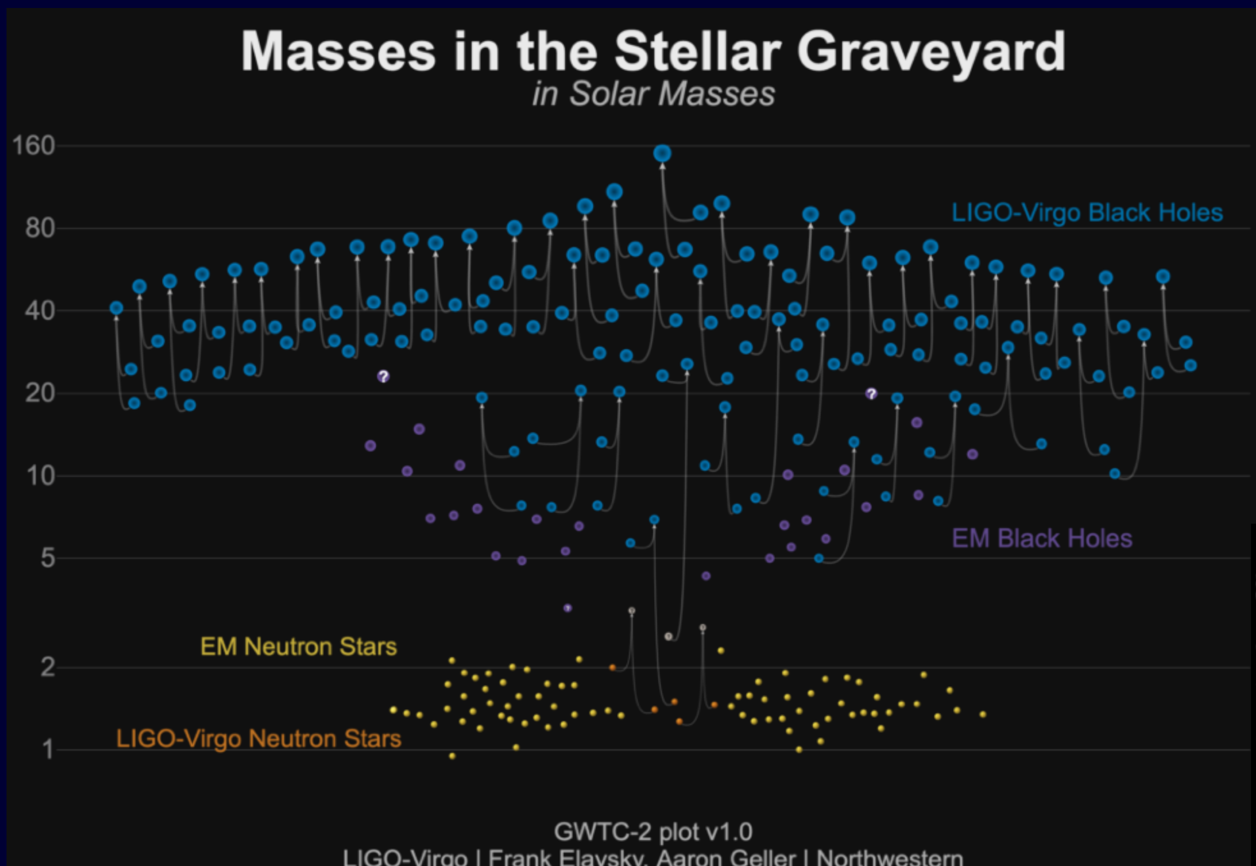
Observation history

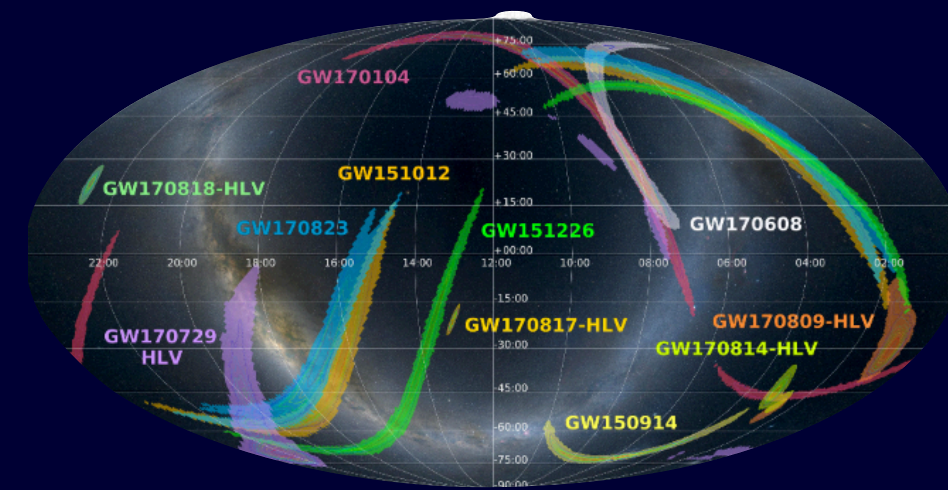


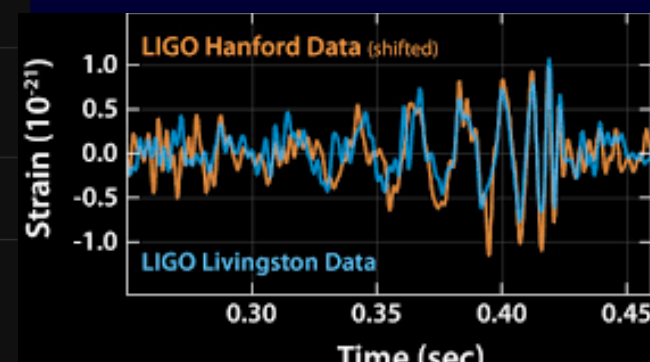


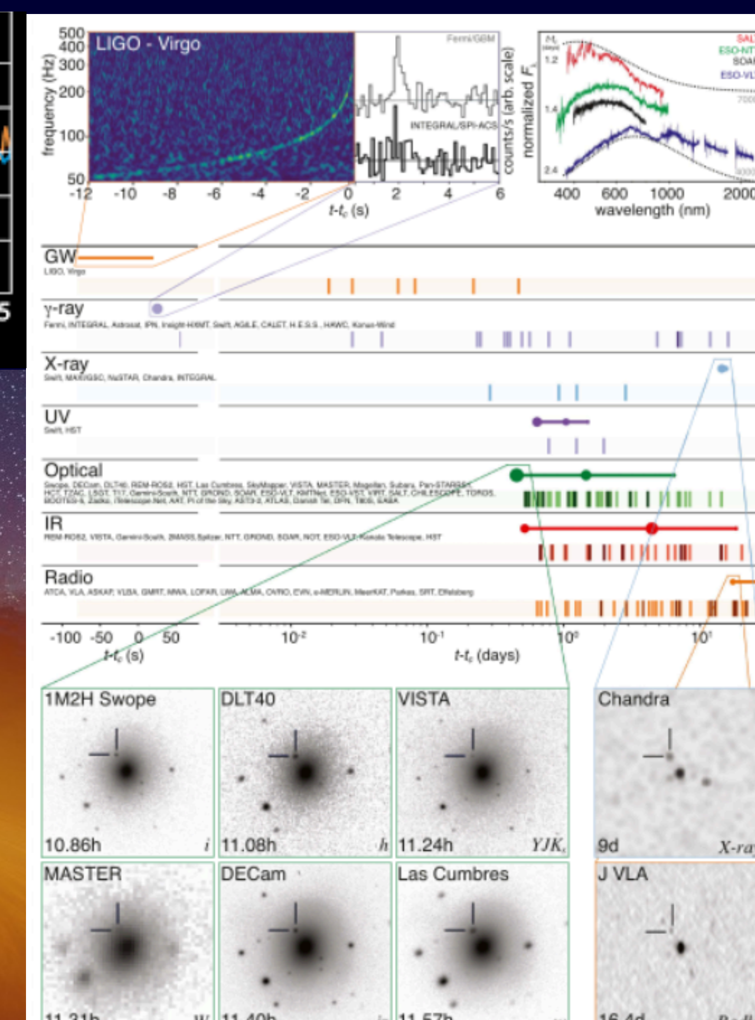
- Now is upgrade period for next observation
- Observation 4 will start from just one years later.

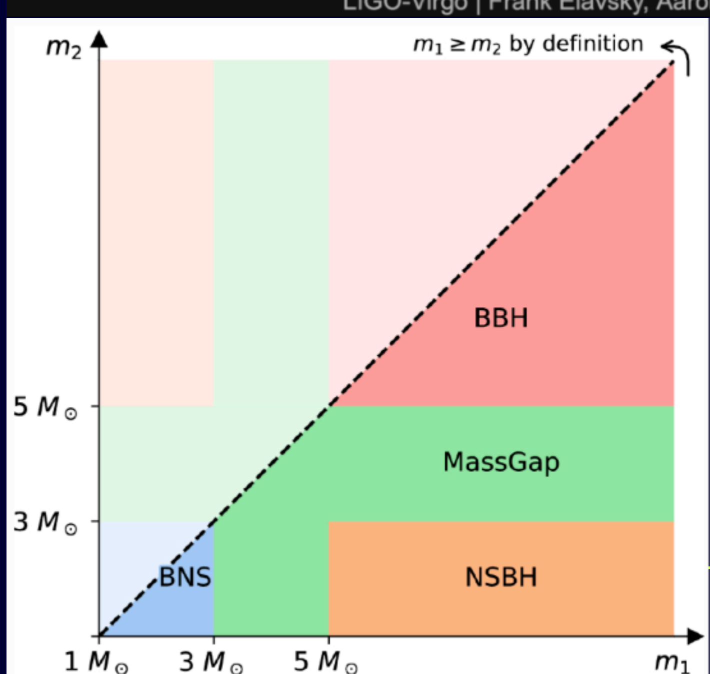
Science of LIGO

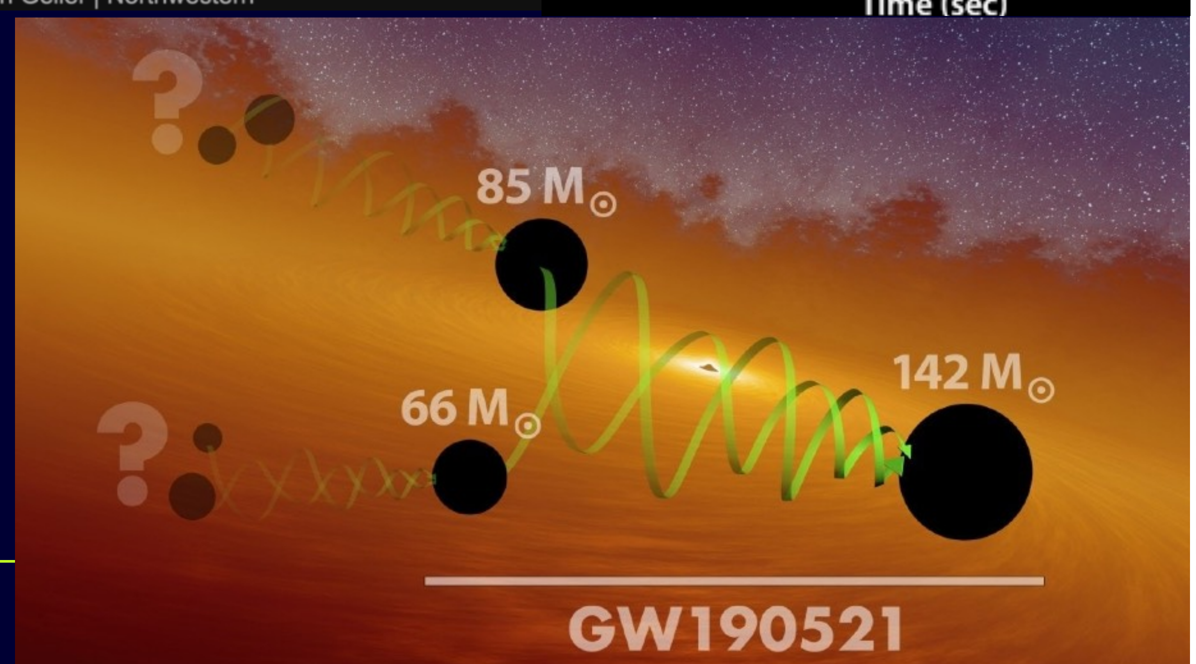




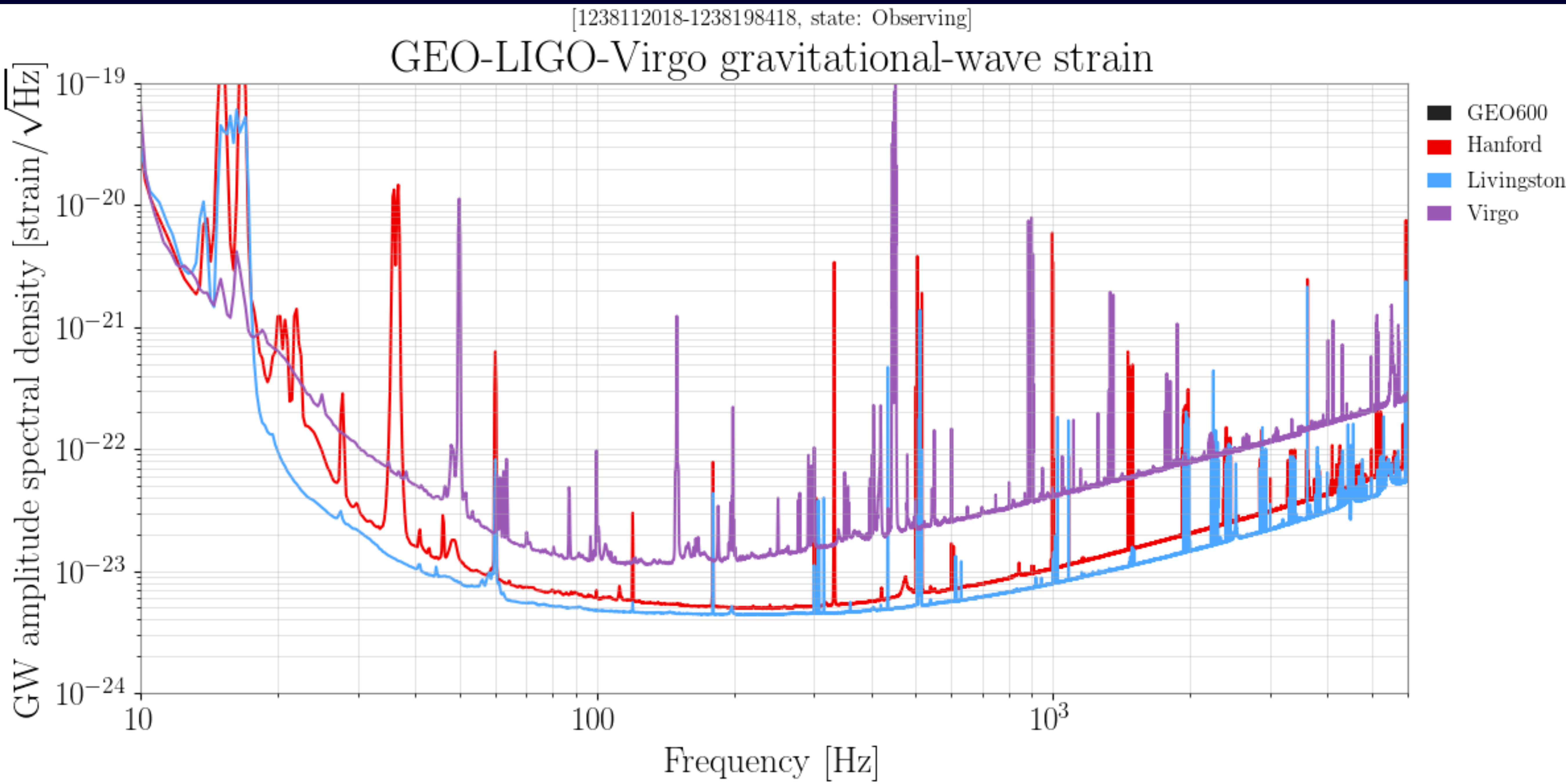








Sensitivity



Interferometer

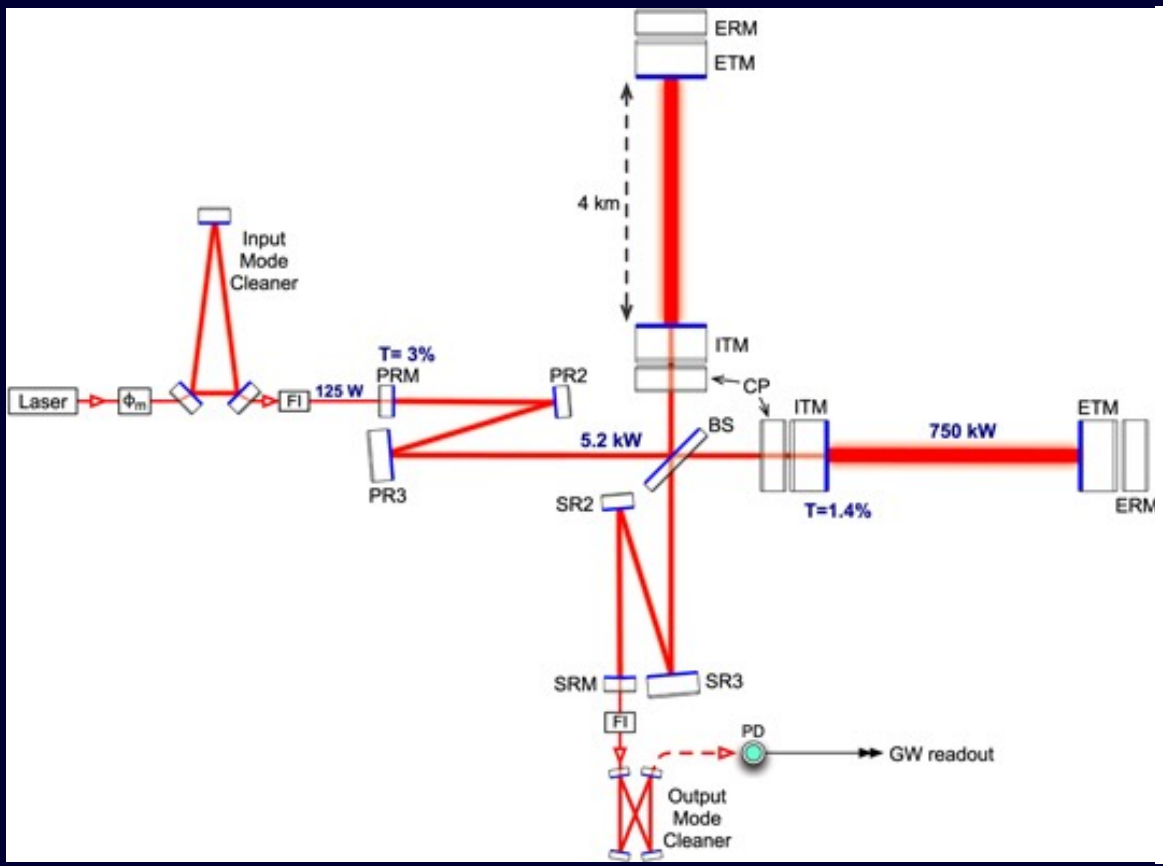


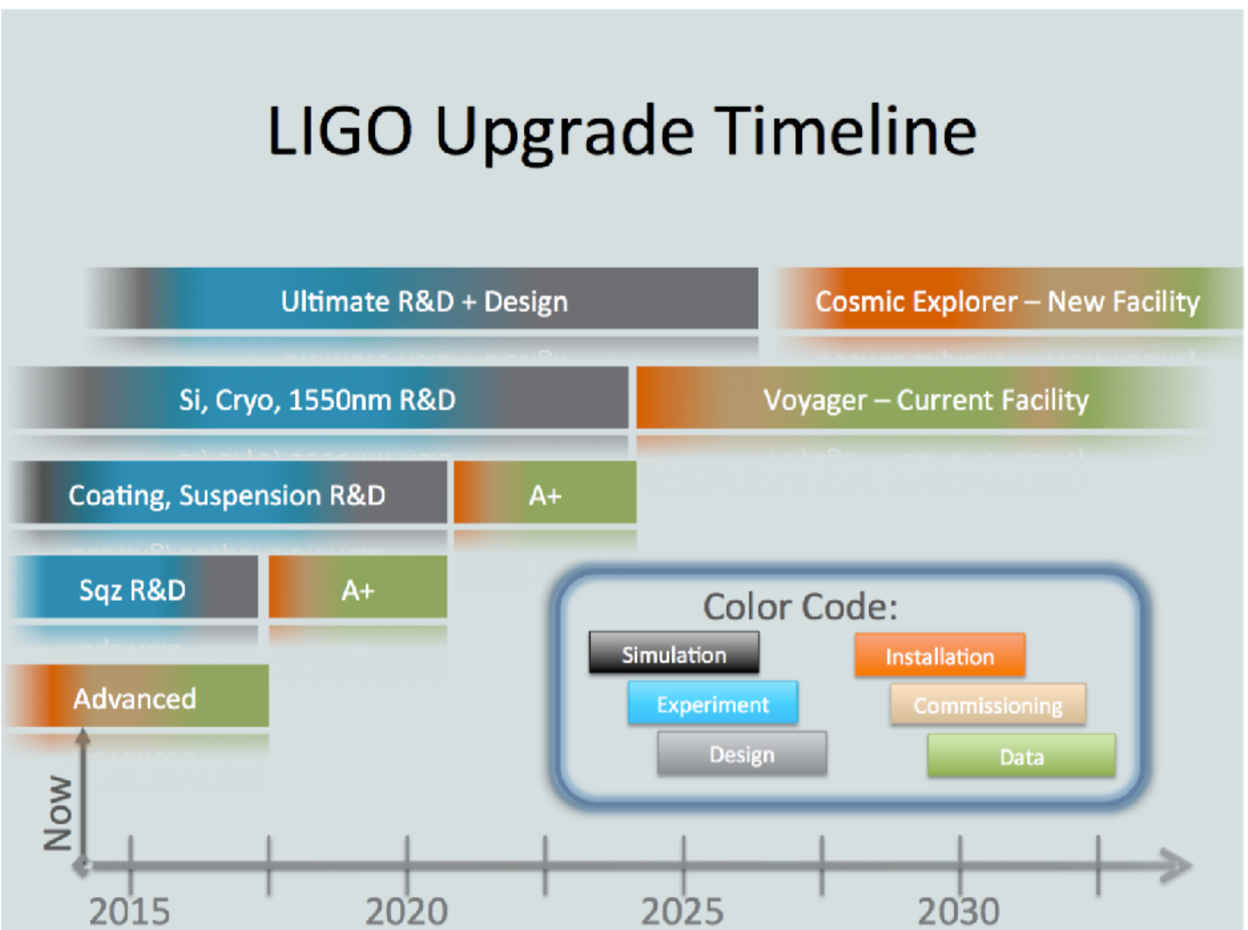
Table 1. Main parameters of the Advanced LIGO interferometers. PRC: power recycling cavity; SRC: signal recycling cavity.

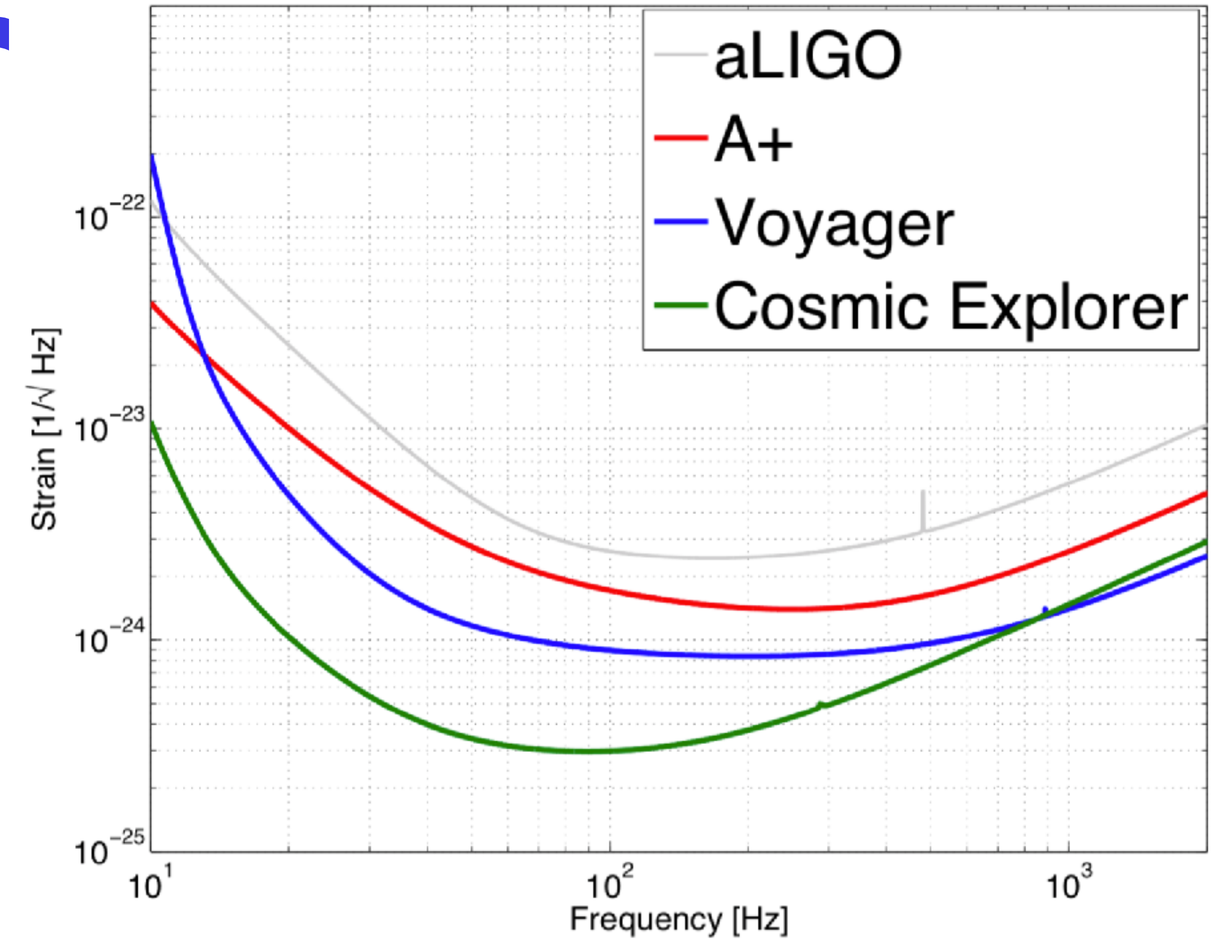
Parameter	Value
Arm cavity length	3994.5 m
Arm cavity finesse	450
Laser type and wavelength	Nd:YAG, $\lambda = 1064$ nm
Input power, at PRM	up to 125 W
Beam polarization	linear, horizontal
Test mass material	Fused silica
Test mass size & mass	34cm diam. x 20cm, 40 kg
Beam radius ($1/e^2$), ITM / ETM	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
- Virgo and KAGRA also use same configuration.

LIGO Voyager

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

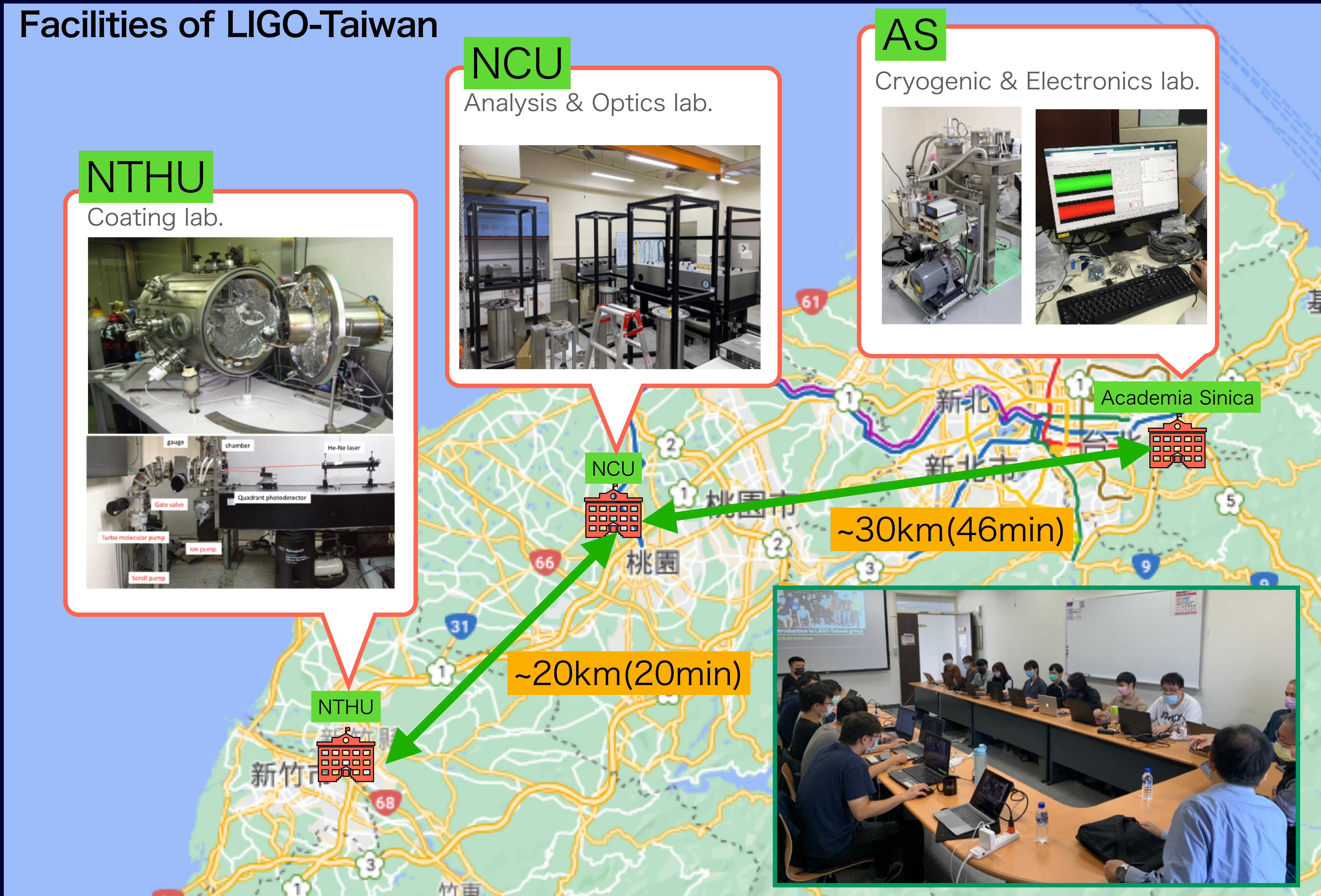




IFO Cases	aLIGO	A+	Voyager	Cosmic Explorer
Mirror Mass [kg]	40	80	160	80
Mirror Material	Silica	Silica	Silicon	Silica
Mirror Temp [K]	295	295	120	295
Sus Temp [K]	295	295	120	295
Sus Fiber	0.6m SiO2	0.8m SiO2	0.6m Si	0.8m SiO2
Fiber Type	Fiber	Fiber	Ribbon	Fiber
Input Power [W]	125	125	450	125
Arm Power [kW]	800	800	3200	800
Wavelength [nm]	1064	1064	1560	1064
NN Suppression	1	5	30	5
Coating Type	SiO:TaO	TBD	AlAs:GaAs	TBD
Beam Size [cm]	5.3 / 6.2	8 / 9.4	5.3 / 6.2	11 / 12
SQZ Factor [dB]	0	6	10	10
F. C. Length [m]	0	16	300	1000

Contribution of Taiwan

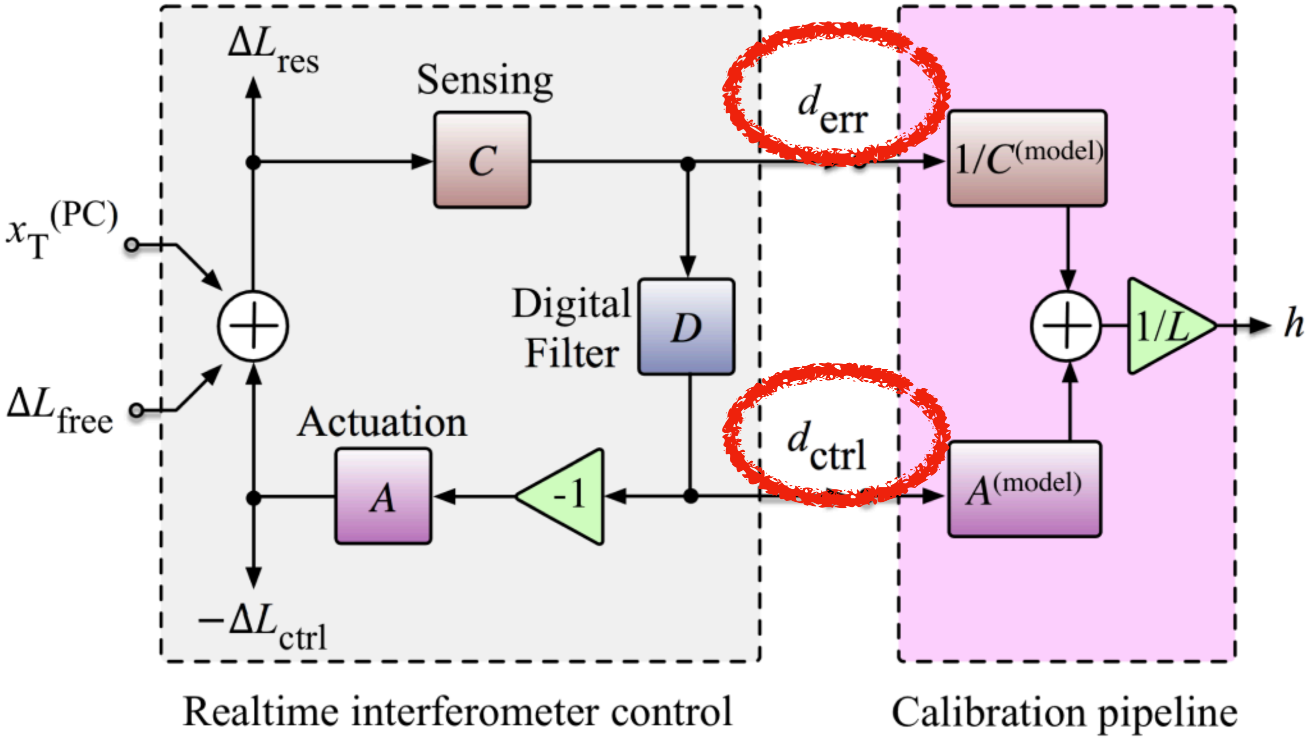
Facilities of LIGO-Taiwan



Current activity of LIGO

- Calibration
  - Error estimation pipeline
  - Systematic error study based on the simulation
- Coating
  - Large coating method
  - Low loss method
  - Cryogenic measurement system

Modeling of Interferometer



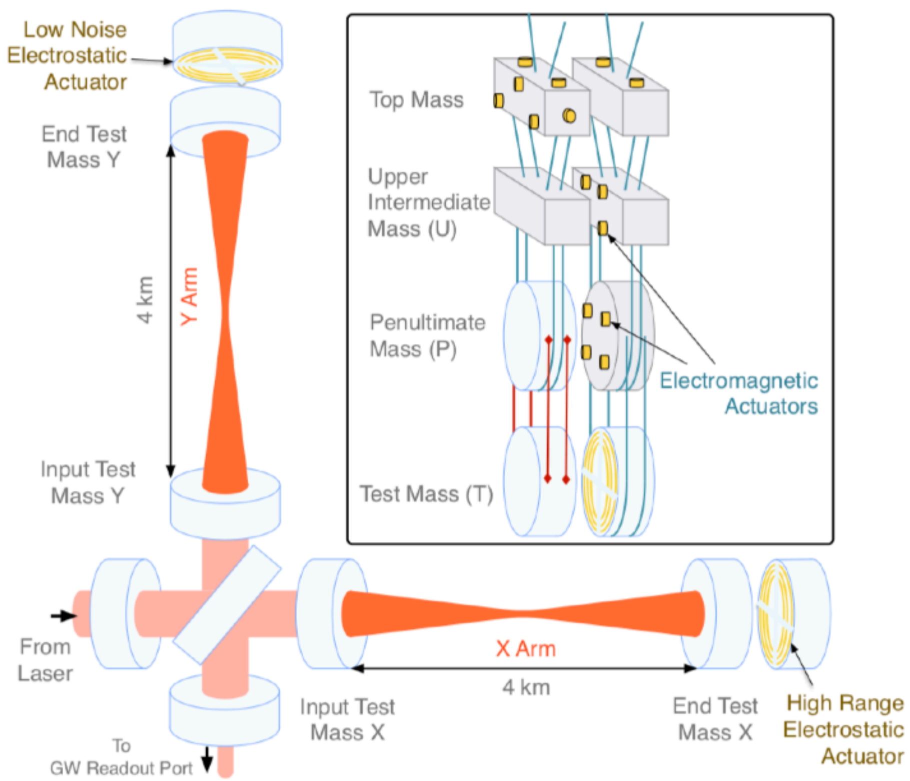
Changes of arm length are measured between Actuator and Detector

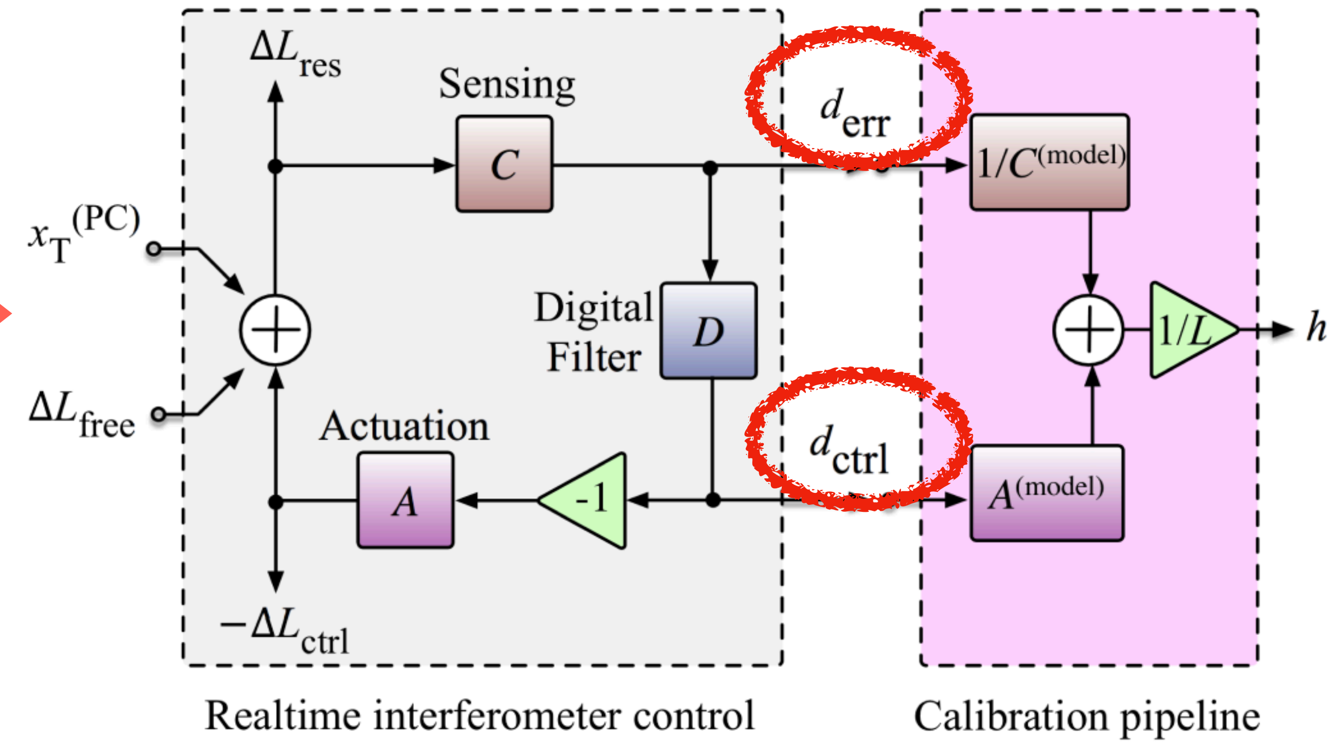
So, we can separate A and C part by estimation accurate model of A and C

→ 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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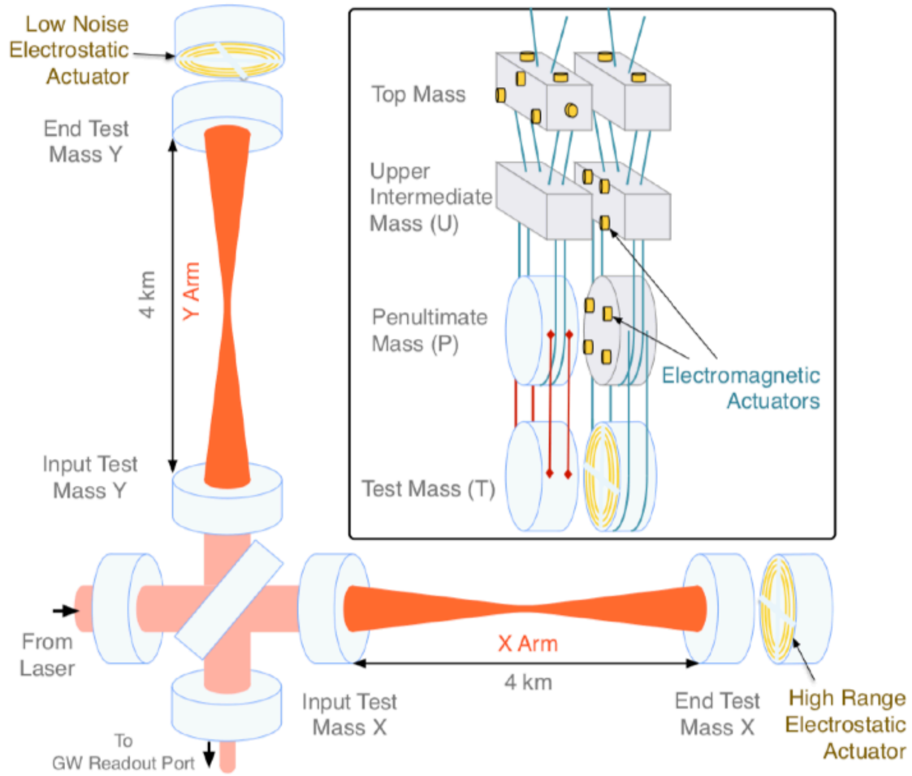
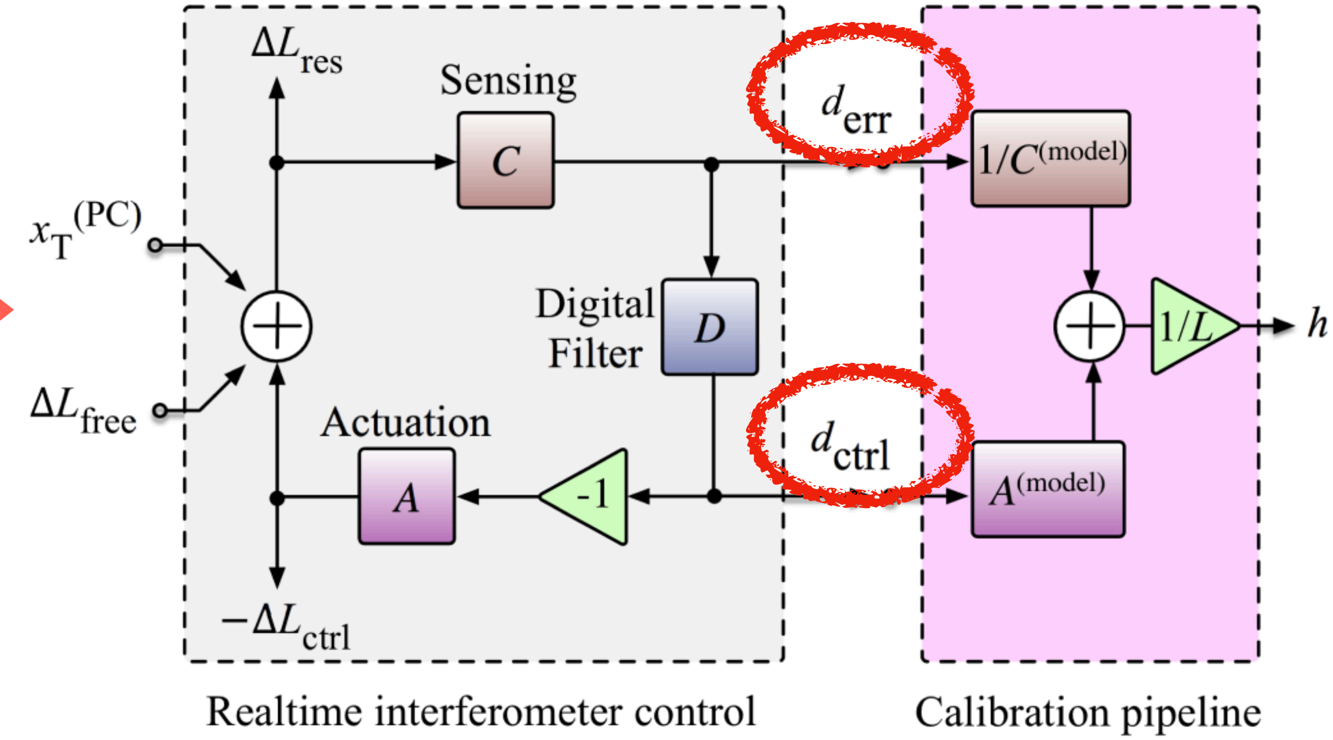
Reconstruction of LIGO





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

Modeling error -> Calibration error

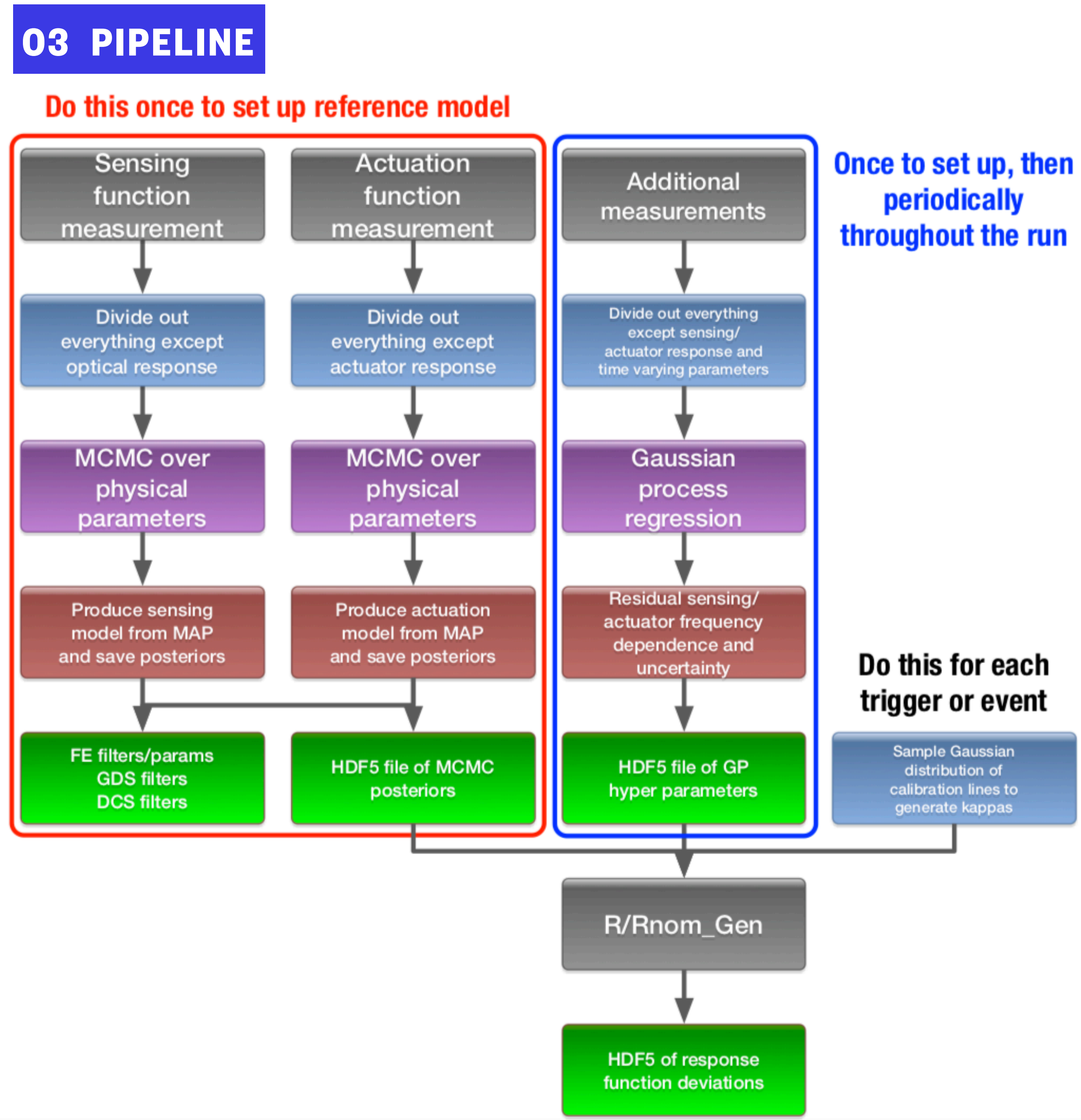
We reconstruct h(t) by modeling time-dependent Sensing and Actuation factor

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

Development of pyDARM

pyDARM

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

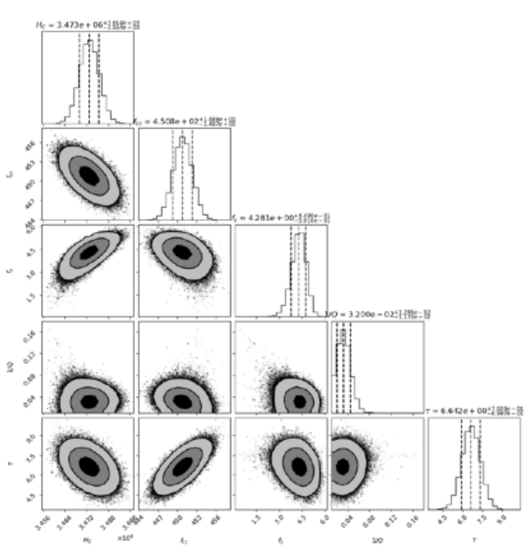


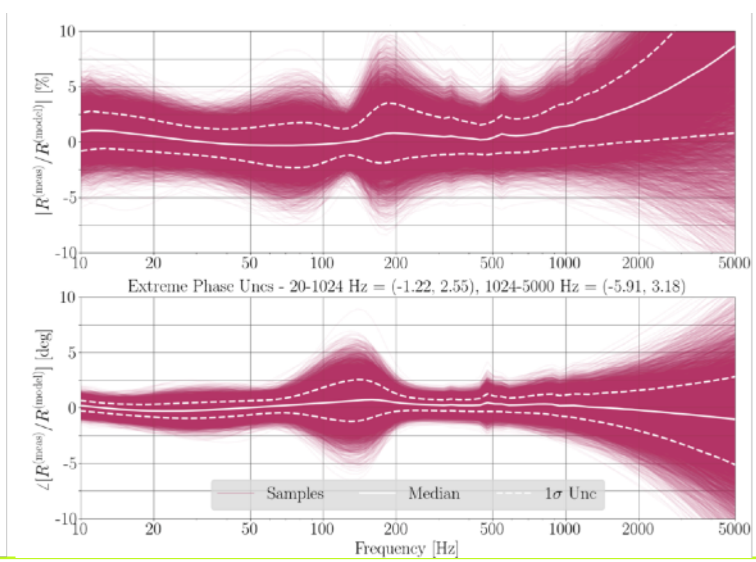
History of pyDARM

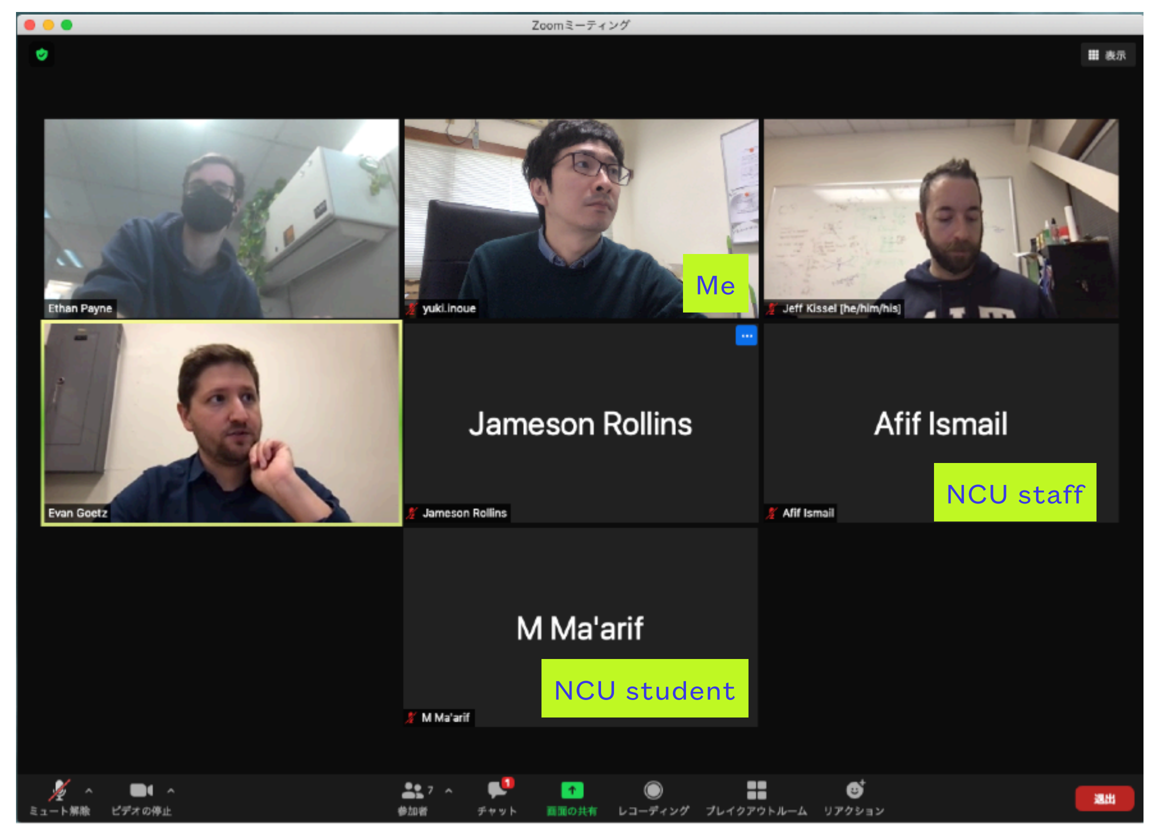
- O1: Matlab model only, simplified error analysis
- O2: Combination of Matlab and python codes used for modeling, filter generation, error/uncertainty (Bayesian) estimation
- O3: pure python codebase, but awkward to use (not modular, not easily extendable, doesn't integrate well, etc.)
- O4: modular python codebase, installable using pip/conda-forge/source

Calibration activity

- Development of systematic error estimation tool based on the interferometer model
- pyDARM = python base Differential ARM length modeling code
- Taiwan team are developing new software

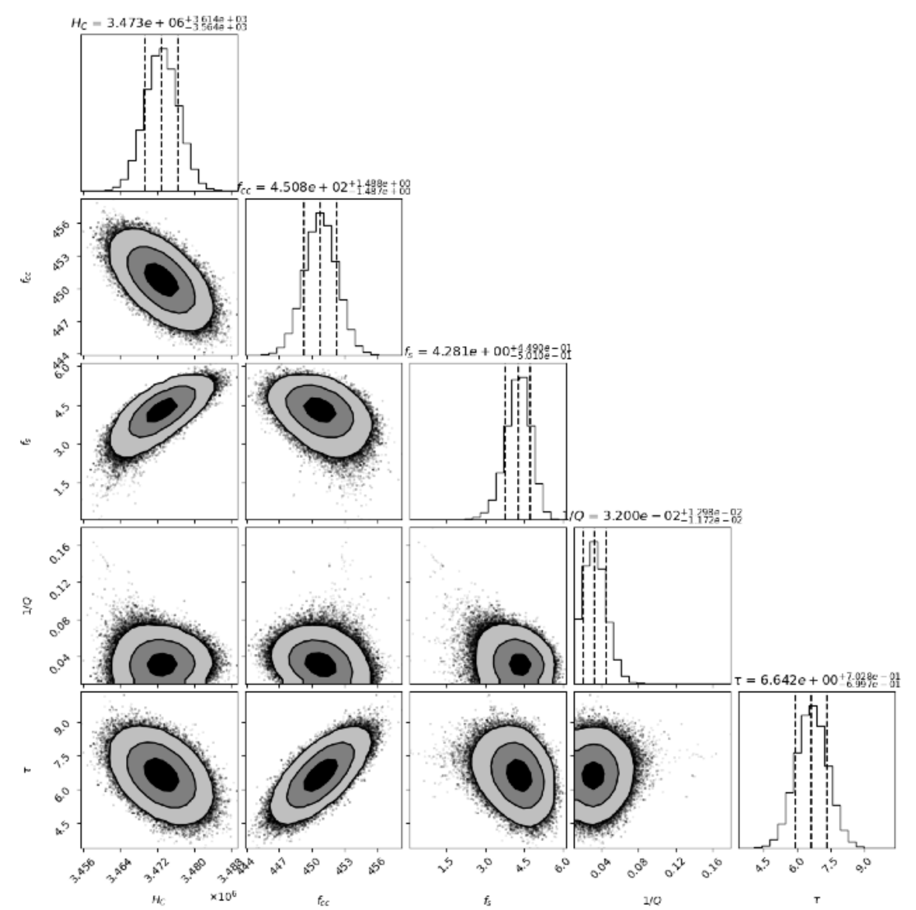




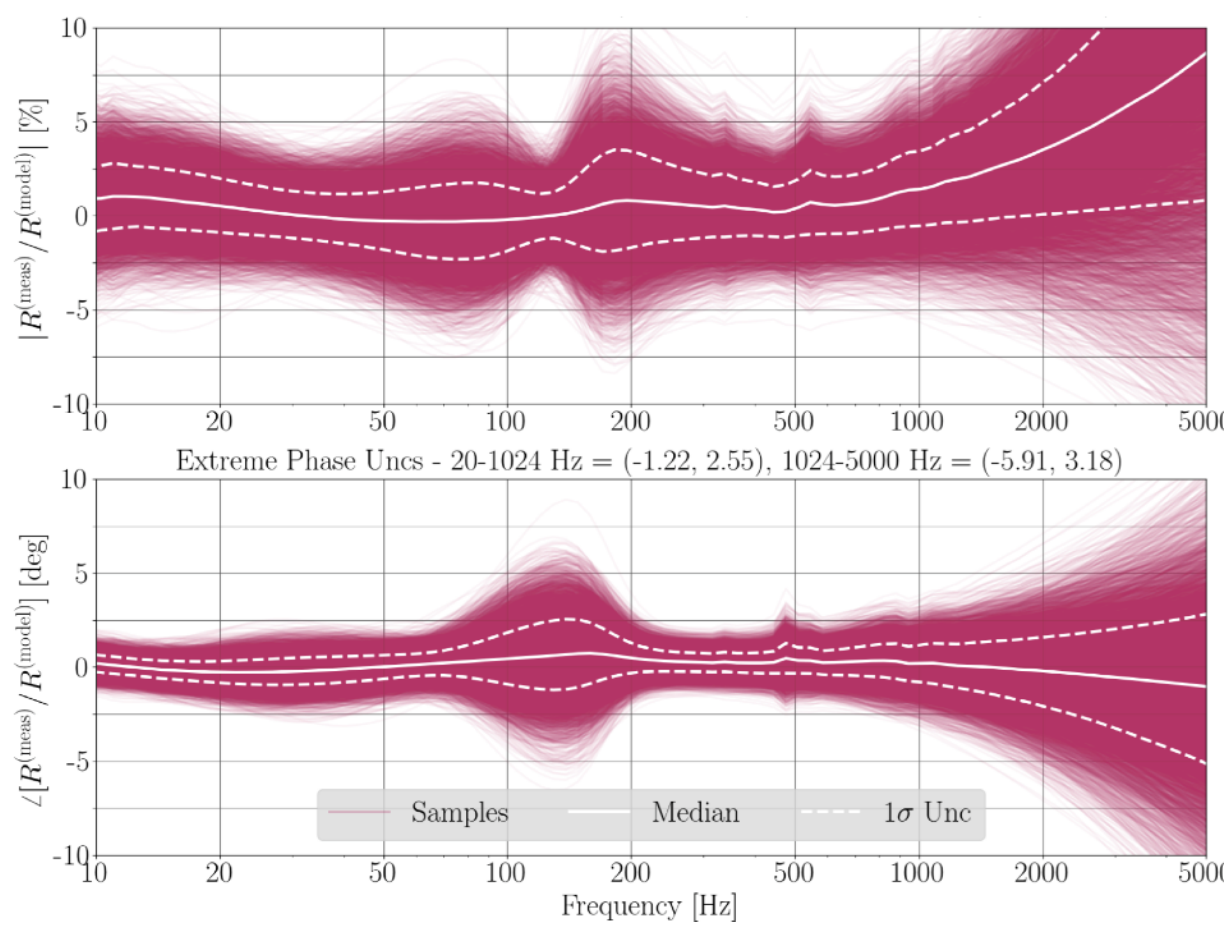


Calibration error envelop

CALIBRATION PARAMETER ESTIMATION



CALIBRATION ERROR OF STRAIN SENSITIVITY



- MCMC and Gaussian process regression
- Provide hourly calibration error for the world wide collaborator

Coating study

NTHU Prof.Chao — NCU&AS Yuki Inoue

- **Prof.Chao will retire at next summer**
- **Yuki is taking over his coating facility**
- **Process of taking over is ongoing**
- **Prof.Chao plan to continue the research in Yuki's group**

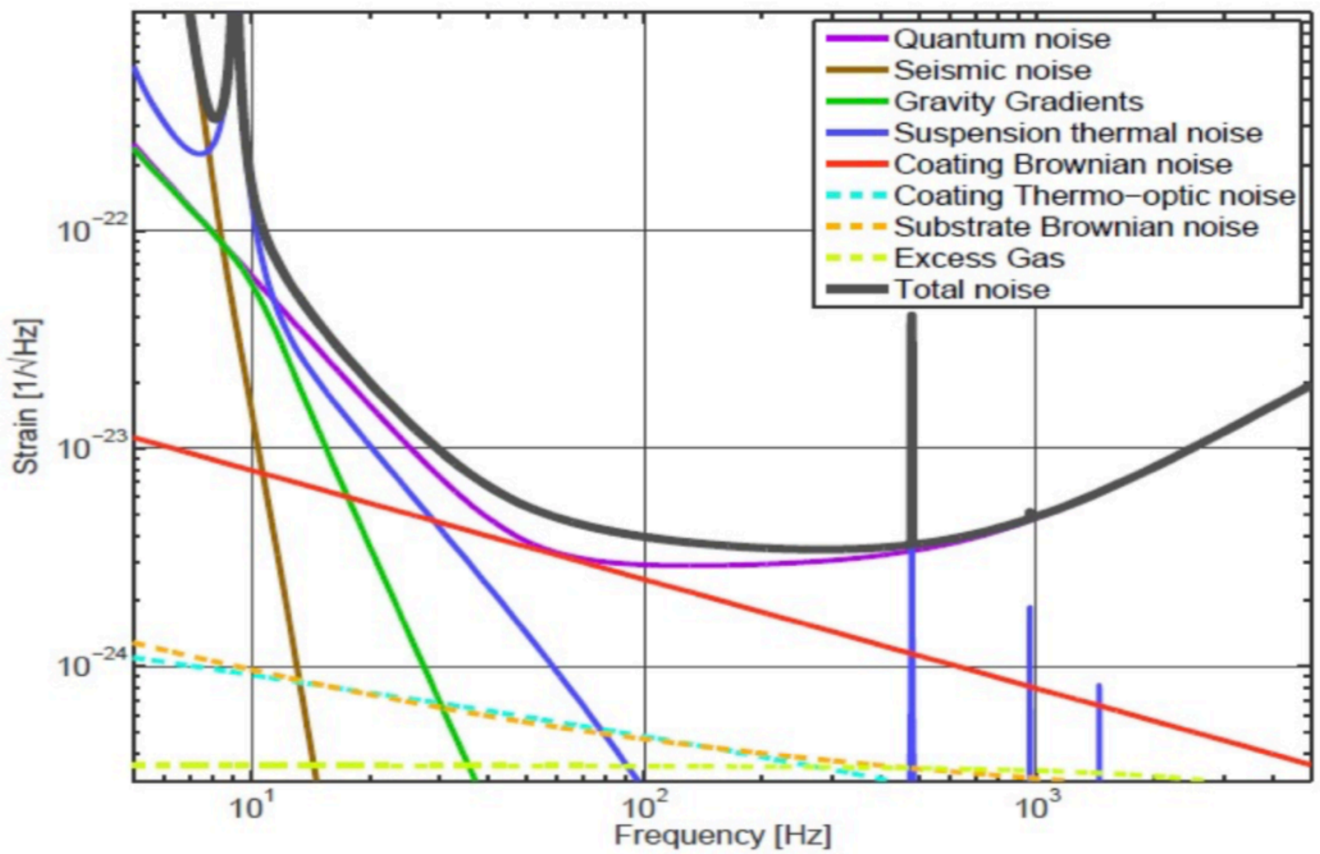
Assignment of human resource for taking over

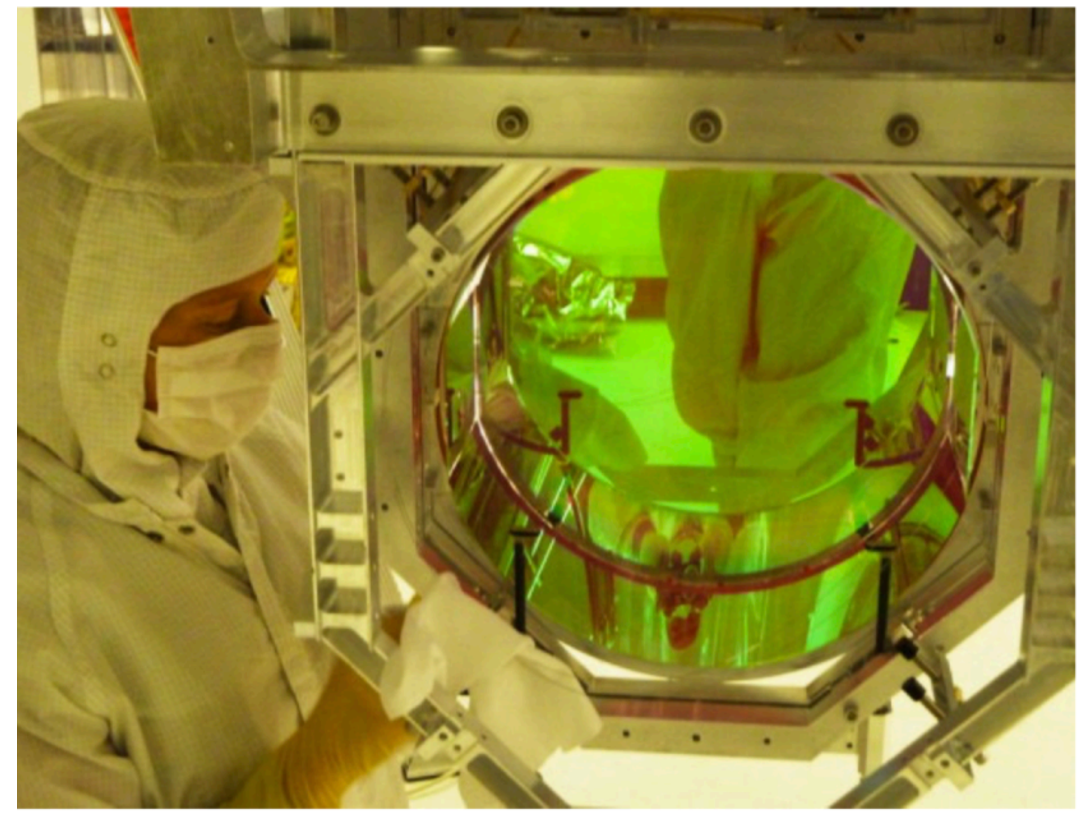
- 1 postdoc and 1 Ph.D. student visit NTHU constantly.
- 1 master student stay in NTHU and focus on CVD method (Training now)
- Technical staffs and 1 master student focus on development of cryogenic loss measurement system in Academia Sinica

High Priority studies → **2022 plan**

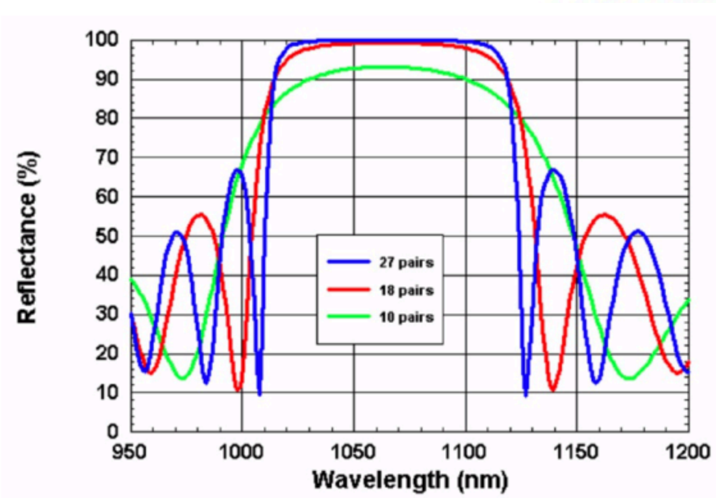
1. Verification of large aria coating with CVD method → Prof.Chao&Yuki
2. Optimization of fabrication process for low loss coating → Prof.Chao
3. Development of cryogenic loss measurement system → Yuki

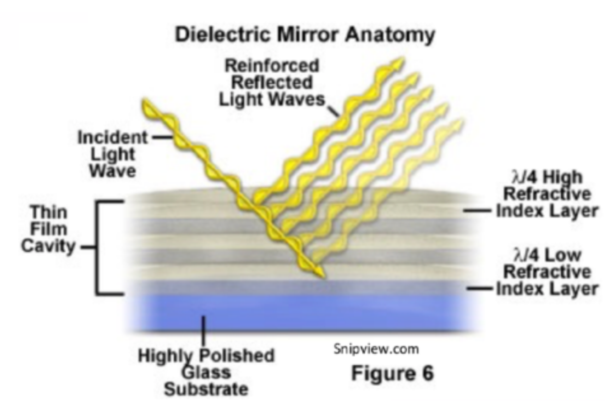
LIGO coating





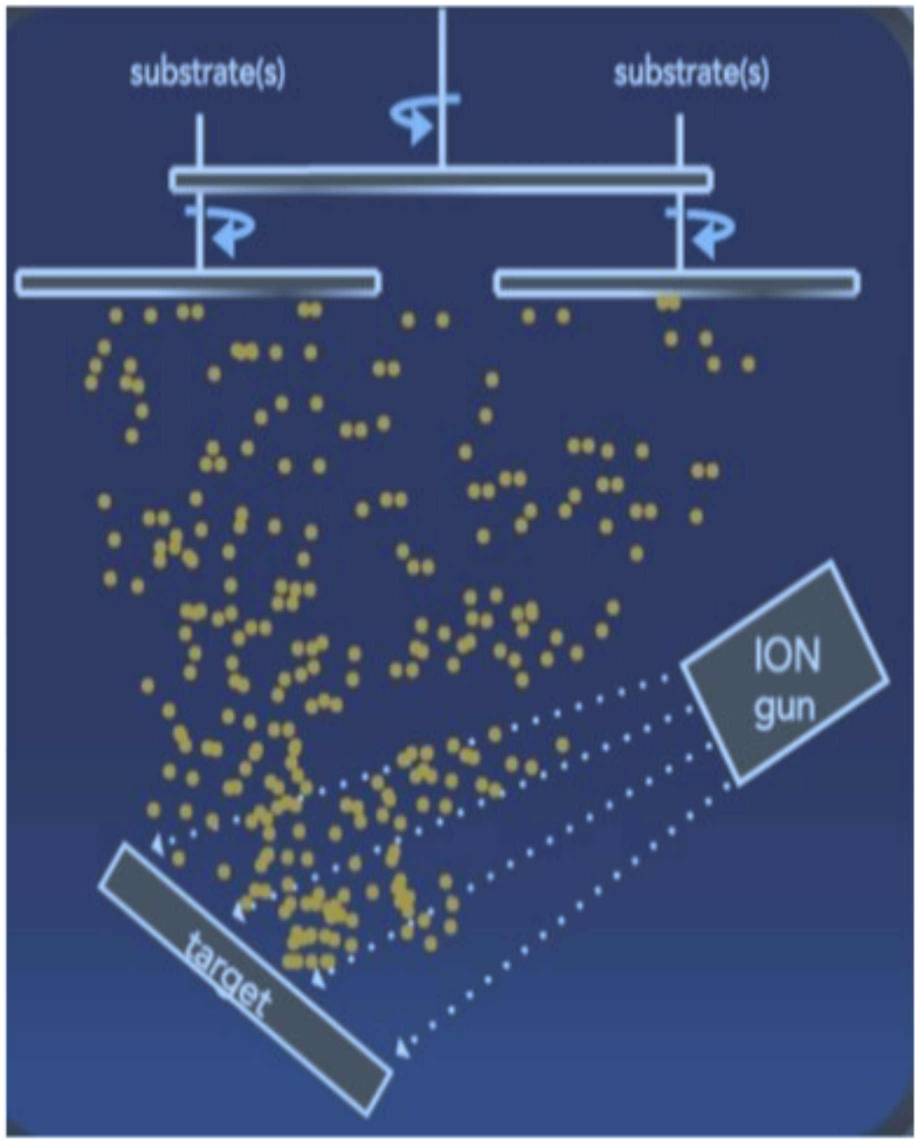
$$S_x(f) = \frac{2k_BT}{\pi^{3/2} f}\frac{1-\sigma^2}{wY}\left\{\phi_{\text{substrate}} + \frac{2}{\sqrt{\pi}}\frac{(1-2\sigma)}{(1-\sigma)}\frac{d}{w}\phi_{\parallel}\right\}$$





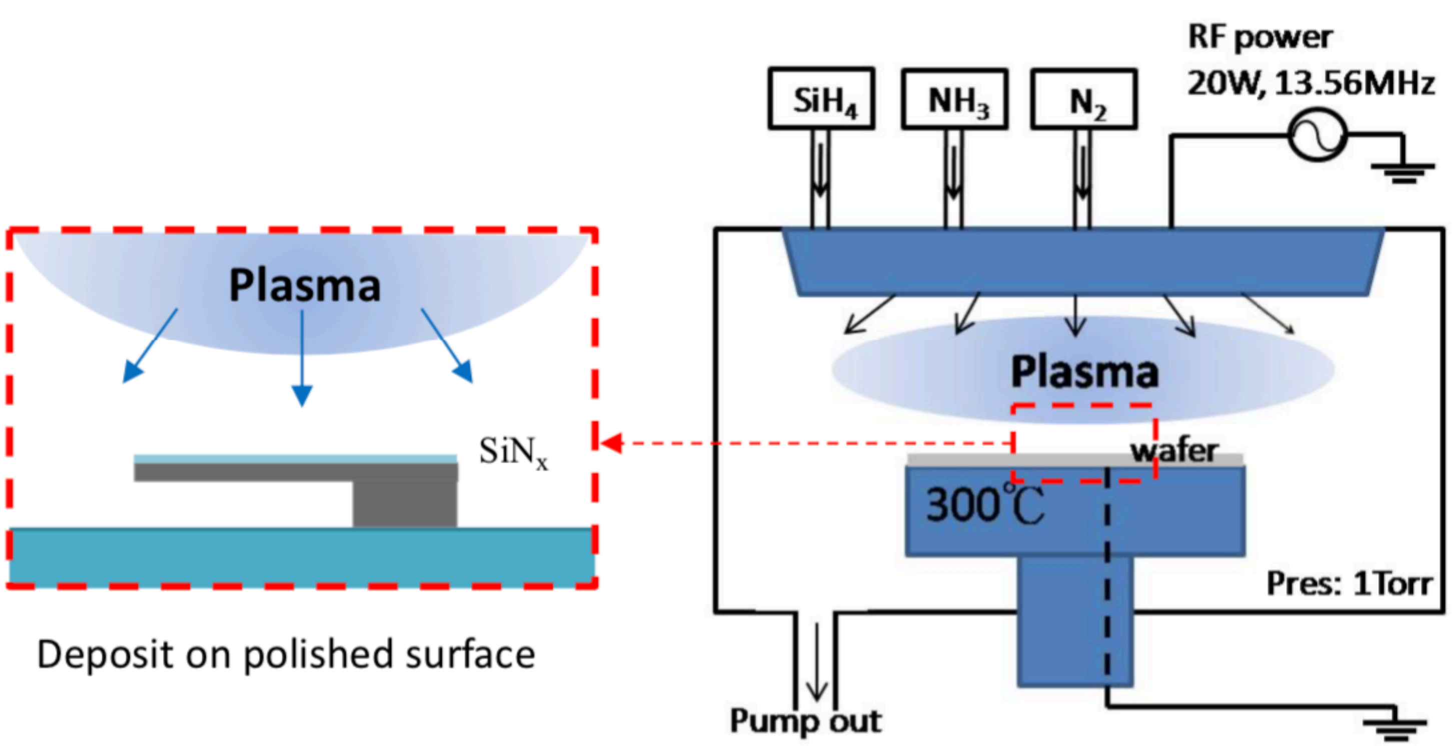
- LIGO employs Ta_2O_5-TiO_2 coating with Fused Silica mirror
- Ion Beam Sputter (IBS) method is used in the fabrication process
- They still have a challenging issue for the large area coating with IBS.

IBS coating in LIGO



Two aLIGO mirrors are coated simultaneously with planetary rotation and masking to ensure the thickness uniformity (all Zernike poly terms <0.5nm was achieved for a-LIGO)

Fabrication of SiN film on Silicon by Plasma Enhanced CVD method



Deposit on polished surface

$$SiH_4 + 4NH_3 \xrightarrow{\text{plasma}} Si(NH_2)_4 + 4H_2$$

$$3Si(NH_2)_4 \xrightarrow{\text{heat}} Si_3N_4 + 8NH_3$$

Ref : Donald L. Smith, et al." mechanism of SiN_xH_y Deposition from NH_3-SiH_4 plasma". J.Electrochem. Soc. **137**, 614-623(1990)

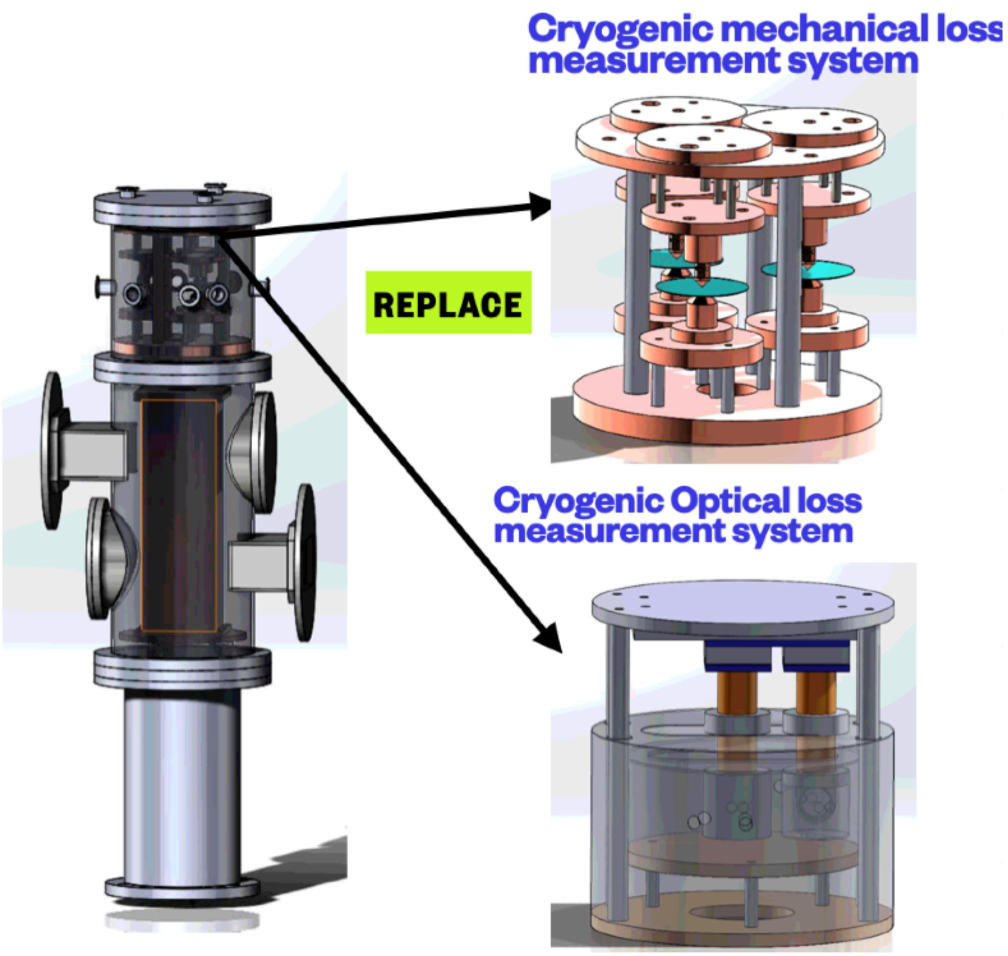
Ref : J. N. Chiang, et al **"**Mechanistic Considerations in the Plasma Deposition of silicon nitride film" J. Electrochem. Soc. **137**, 2222-2226.(1990)

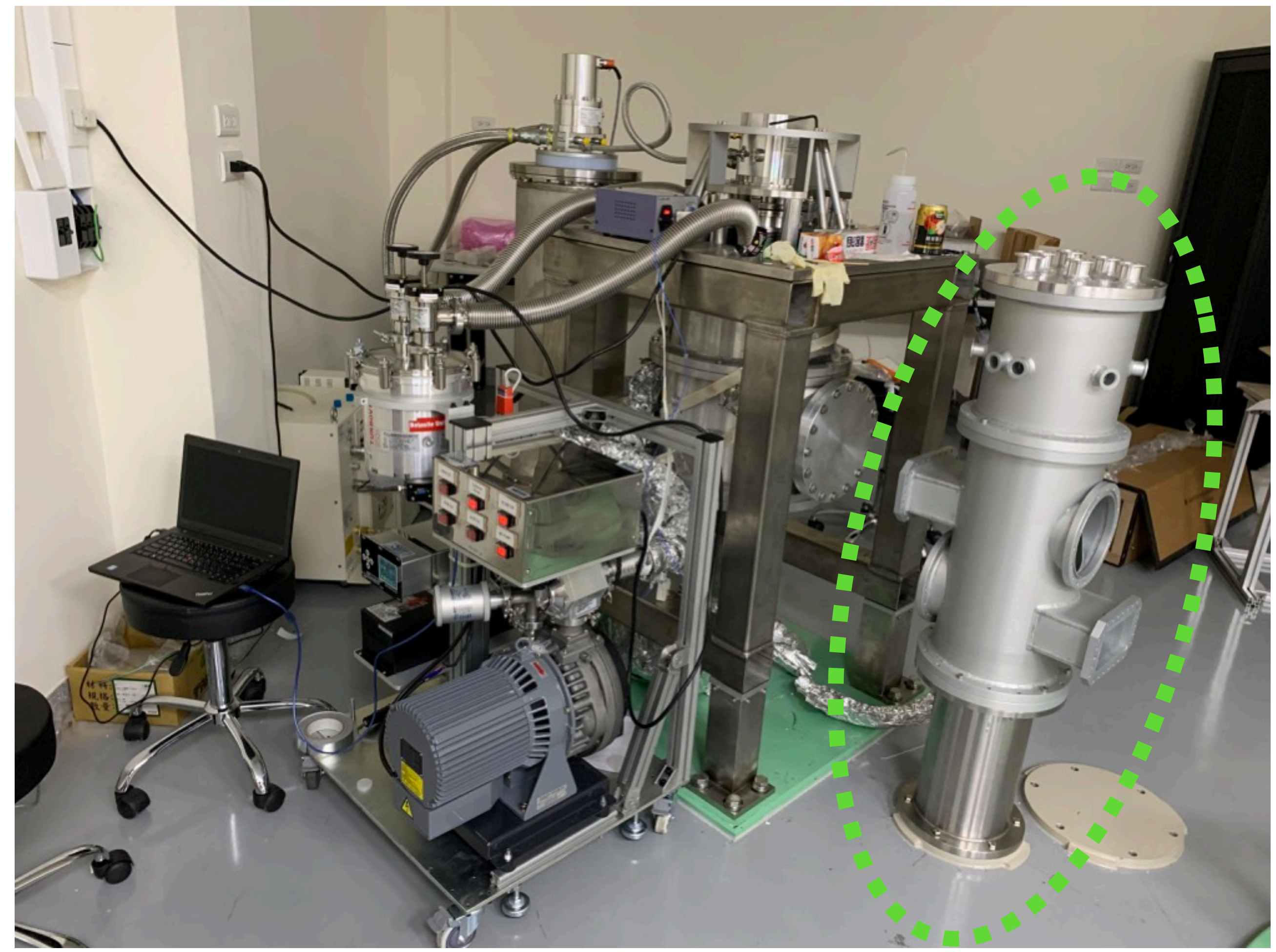
Adjusting the ratio of the gas flow rate, the composition of the SiN film can be changed

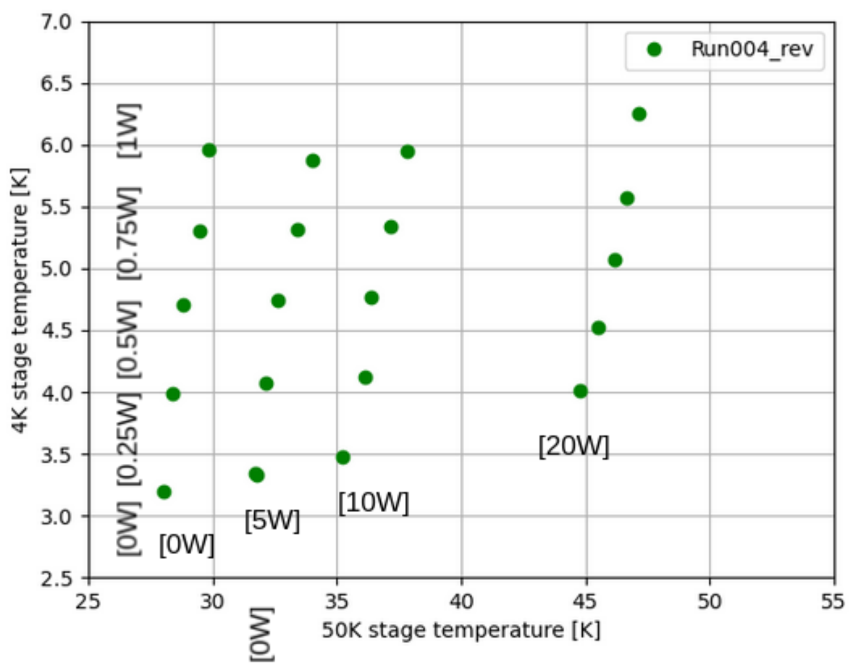
With fixed N_2 gas flow at 980 sccm, we used 5 recipes with different gas flow rate :

Gas flow rate SiH_4/NH_3(sccm)	Composition	thickness * (nm)	Refractive index† @1550nm	Young's modulus (GPa)	Stress (MPa)	Uncoated cantilever frequency	Coated cantilever frequency
45/15	$SiN_{0.40}$	159.1±2.7	2.300±0.006	103.7±5.6	120.2±15.5	103.42	103.47
38/22	$SiN_{0.49}$	179.2±1.4	2.138±0.005	107.0±10.8	143.8±13.2	107.32	107.38
25/30	$SiN_{0.65}$	198.5±0.8	1.930±0.002	131.6±4.8	256.7±6.6	104.88	105.02
15/45	$SiN_{0.79}$	204.4±1.5	1.816±0.001	137.7±9.7	382.2±21.3	107.37	107.53
8/48	$SiN_{0.87}$	211.8±0.1	1.783±0.001	137.0±9.2	412.7±20.0	106.93	107.5

Development of loss measurement system
- Characterization of thermal property-



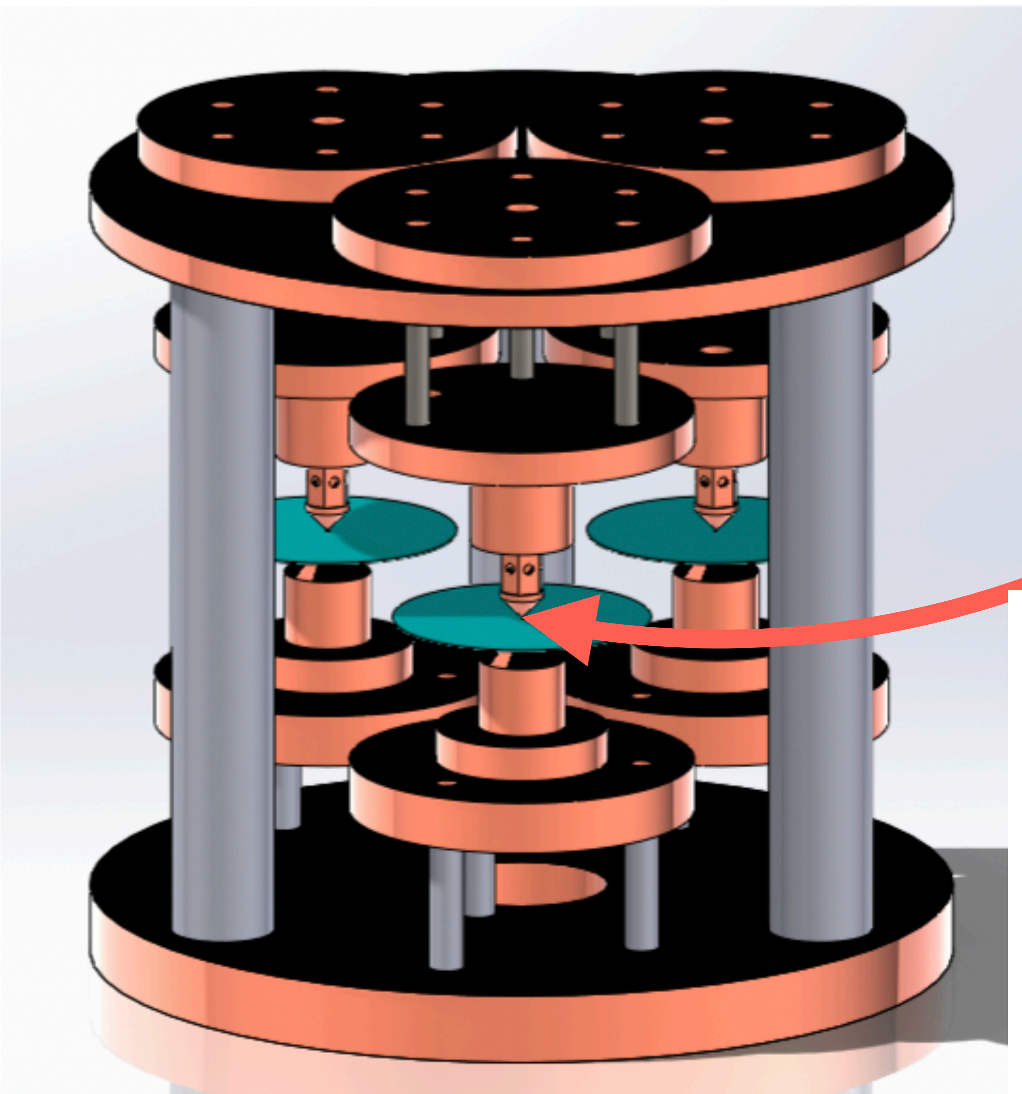




- Installed two thermal stages pulse tube cooler for coating system
- By injecting power for each stage, we measured thermal loading map
- We can keep 4.2 K with 0.25 W (low stage), 10W (high stage)

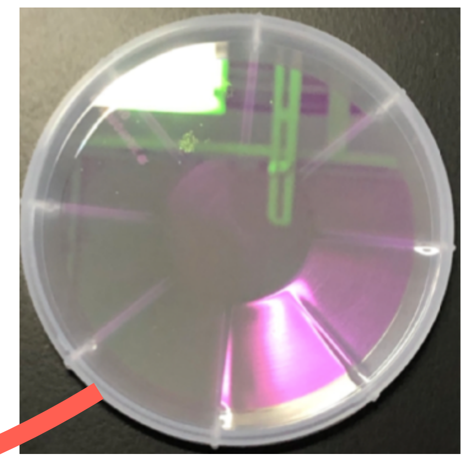
We confirmed the enough heat capability of our cryogenic system

Coating measurement system

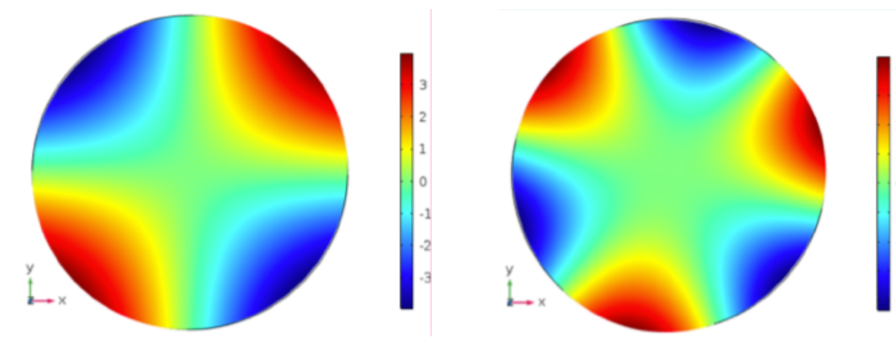


$$G_{\text{thermal noise}} \propto \sqrt{T\phi_{\text{loss}}(\omega)}$$

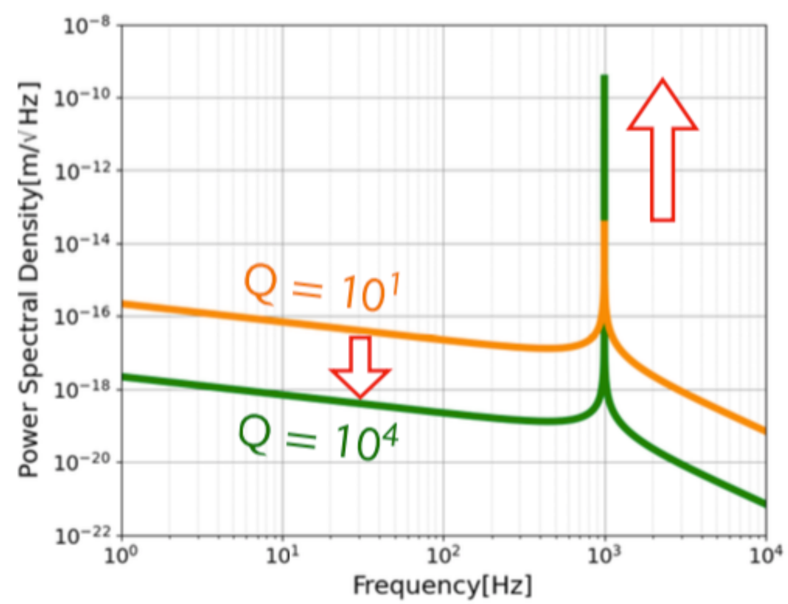
t0.5mm×ϕ3 inchs

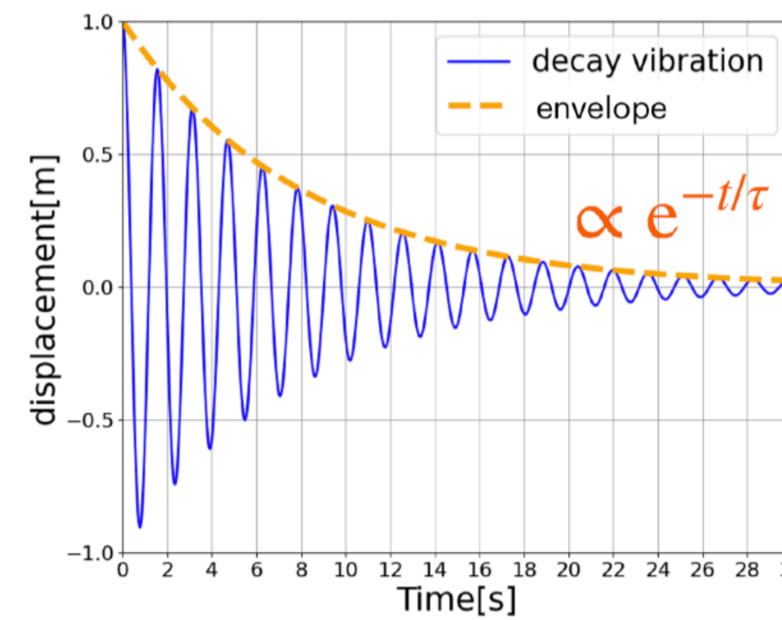


720Hz 1653Hz



1st mode 3rd mode

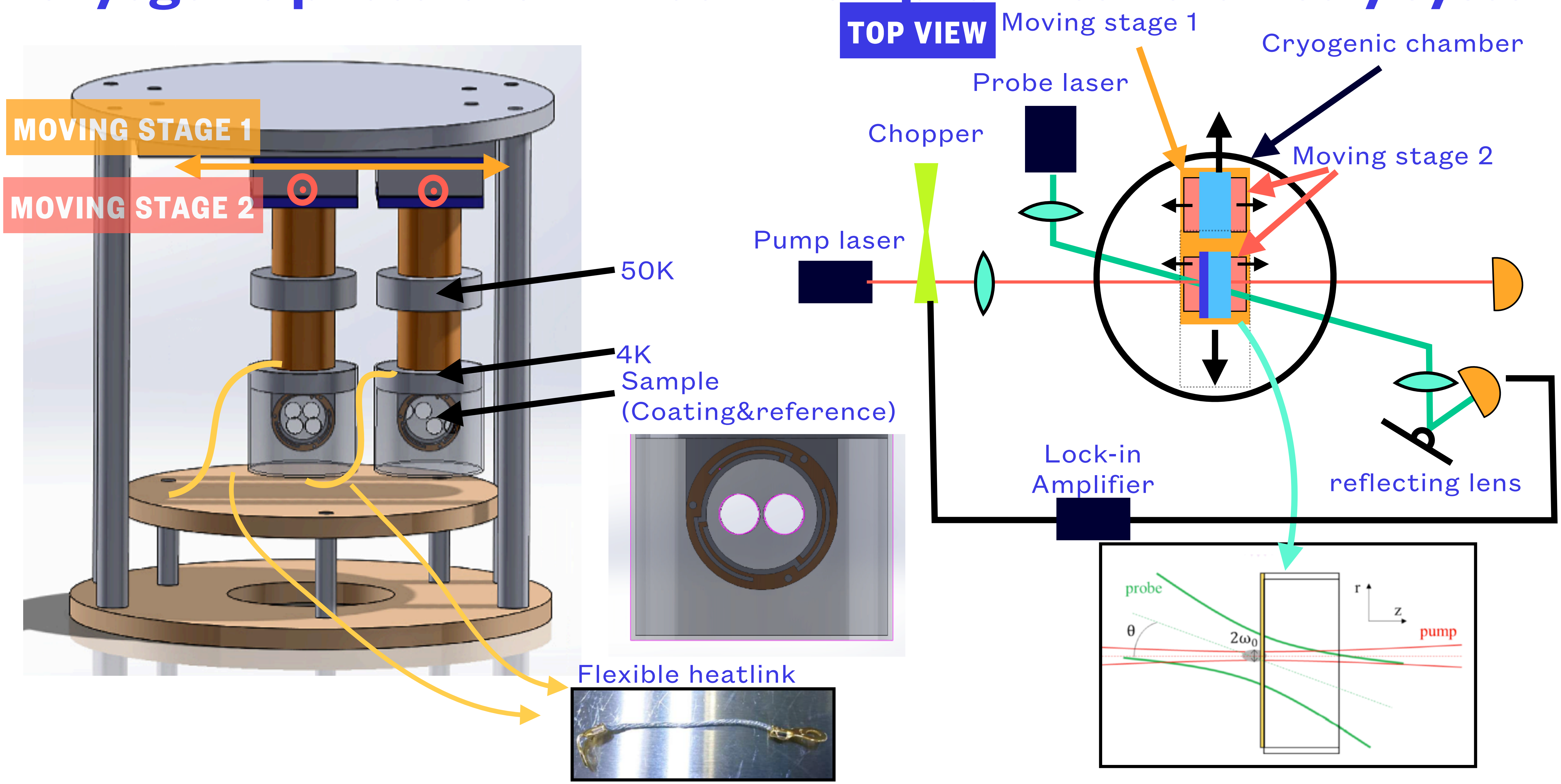




- We are developing the coating characterization system for measurement of coating in CHRONOS.

CHRONOS

Cryogenic photo-thermal common-path interferometry system



Moving stage 1: Replace Coating sample and reference sample

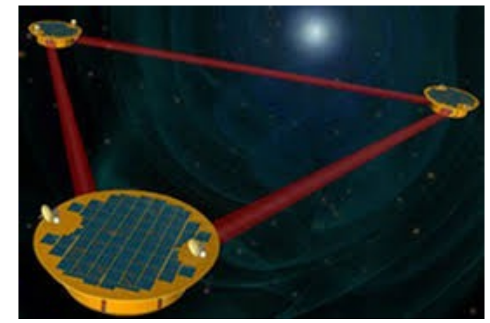
Moving stage 2: Alignment of sample position

- We will mount the radiation shield around the sample
- We can replace the mirrors with piezo motor.
- We employ the high purity aluminum wire for moving cryogenic stage.

ASGRAF and CHRONOS

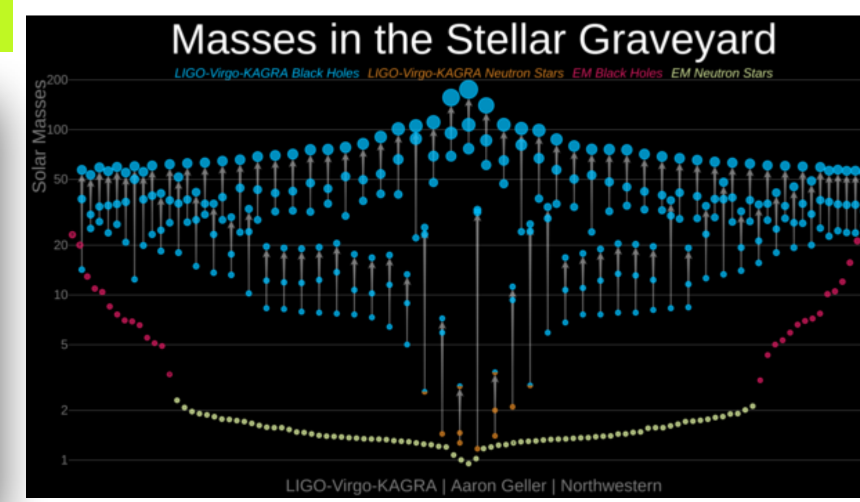
Introduction

2035: START OF GW SATELLITE MISSION



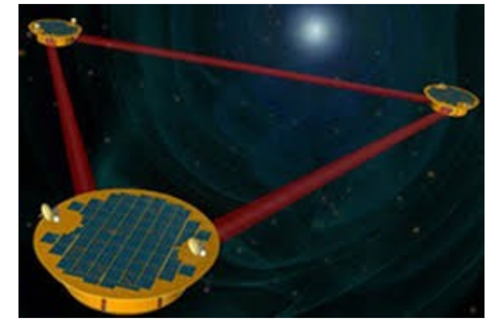
15 years What should we do 15 years for GW science in Taiwan??

2020: START OF WORLDWIDE JOINT OBSERVATION



Introduction

2035: START OF GW SATELLITE MISSION

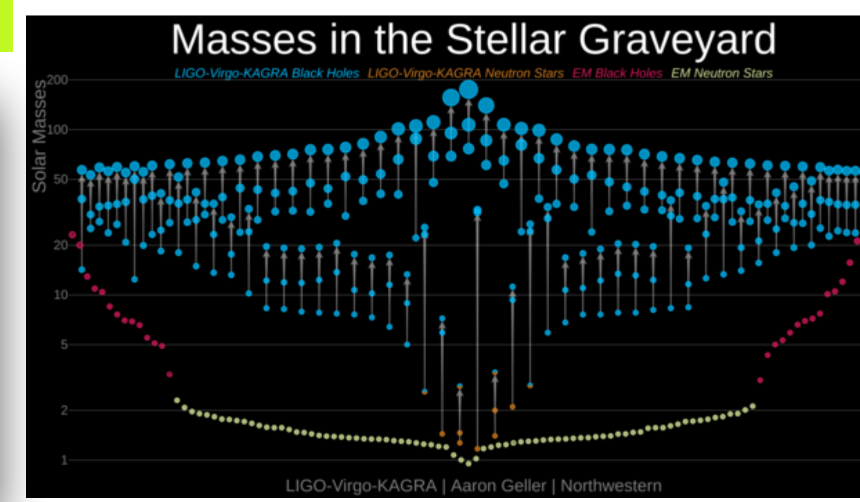


CHRONOS

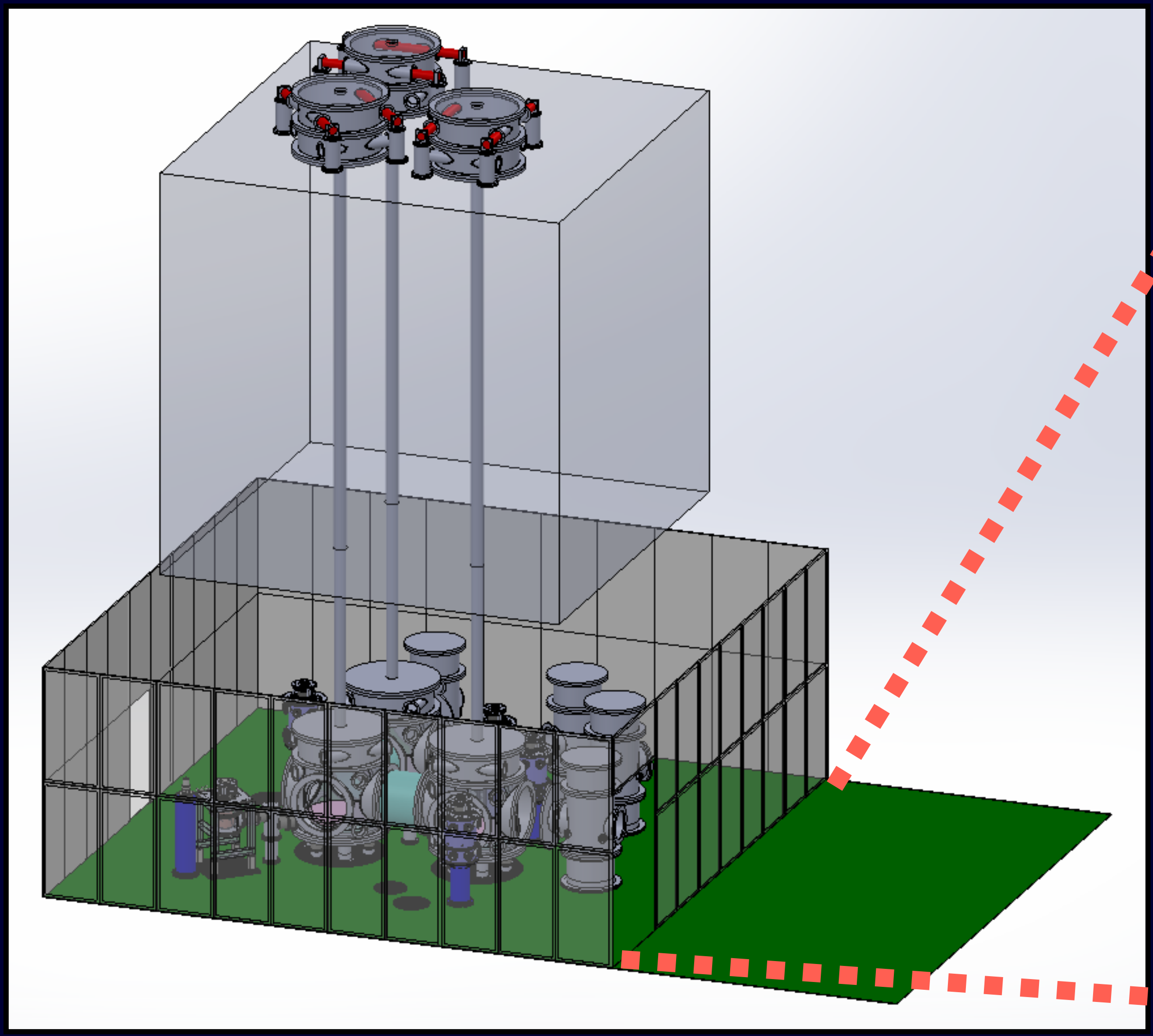
15 years

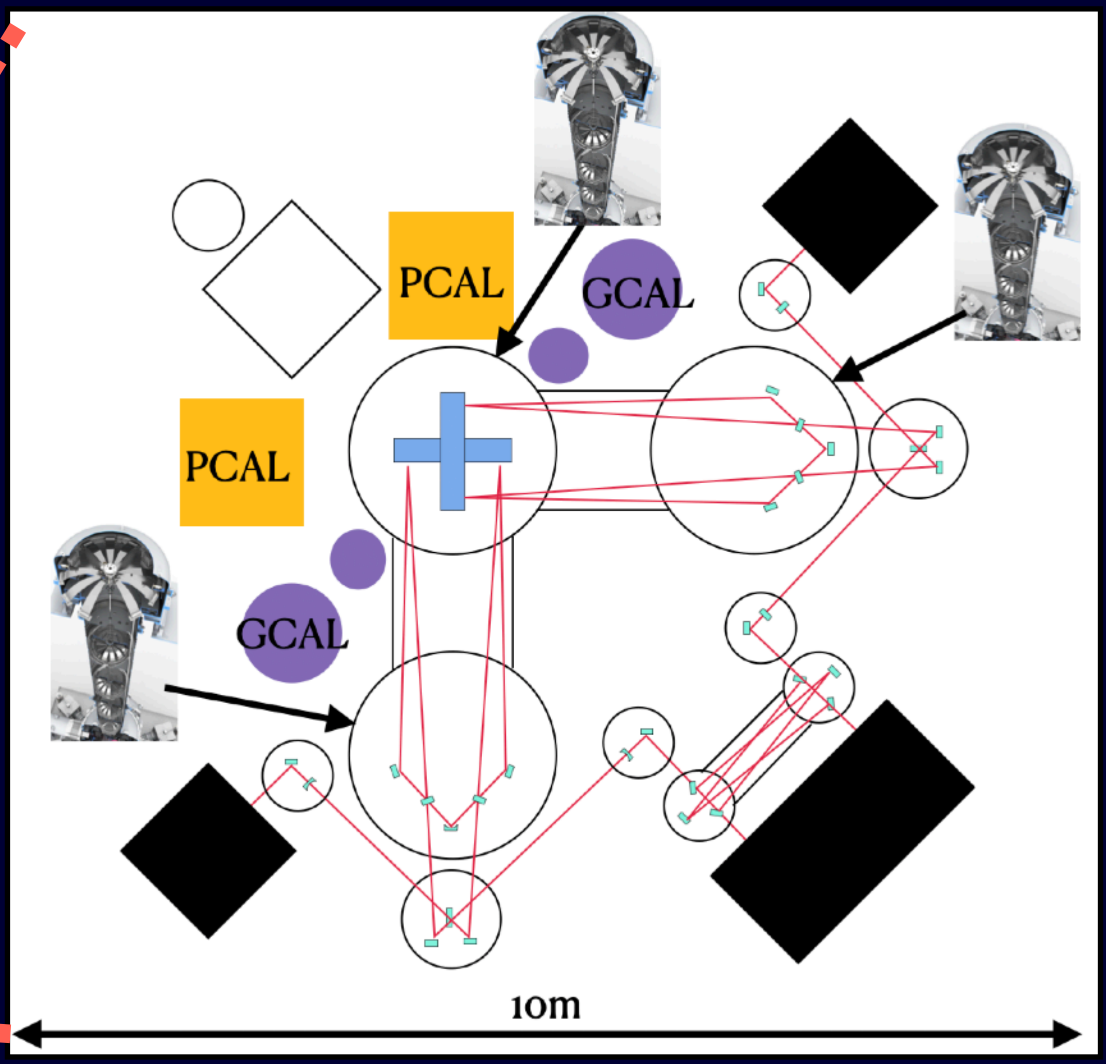
What should we do 15 years for GW science in Taiwan??

2020: START OF WORLDWIDE JOINT OBSERVATION



CHRONOS Overview





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

CHRONOS

Collaborator of CHRONOS

National Central University
Yuki Inoue (PI)
Daiki Tanabe
Ko-Han Chen
Miftahul Ma'arif
Hong-Lin Lin
Tsung-Chieh Ho
Dennis
You-Ru Lee
Hsiang-Yu Huang
Chiu Yi-Hsuan
Tseng Shun-Lin

Academia Sinica
Tsz-King Wong
Fong-Kai Lin
Cheng-I Chiang
Hsiang-Chieh Hsu
Afif Ismail
Niko
Chen Yung-Ying

NTHU
Chao Shiuh
Debby Lin
Martin Spinrath

TKU
Guo-Chin Liu

KEK
Masaya Hasegawa

NTNU
Chen Chuan-Ren
Chrisna Setyo Nugroho

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

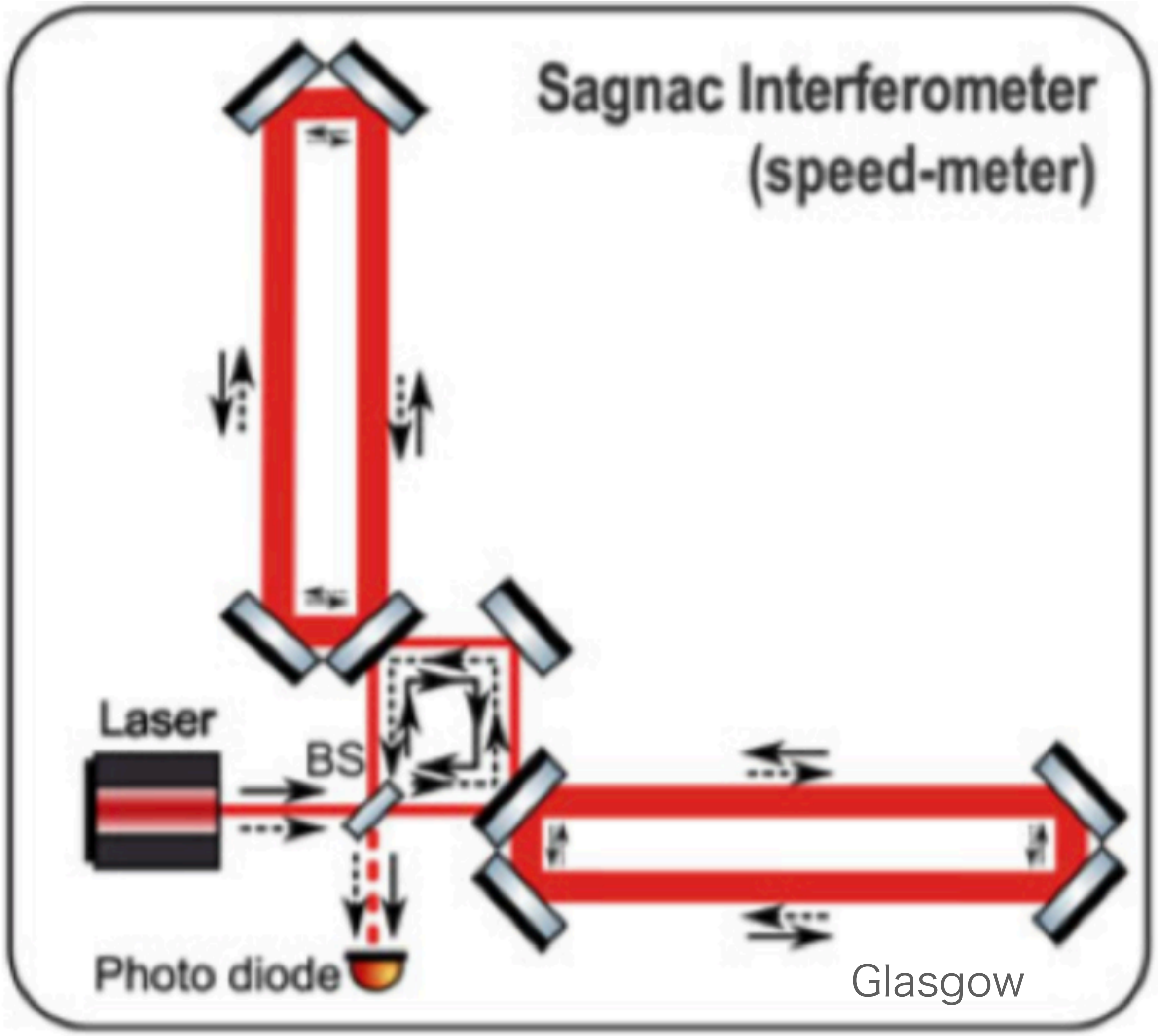
CHRONOS Phase

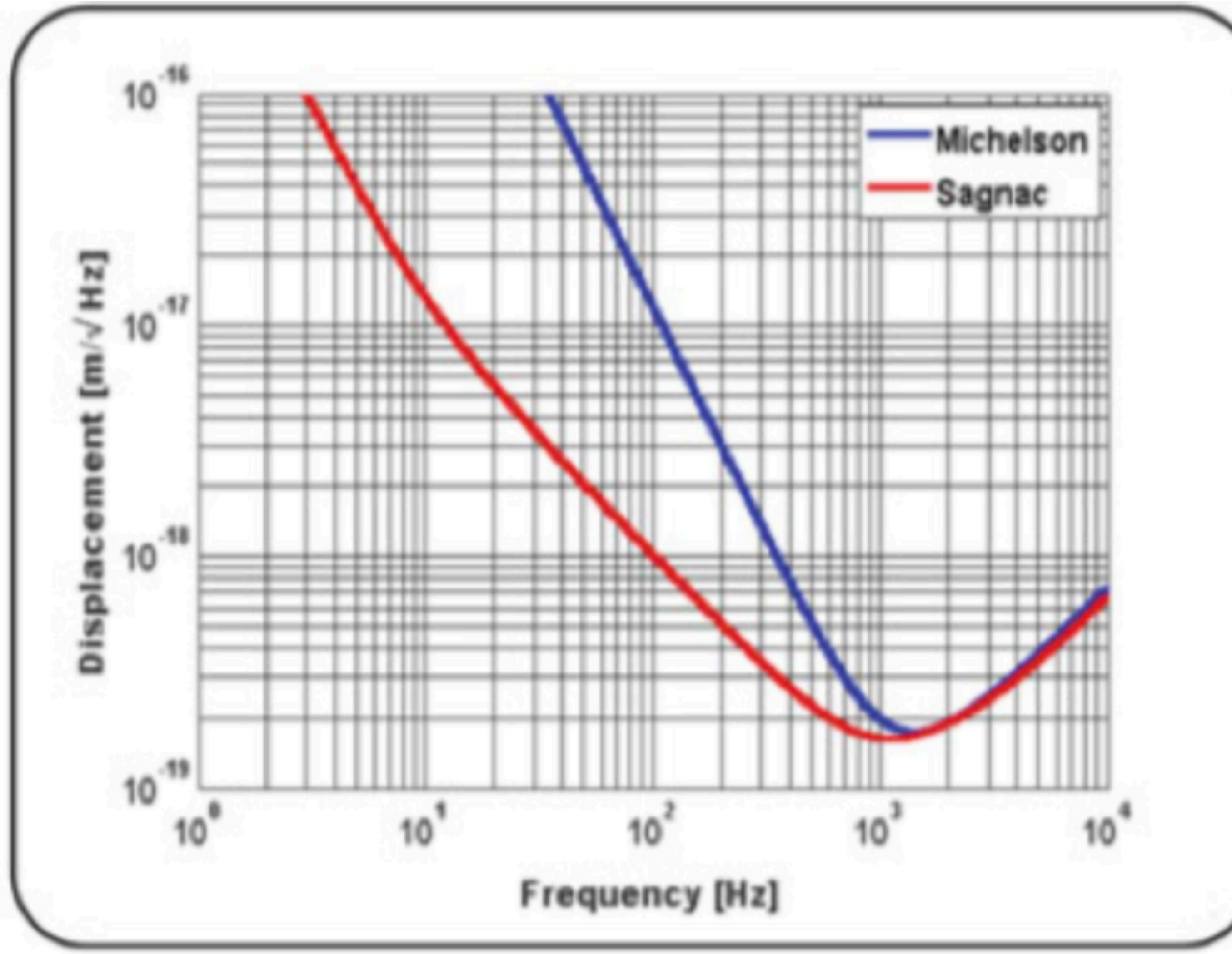
- Location: Underground site in Taiwan
- R&D is ongoing
- Phase 1: R&D for Key technologies (2020-2022)
- Phase 2: Integration test in ASGRAF (2022-2025)
- Phase 3: Insulation and Commissioning of CHRONOS in Underground lab (2025-2027)

CHRONOS's target observation year = 2027

CHRONOS

Fabry–Pérot Michelson vs. Sagnac Speed meter





	Fabry–Pérot Michelson	Sagnac speed meter
Input	ma=F=Aexp(iωt)	ma=F=Aexp(iωt)
Output	$\|x\|=A/(m\omega^2)\exp(i\omega t)=F/(m\omega^2)$	$\|v\|=A/(m\omega)\exp(i\omega t)=F/(m\omega)$

CHRONOS

LIGO White paper

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
LIGO SCIENTIFIC COLLABORATION

Technical Note	LIGO-T2000407–v3	2020/08/31

Instrument Science White Paper 2020

LIGO Scientific Collaboration

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http://www.ligo.org/

SPEED METER

LT-4.4.5 Speed meter

Normally, a GW detector measures the test mass position at different times to infer the signal. However, position at different times does not commute with the Hamilton operator of a free mass. According to quantum measurement theory (151), such a measurement process inevitably introduces quantum back action and perturbs the test mass motion. (In the context of GW detectors, the back action is the radiation-pressure noise.) In order to evade back action, one needs to measure the conserved dynamical quantity of the test mass—the momentum. The latter is (approximately) proportional to speed, which is why a *speed meter* is ideal for measuring gravitational waves with greatly reduced radiation-pressure noise (105).

CRYOGENIC

LT-7.3.5 Cryogenics

It has long been known that cryogenically cooled test masses can have much improved material parameters which lead to significant reductions in thermal noise. However, operating at cryogenic temperatures presents multiple new challenges which need to be addressed. The most pressing is to find ways to cool the temperature, to isolate the mirrors from their hot surroundings and to constantly extract the deposited laser heat without short-circuiting the suspension and seismic isolation system. Detailed thermal models have to be developed and tested to maximize radiative and conductive cooling paths.

LIGO also has common technical issue for future GW technology

CHRONOS

Procedure of technical demonstration in LIGO

TEST FACILITYIES

US

CAHTECH 40M

EU

GEO600

GLASGOW 10M

ASIA

There is no test facility of LIGO in Asia!

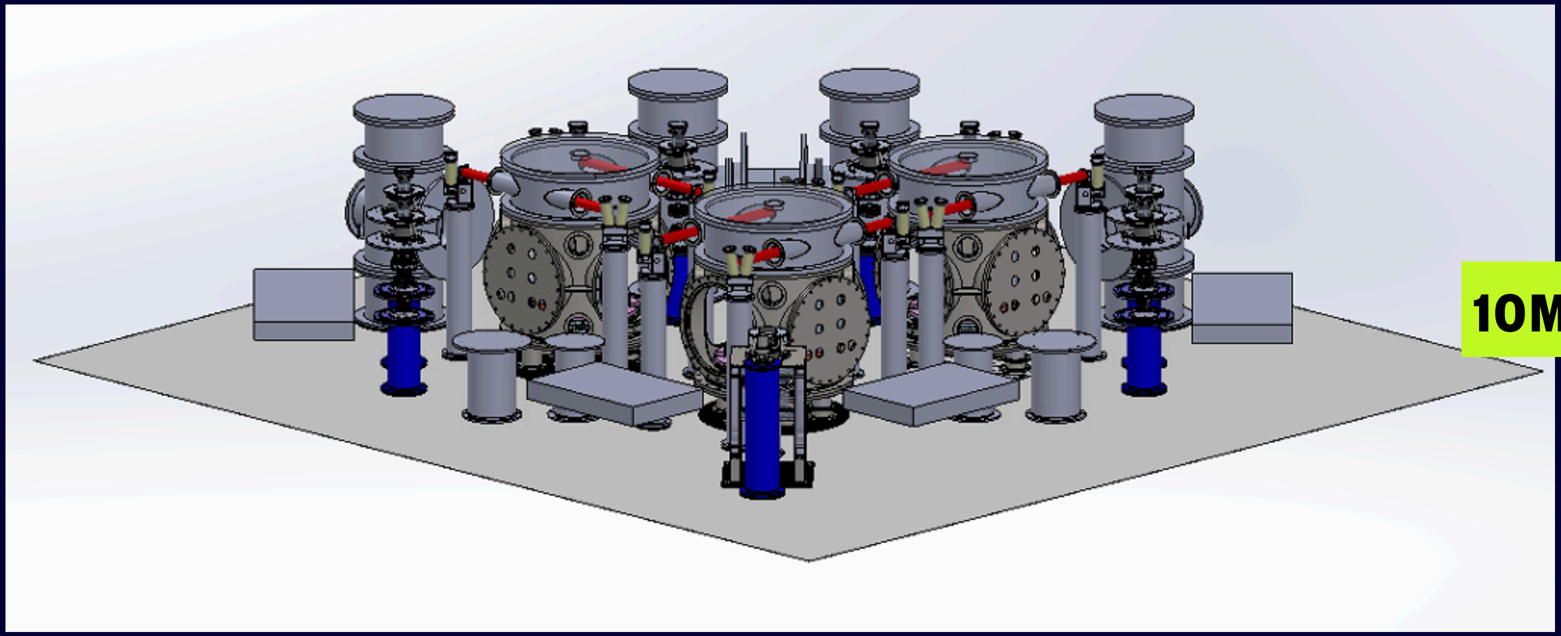
LIGO HANFORD OBSERVATORY

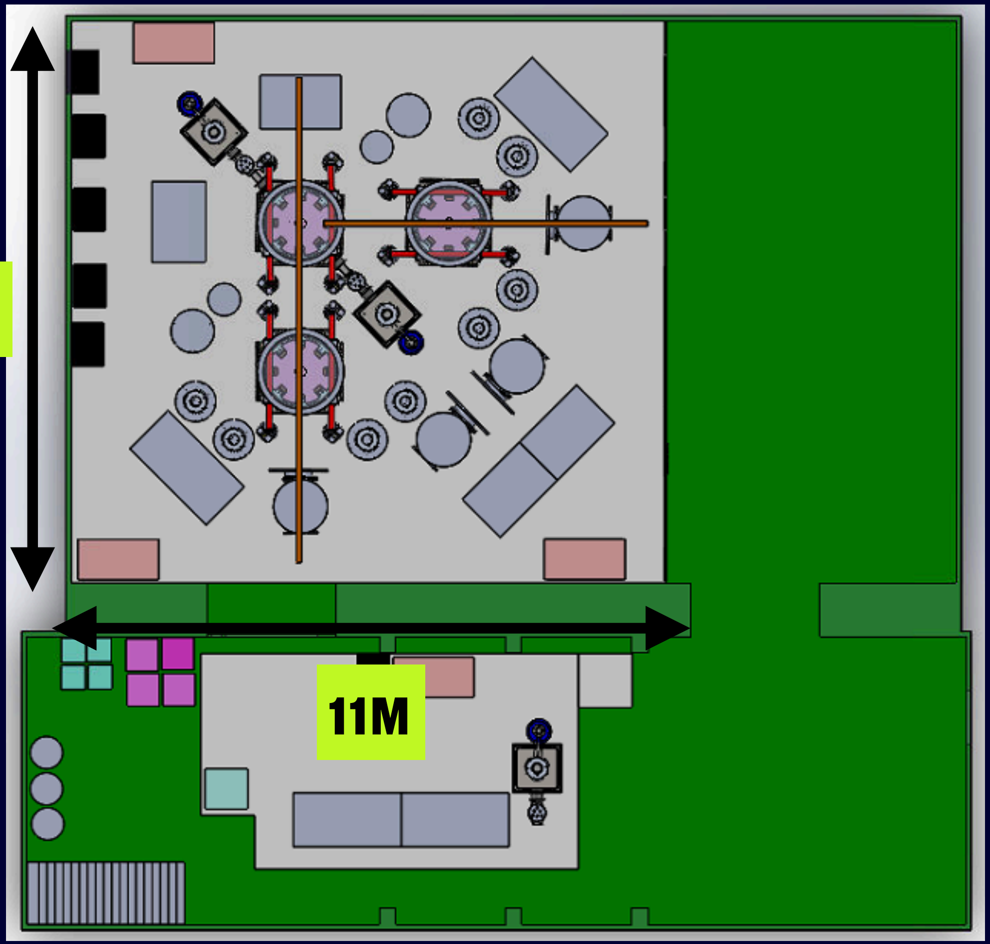
LIGO LIVINGSTON OBSERVATORY

Academia Sinica Gravitational physics Research Facility (*ASGRAF*)

- Location: Academia Sinica Institute of Physics (B1 floor)
- Environment: 10m x 11m Class 10000 clean room and Class1000 clean booth
- Cryogenic Interferometer
- Main purpose: R&D of gravitational wave technologies

Academia Sinica Gravitational physics Research Facility (*ASGRAF*)





- Cryogenic Active Vibration isolation system
- Controlled by Digital Control System
- Dual recycling interferometer
- Verification of calibration instruments
- Apply for Geoscience

CHRONOS

Benefit of ASGRAF for future application

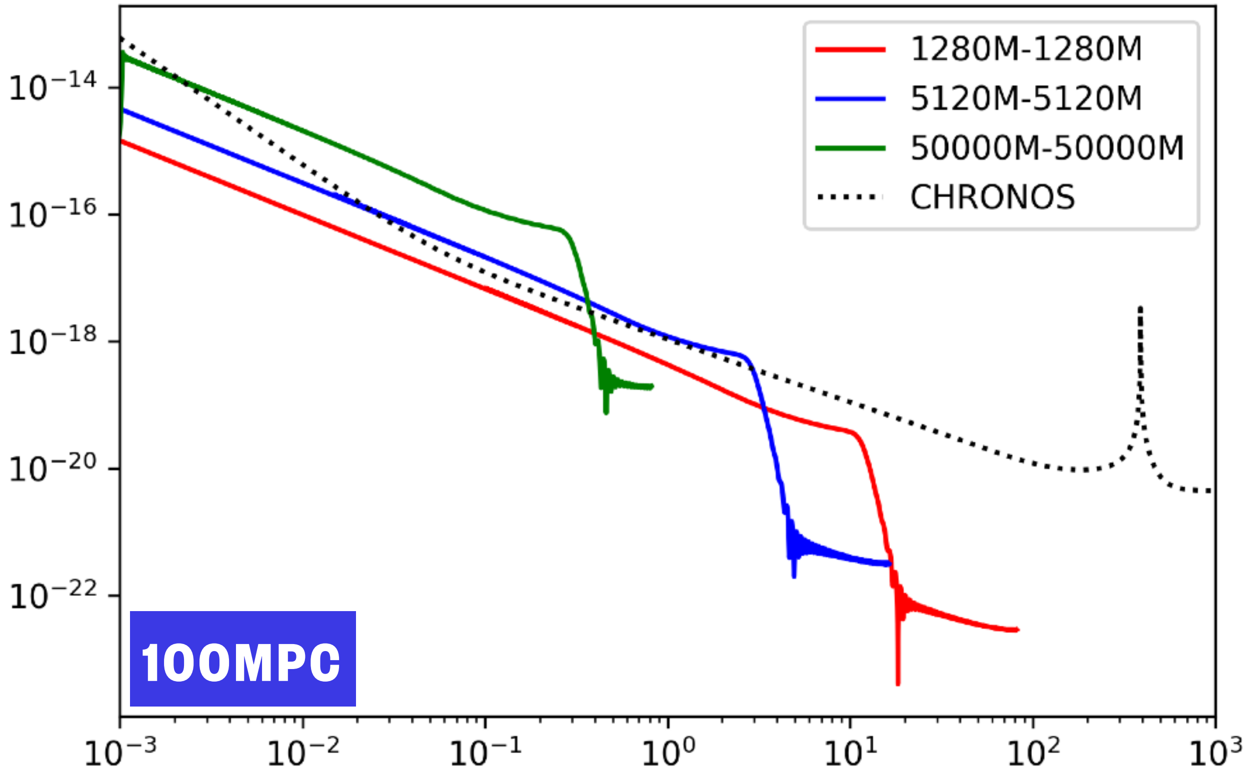
- We can give a good training of interferometer control in Taiwan. We will send the human resource to LIGO after COVID-19.

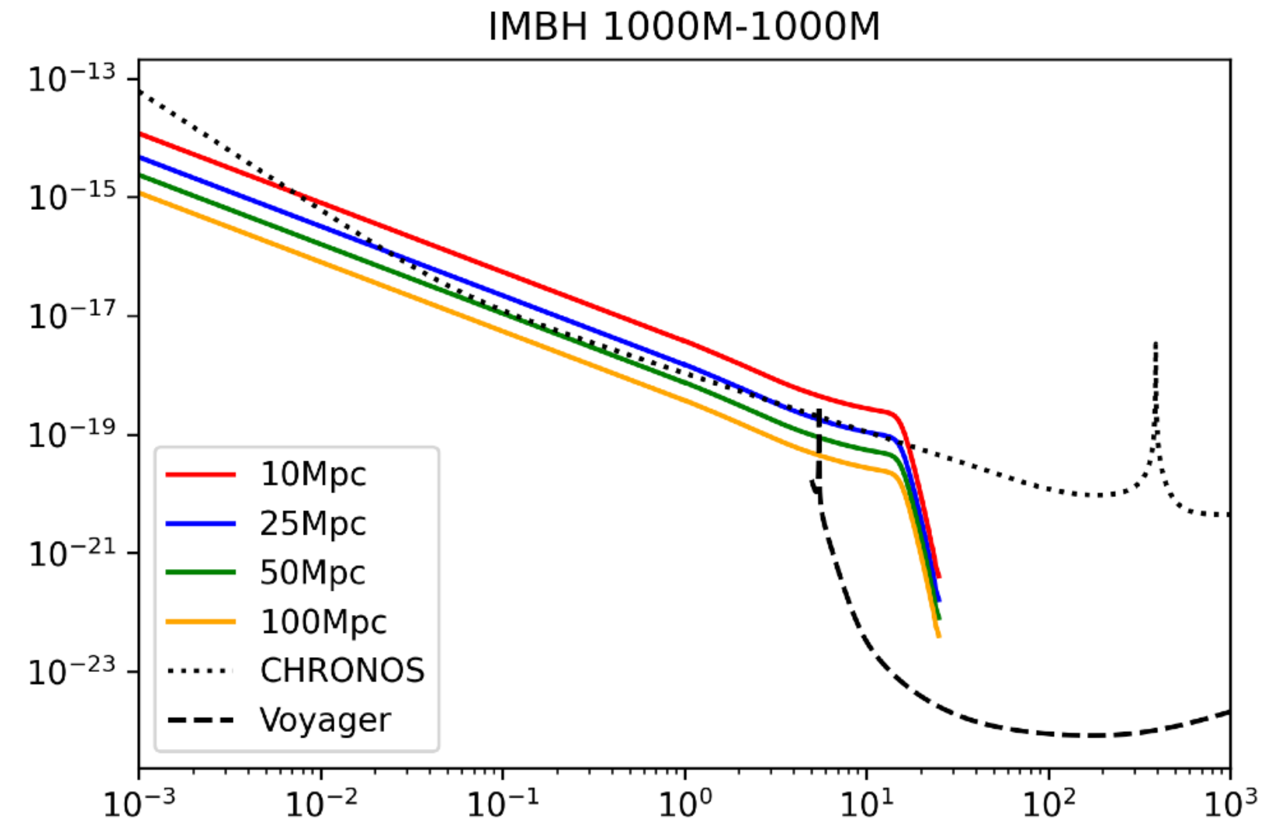
- We can test the new GW technology in Taiwan. If we can try actual contribution, ASGRAF will be a test facility of LIGO in Asia.

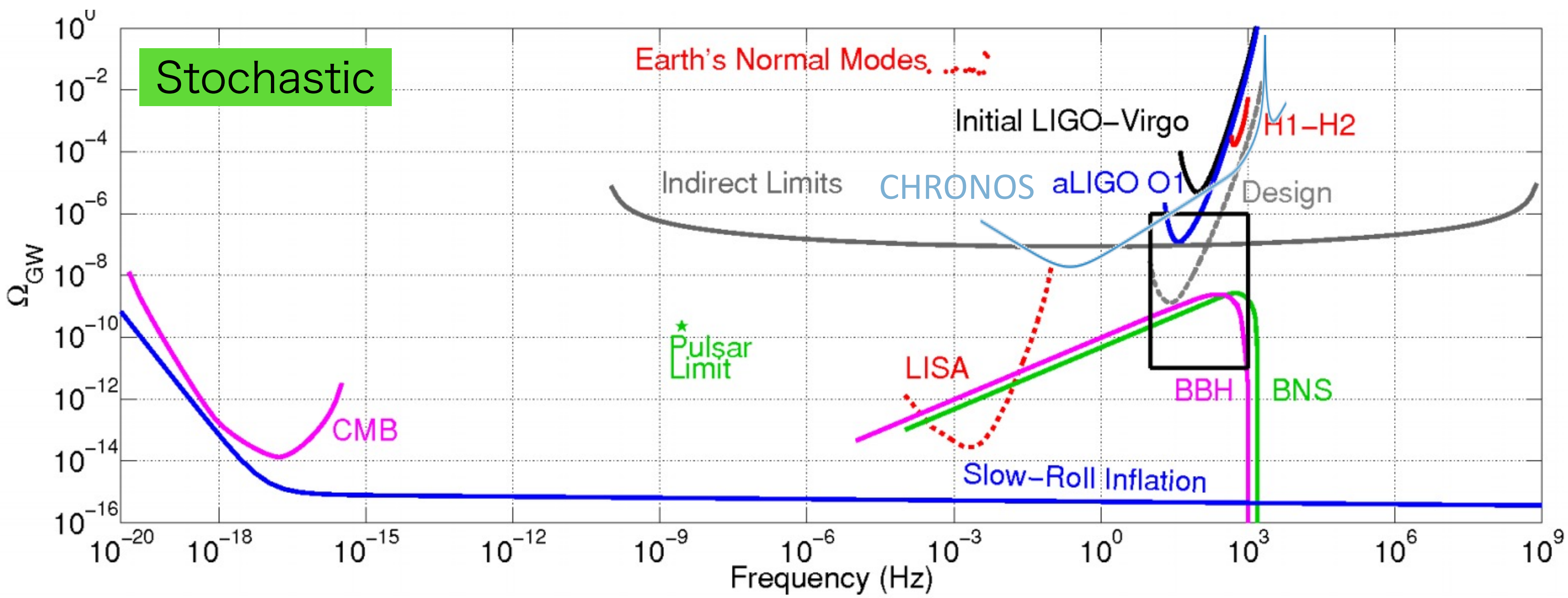
- CHRONOS itself has interesting science. This technology can be applied for future LIGO. In any case, our effort can be led for the essential contribution in GW science

- System is totally same as LIGO. So, we can test the LIGO's software in ASGRAF.

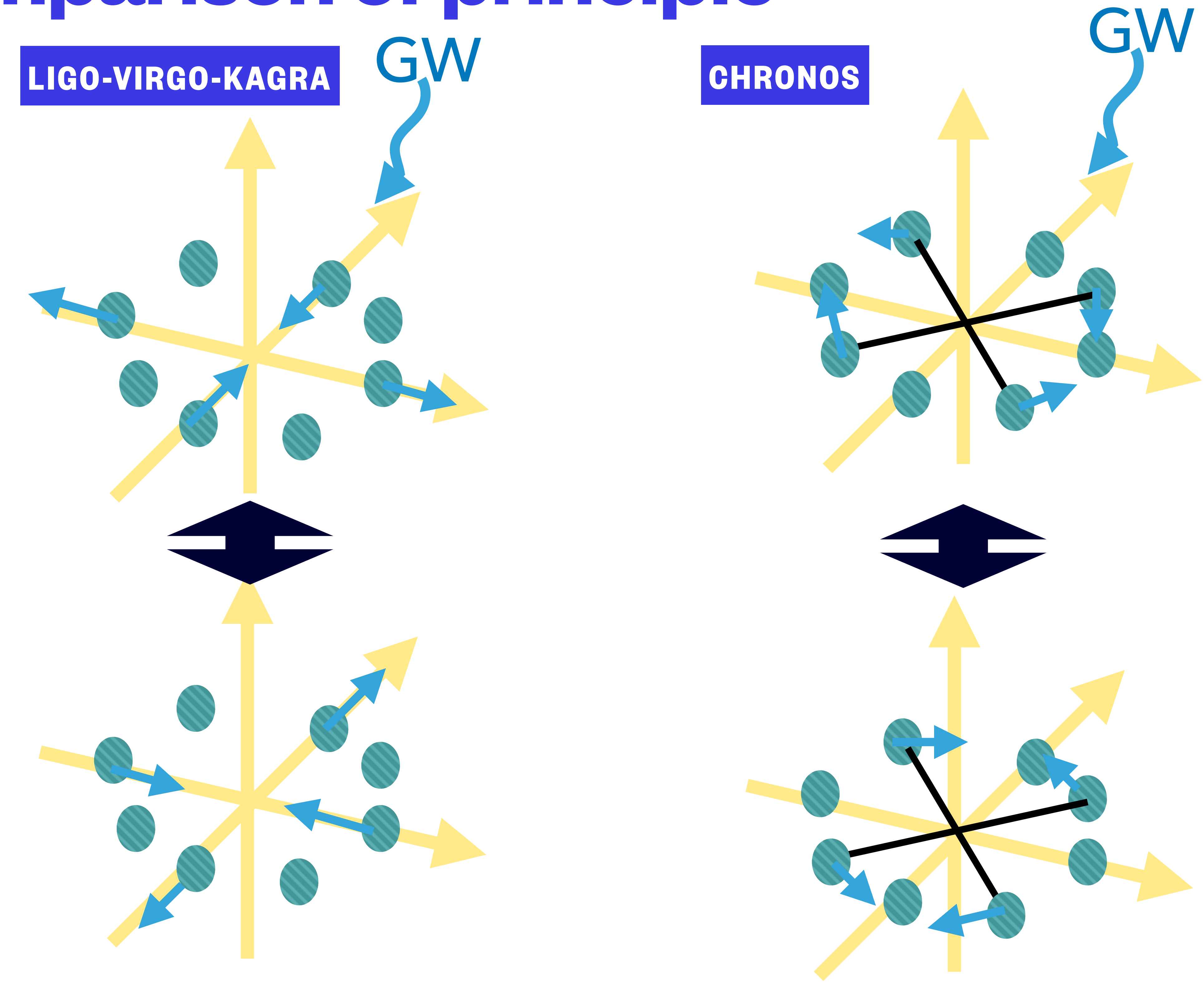
Expected Science



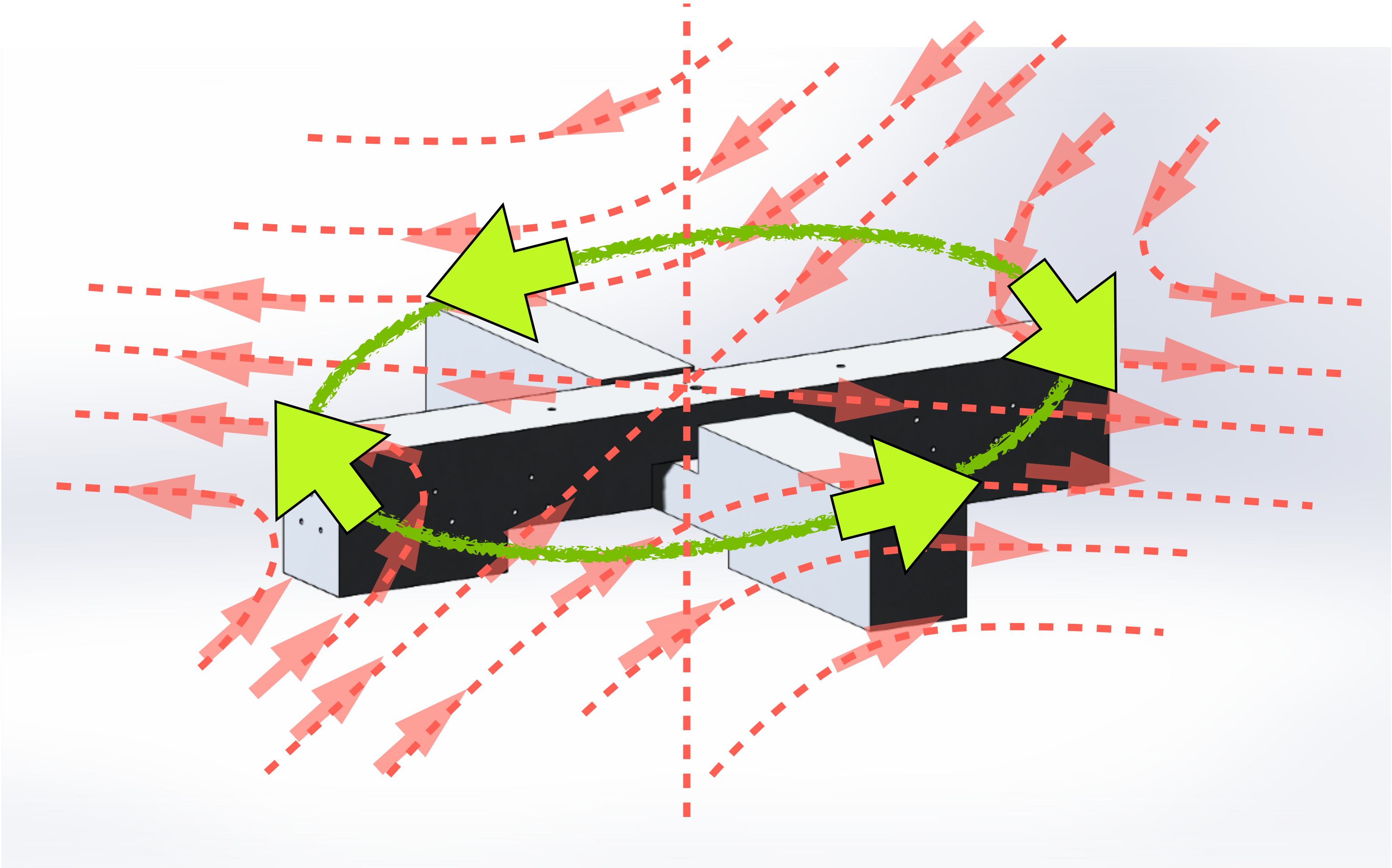




Comparison of principle



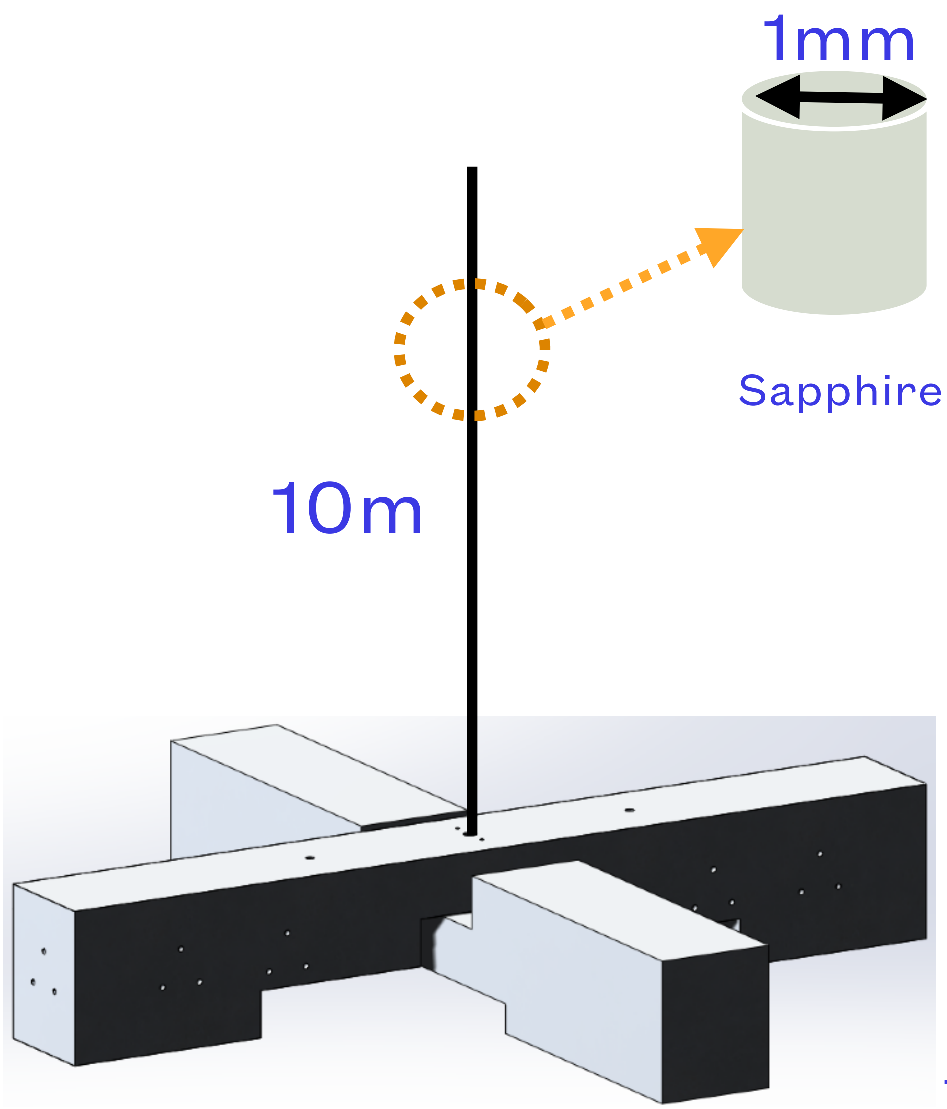
Torsion bar in Gravitational Wave



- 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).

CHRONOS

Resonant frequency

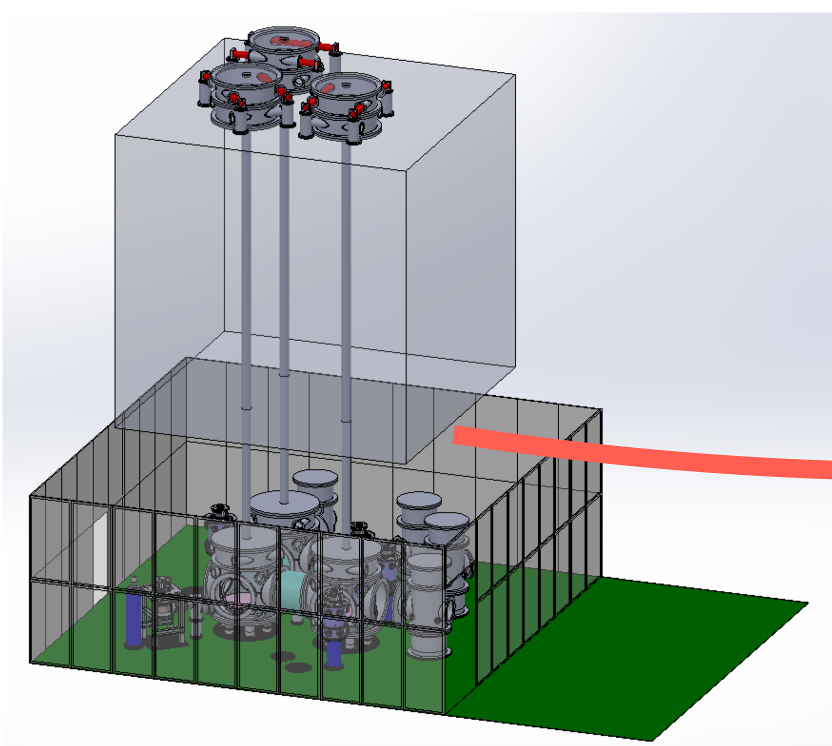


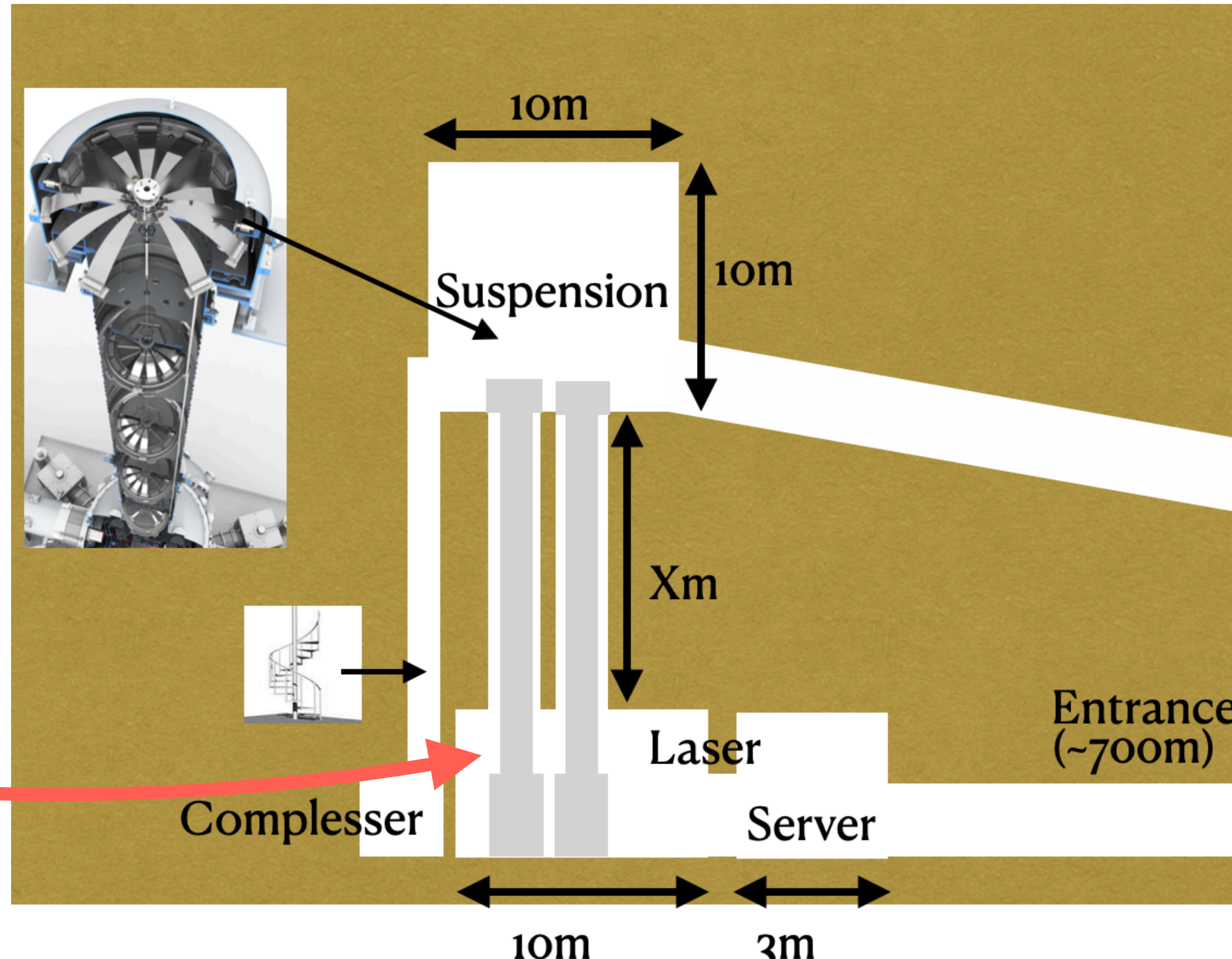
	LVK	CHRONOS
type	Pendulum	Torsion bar
EOM	$m\ddot{x} + c\dot{x} + kx = F$	$I\ddot{\theta} + \Gamma\dot{\theta} + \mu\theta = \tau$
Resonant Freq.	$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$	$f = \frac{1}{2\pi}\sqrt{\frac{\mu}{I}}$ $\mu = \frac{\pi G r^4}{2l}$ $G = \frac{E}{2(1+\nu)}$
Typical value (l=10m,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

We can dramatically reduce resonant frequency

CHRONOS

Cross section of CHRONOS observatory

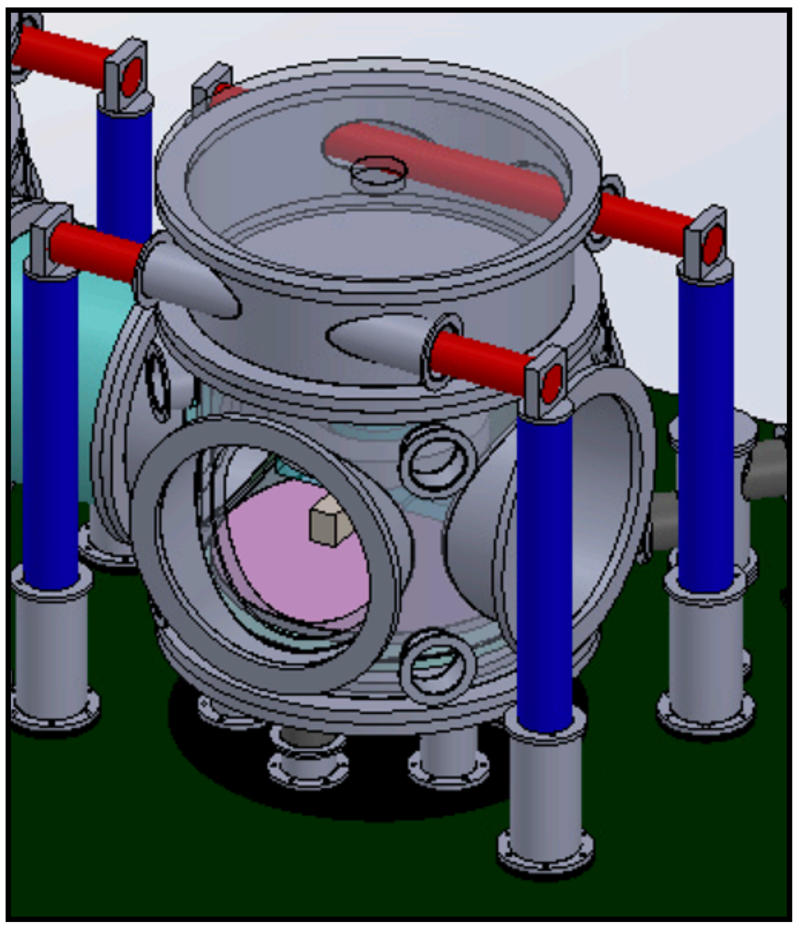




CHRONOS

Seismic isolator

Lab test



STAGE 0

x1/10

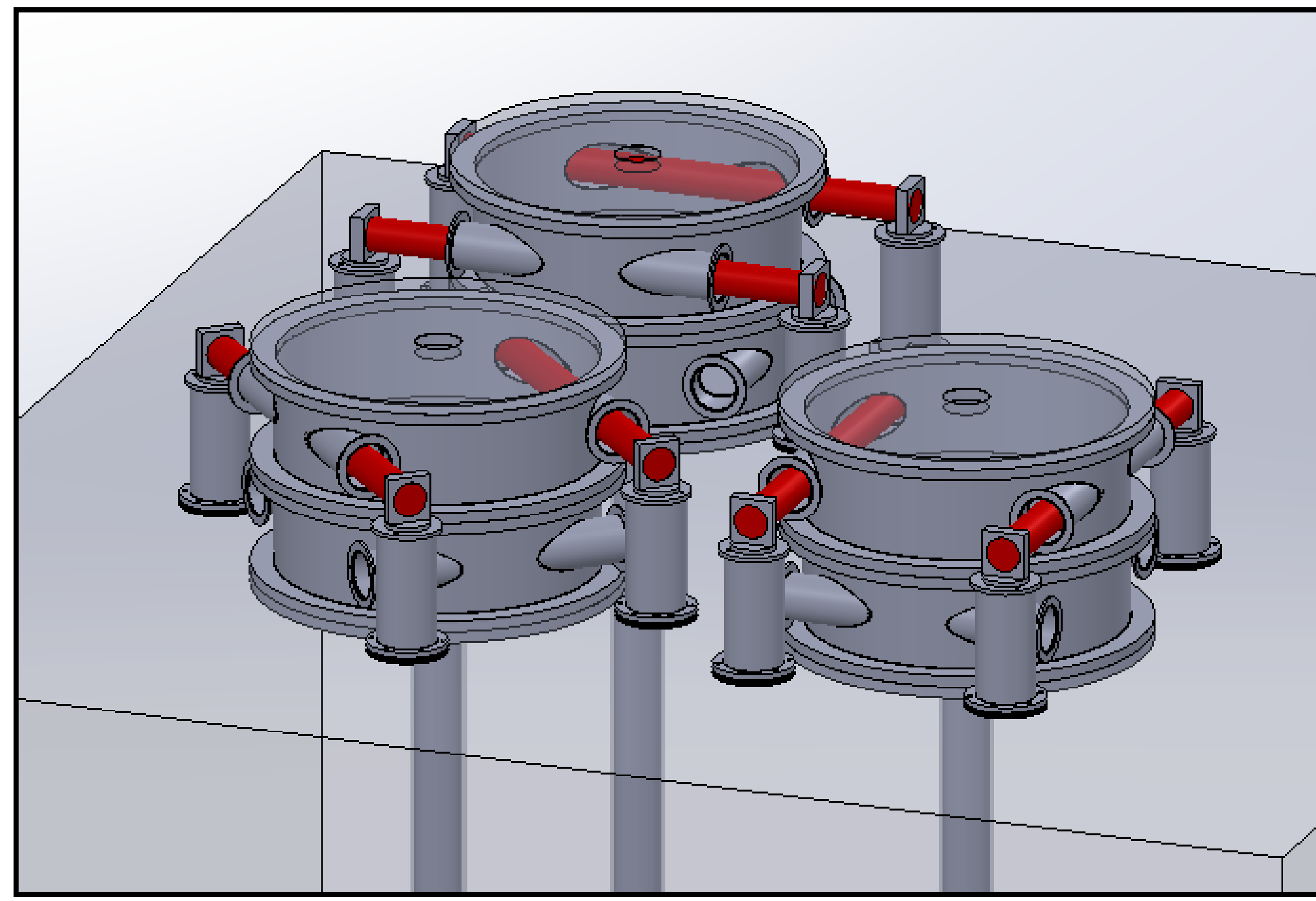
STAGE 1-3

x1/1000

10M PENDULUM

x1/10^8

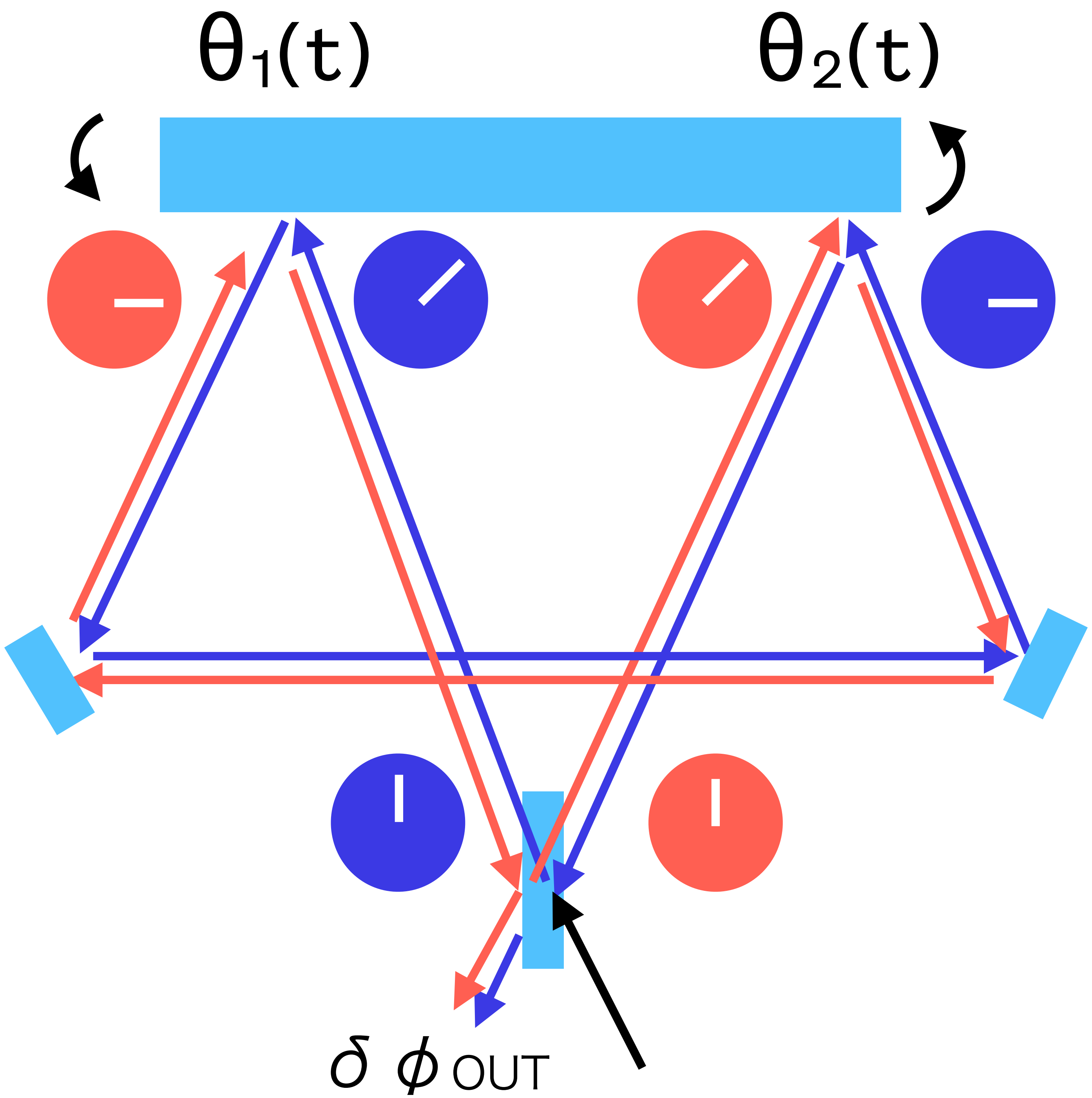
Underground site



Expected Attenuation factor for rotation: 1/10^{12}

CHRONOS

Speed meter technique

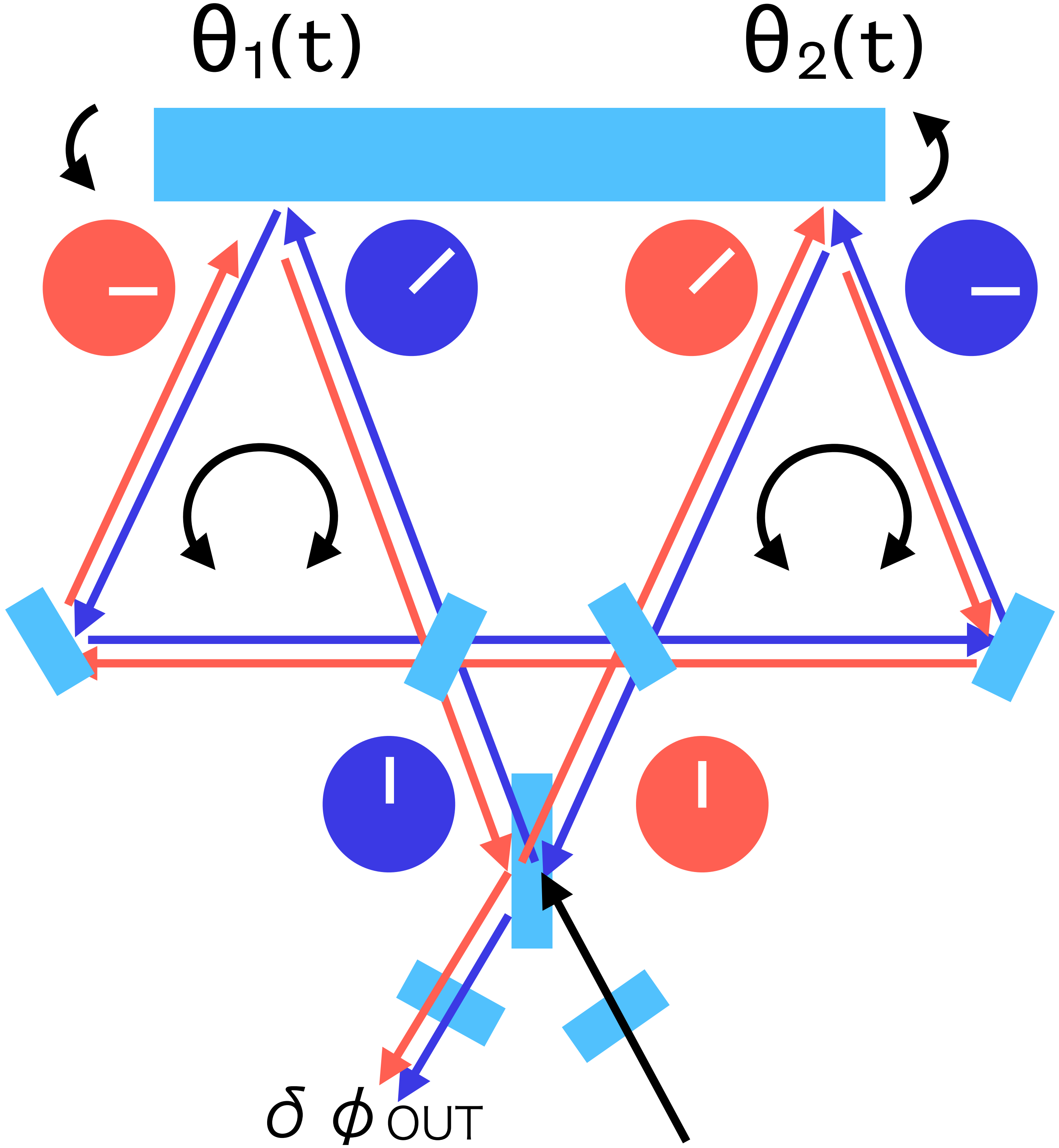


- $\delta\phi_{CW} \propto \theta_1(t)+\theta_2(t+\tau)$
- $\delta\phi_{CCW} \propto \theta_2(t)+\theta_1(t+\tau)$
- $\delta\phi_{OUT}=\tau(\omega_{CCW}-\omega_{CW})$

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

CHRONOS

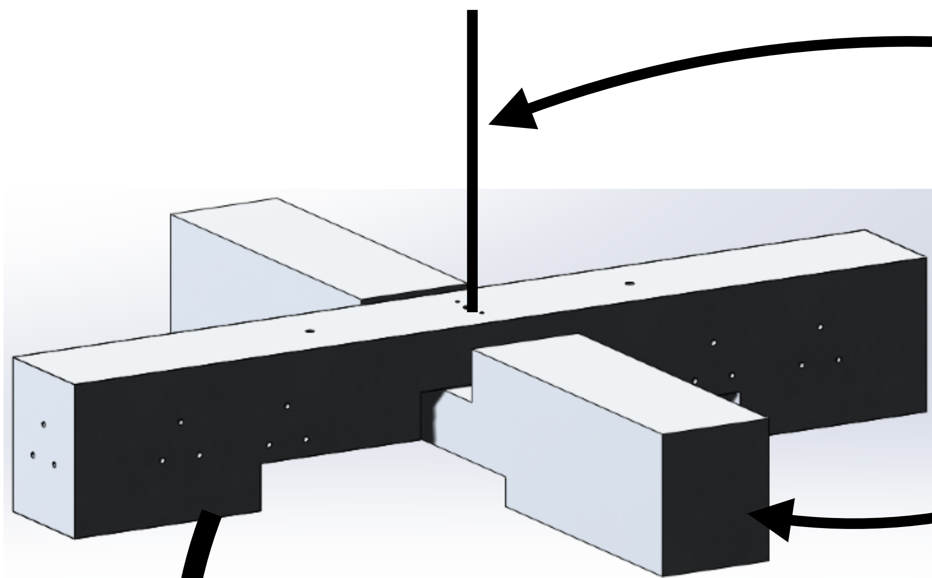
Speed meter technique



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

CHRONOS

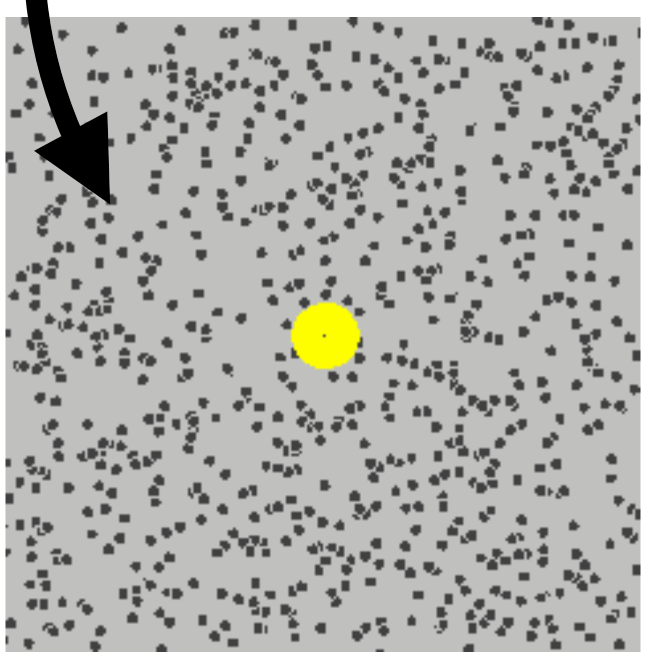
Cryogenic vibration isolation technology



$$\delta\theta_{\mathrm{sus}} = \sqrt{4\gamma k_B T}/(I\omega^2)$$

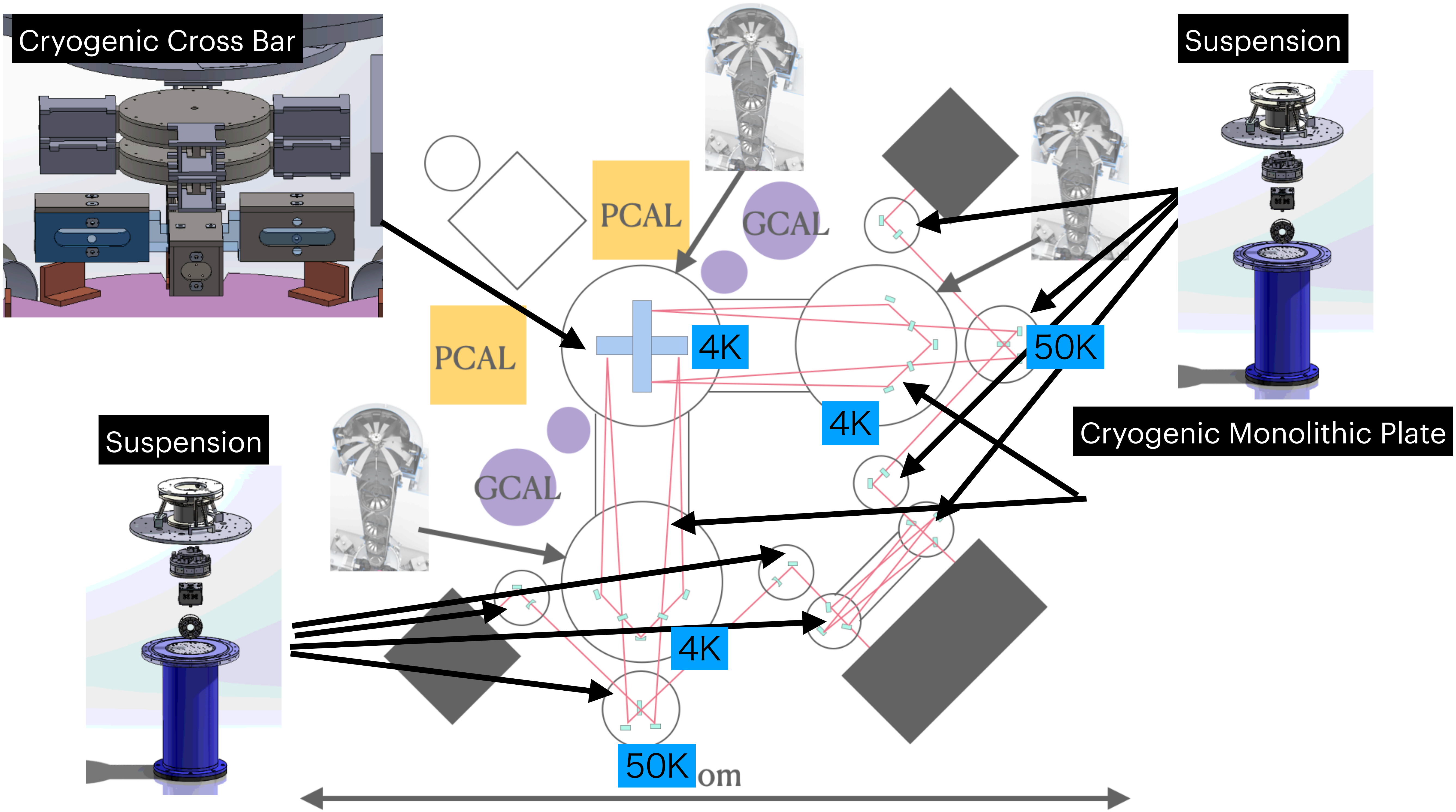
$$\delta\theta_{\mathrm{mass}} \simeq \frac{8}{L}\sqrt{\phi_{\mathrm{mass}} k_B T/(M\omega_{\mathrm{bar}}^2\omega)}$$

Brownian Motion

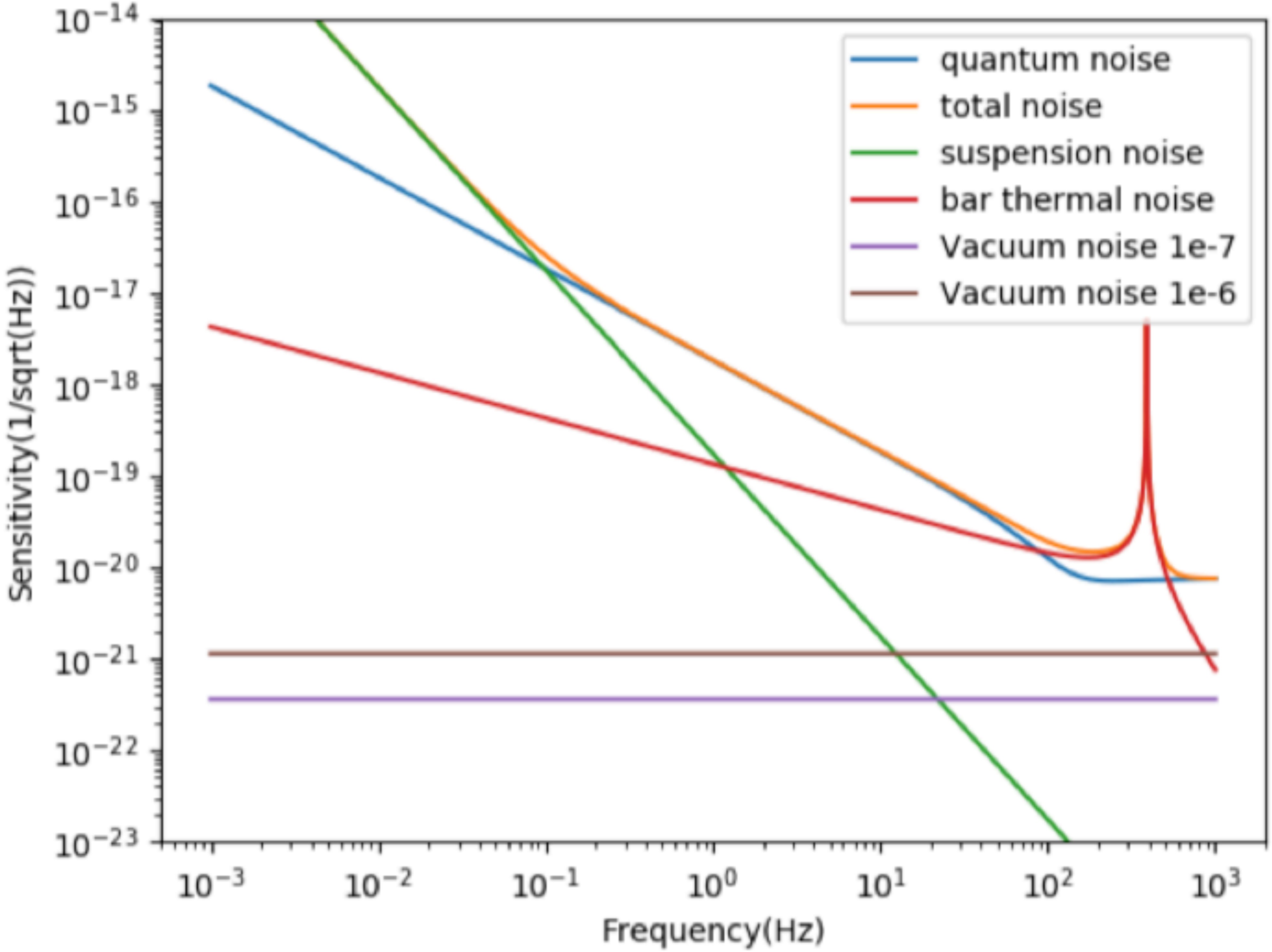


To attenuate the brownian motion, we cool down the suspension system

Overview of CHRONOS Cryogenic suspension system



Sensitivity



CHRONOS

Progress of ASGRAF construction

Research team of CHRONOS

PI: Yuki Inoue Co-PI: Henry Wong

MAIN INTERFEROMETER

Leader: Daiki

- Optics: **Jeff**, Niko, Ko-Han
- VIS: **Daiki**, You-Ru, Hsiang-Chieh
- Onsite Analysis: **Hsiang-Yu**, Afif, Arif

ASGRAF

Leader: Yuki

- Cryogenic: **Hsiang-Chieh**, Yung Ying
- Coating: **Chao Shiuh,** Debby
- Infrastructure: **Feng-Kai**, Cheng-I

THEORY

Leader: Henry

Sensitivity

- Code A: **Jeff**, Hsiang-Chieh, Daiki
- Code B: **Afif**, Arif, Chrisna, Hsiang-Yu

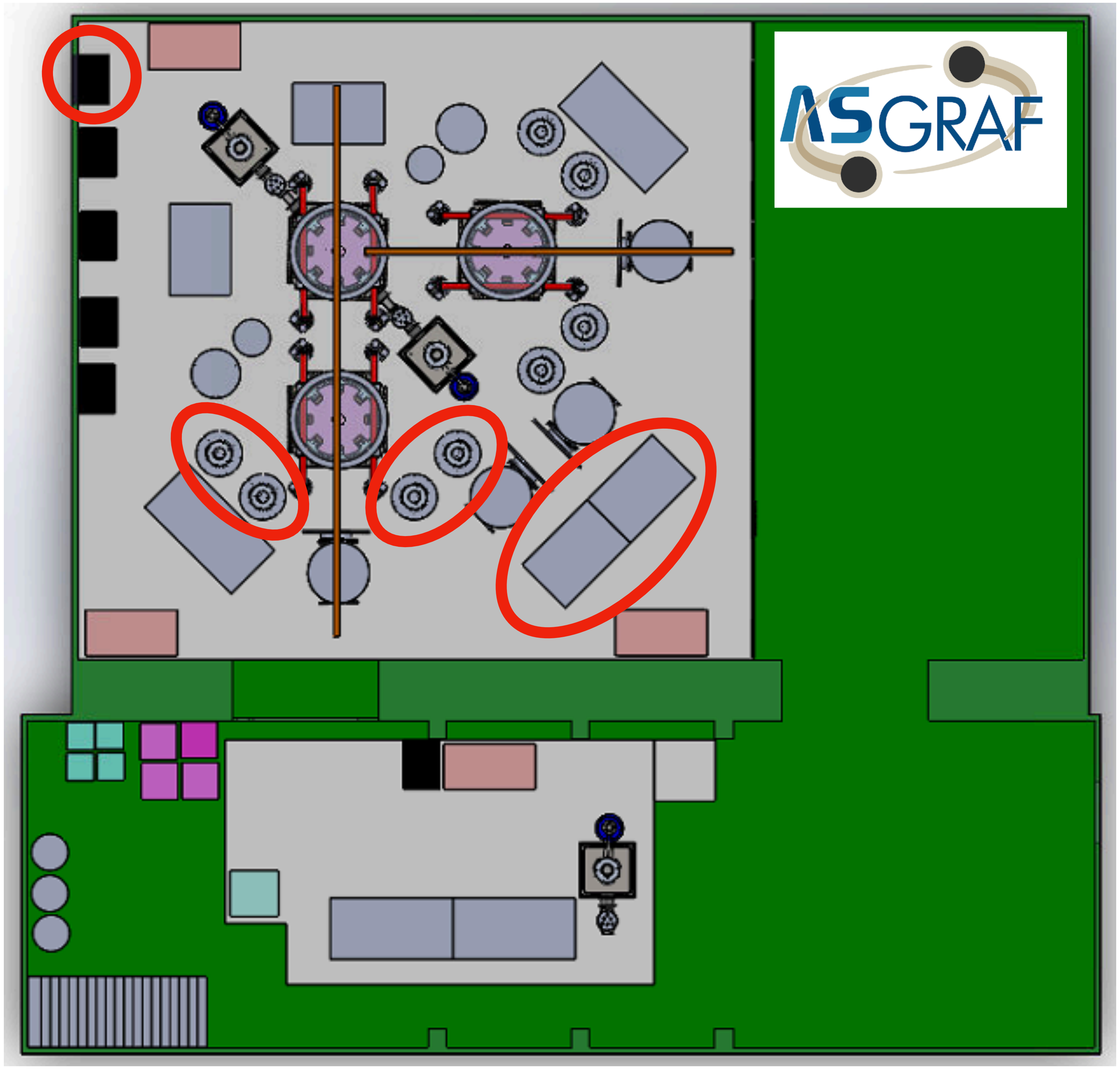
- Exotic science: Chrisna, Arif, Afif, Martin
- Earth quake: Afif
- Astronomy & Cosmology: Guo-Chin, Hsiang-Yu

→ Demonstration of locking and onsite analysis tool for the observation

→ Preparation of Lab environment to accept main interferometer in 2023 June

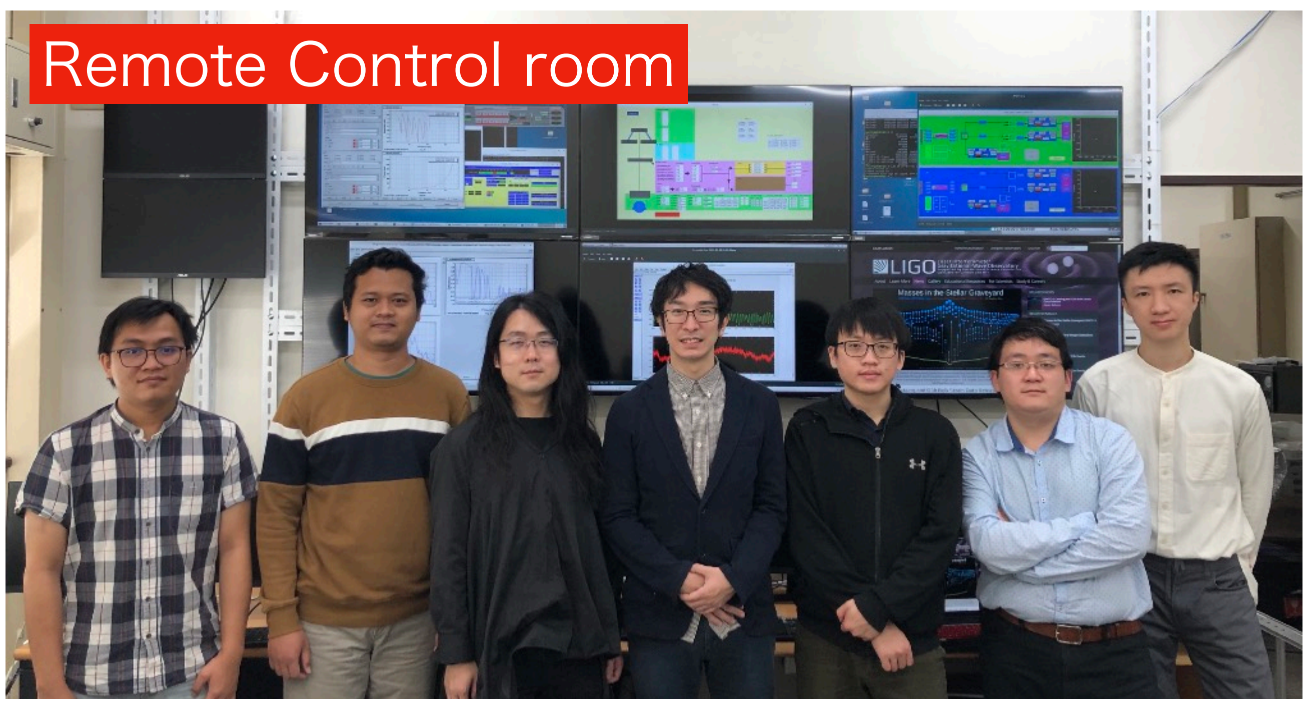
→ Listing up the possible science of CHRONOS based on the expected sensitivity

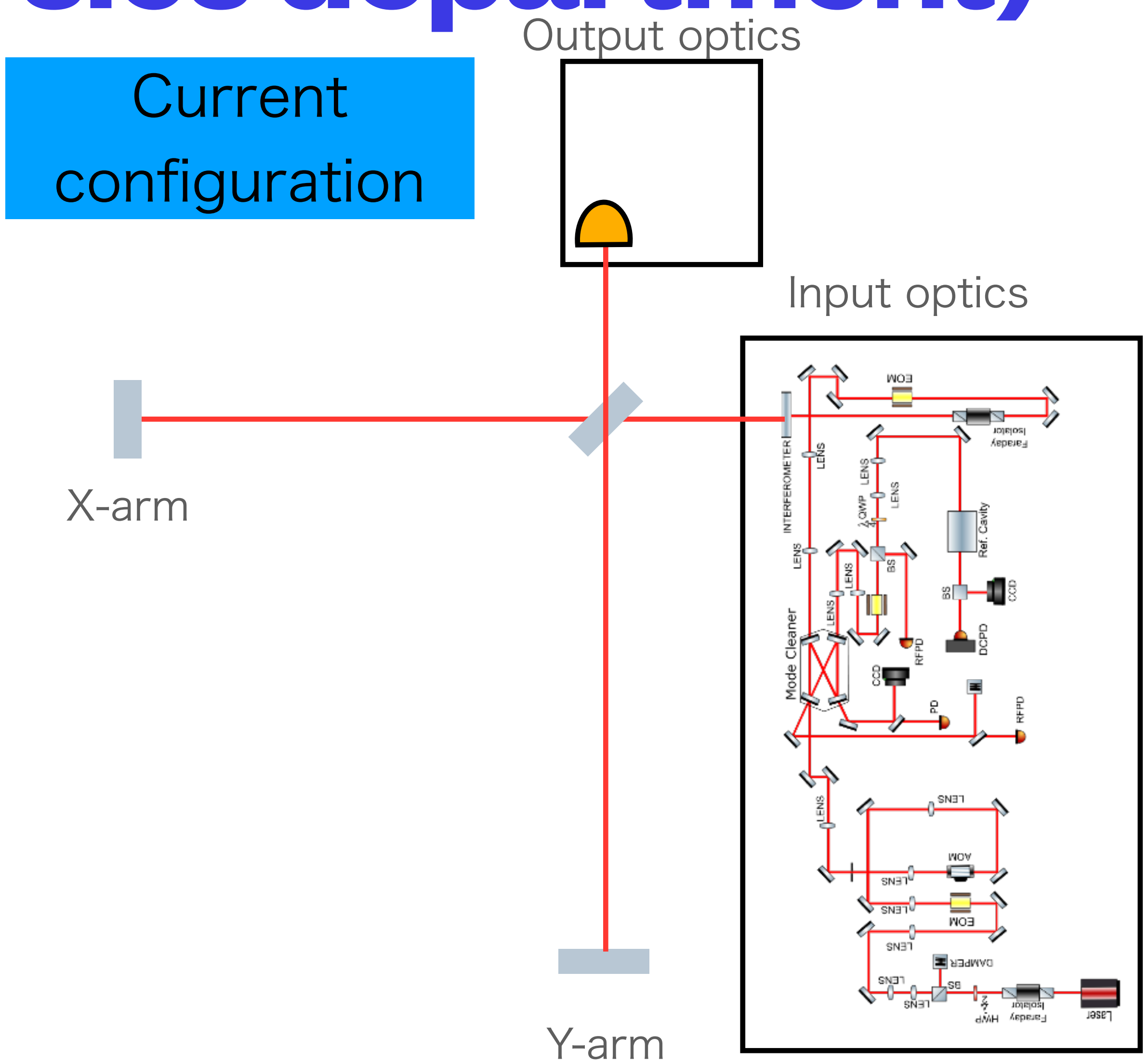
Test in National Central University



- R&D of interferometer control
- Establishment of procedure for digital feedback control and onsite analysis
- R&D for input optical system to provide high quality laser
- Training for staff and student for ASGRAF phase

NCU observatory (Physics department)

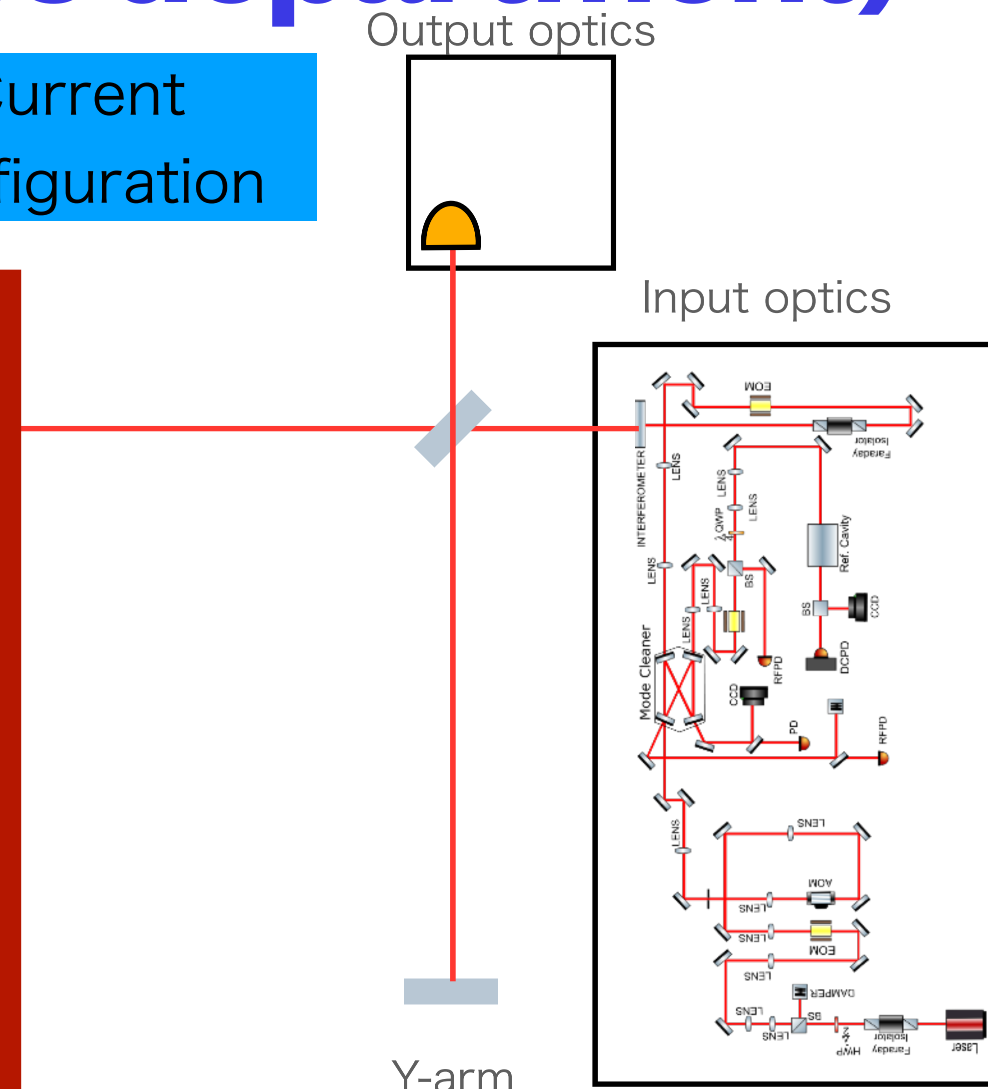




We develop the Michelson interferometer system for the test of the digital feedback control.
We will test the Sagnac interferometer for the test of speed meter after Michelson test.
Even if it is COVID-19, we can learn LIGO's interferometer system in Taiwan.

NCU observatory (Physics department)

Current configuration

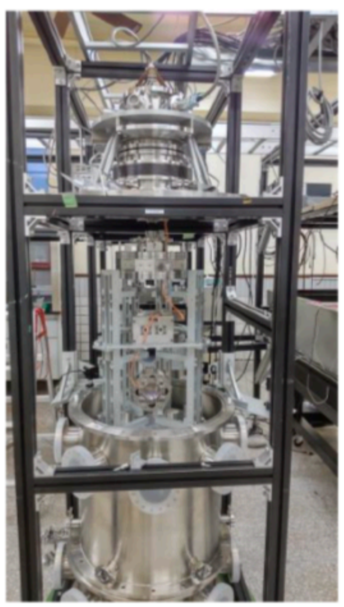


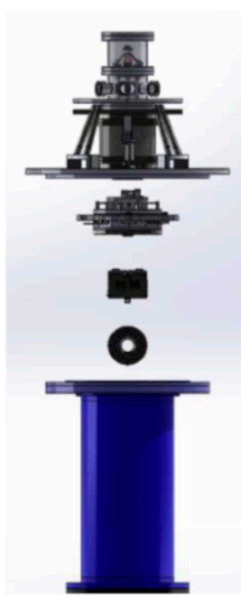
…op the Michelson interferometer system
…test of the digital feedback control.
…test the Sagnac interferometer for the
test of speed meter after Michelson test.
Even if it is COVID-19, we can learn LIGO's interferometer system in Taiwan.

Studies of main interferometer

VIS
(suspension)

- ✓ Two suspension
- ✓ Passive damping
- \- Active control
- \- Vacuum chamber



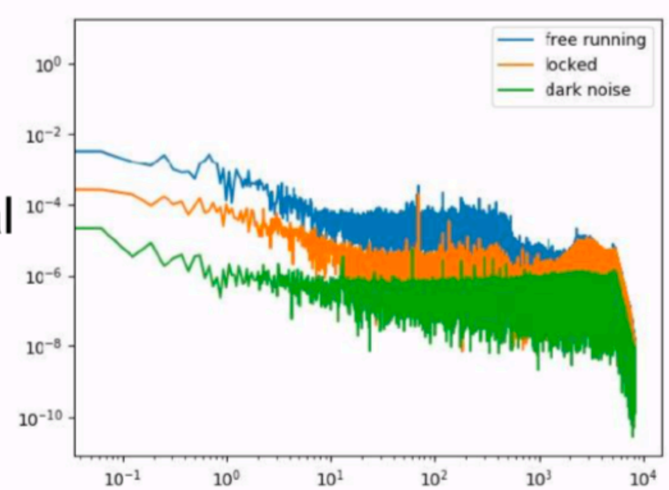


Optics

- ✓ Mode cleaner
- ✓ Intensity stabilization
- \- Frequency stabilization

Noise improvement by intensity stabilization

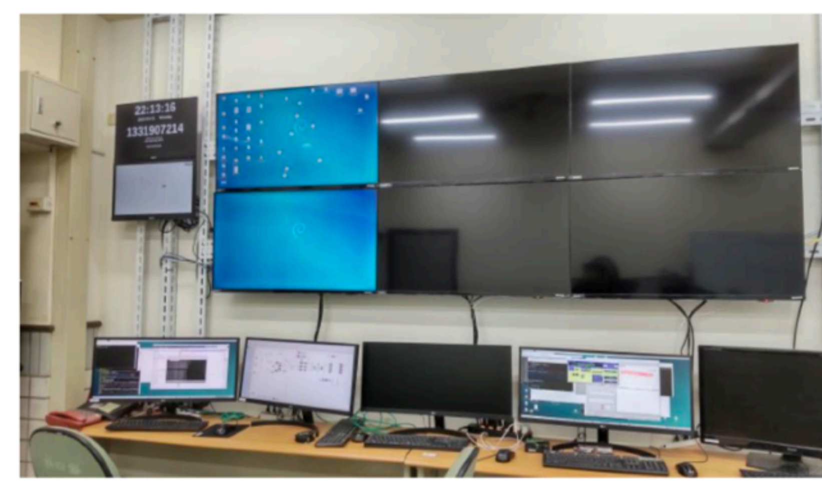
PD signal (V/rHz)



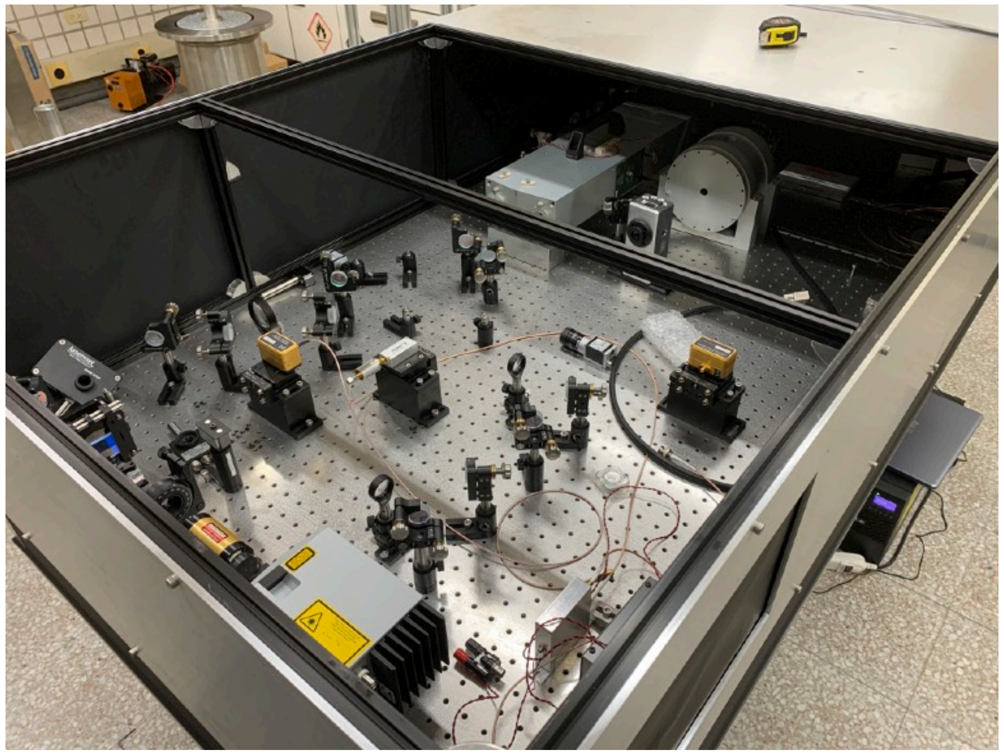
Frequency (Hz)

DGS
(digital system)

- ✓ Monitors
- ✓ Digital feedback
- ✓ Data storage
- \- Control GUI



Input optical system



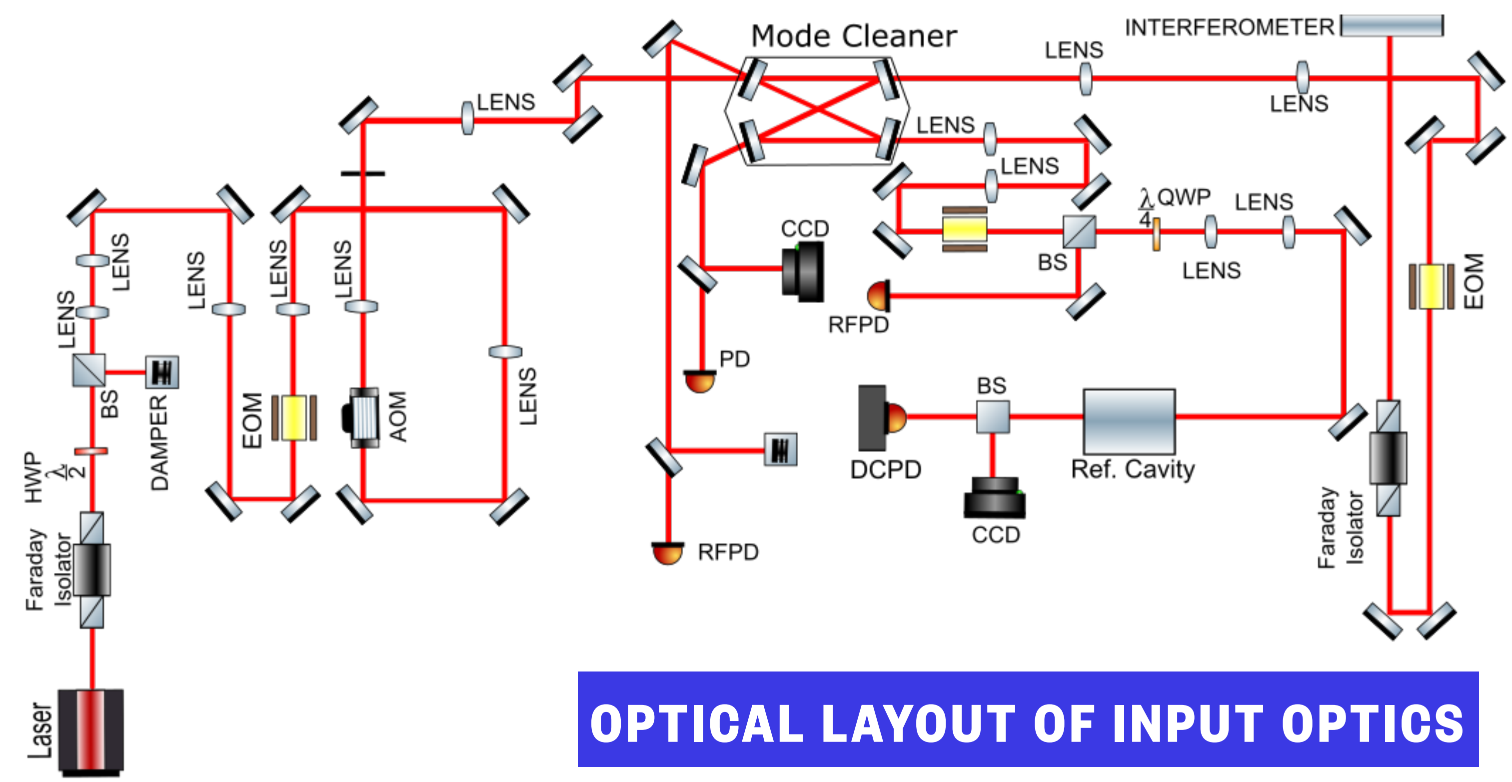
- To keep the lock acquisition state constantly, we need to provide high quality laser beam
- By using feedback control system, we stabilize the laser beam.

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

Beam → Mode cleaner

Intensity → Intensity Stabilization

Phase → Frequency Stabilization

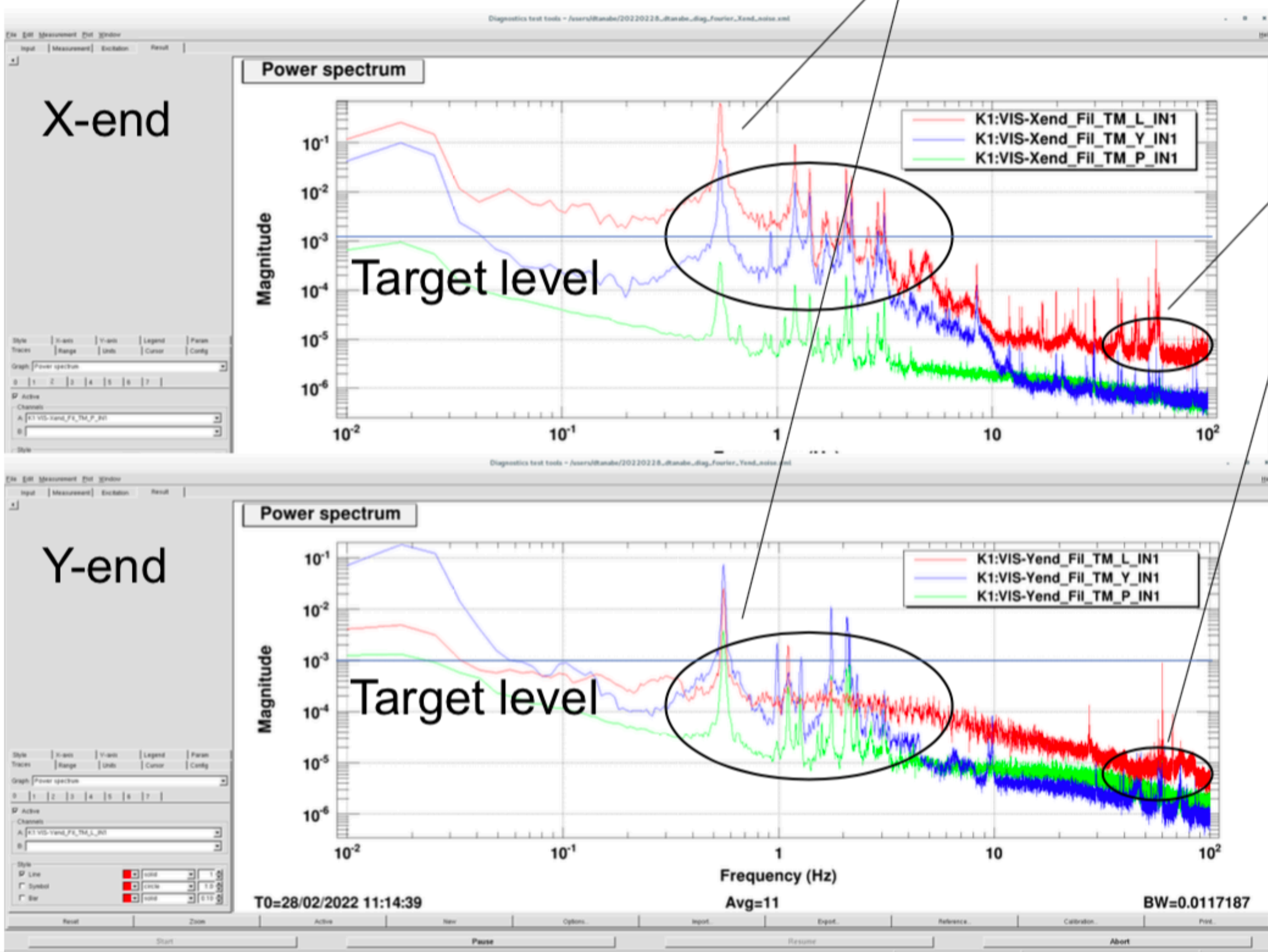


OPTICAL LAYOUT OF INPUT OPTICS

CHRONOS

VIS: Suspension noise

We need further vibration isolation to make interference.

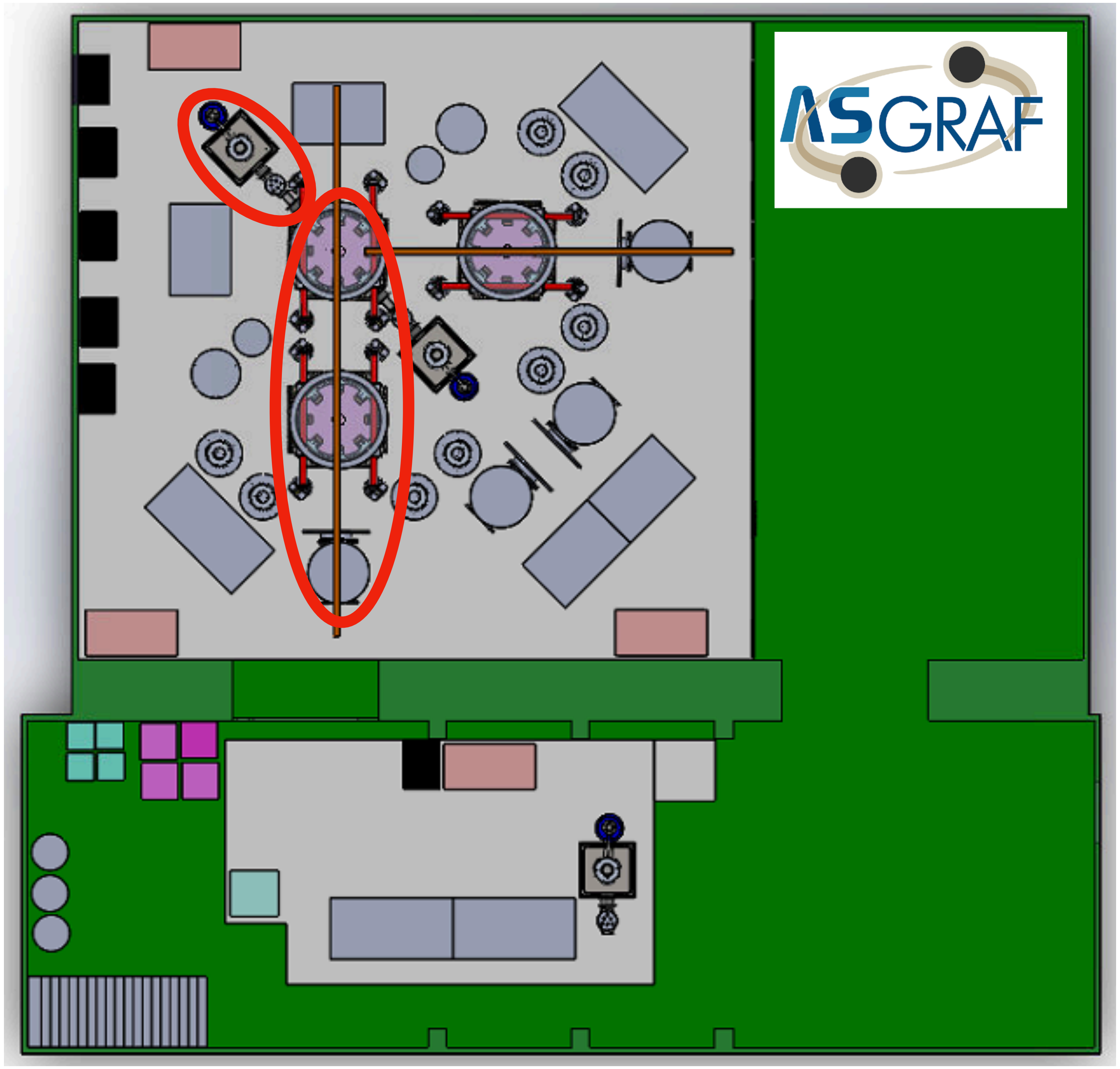


Now the suspension noise is limited by

- Oscillation of the building
- Wind

Next we apply active damping and vacuum pumping.

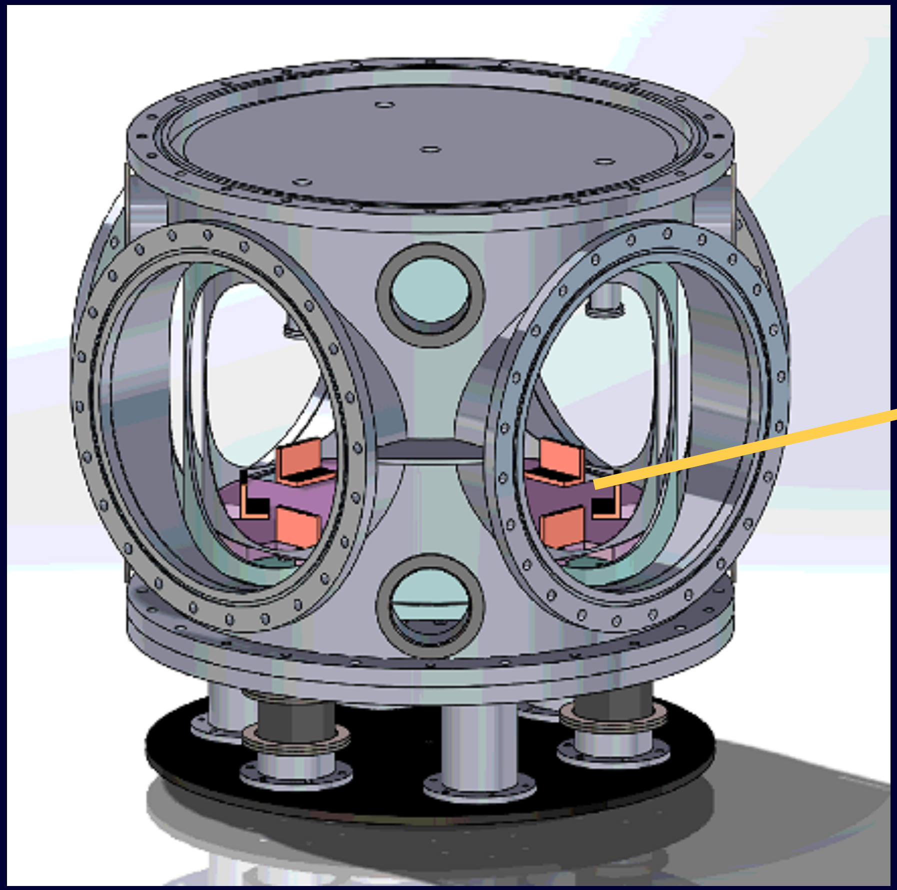
Test in Academia Sinica

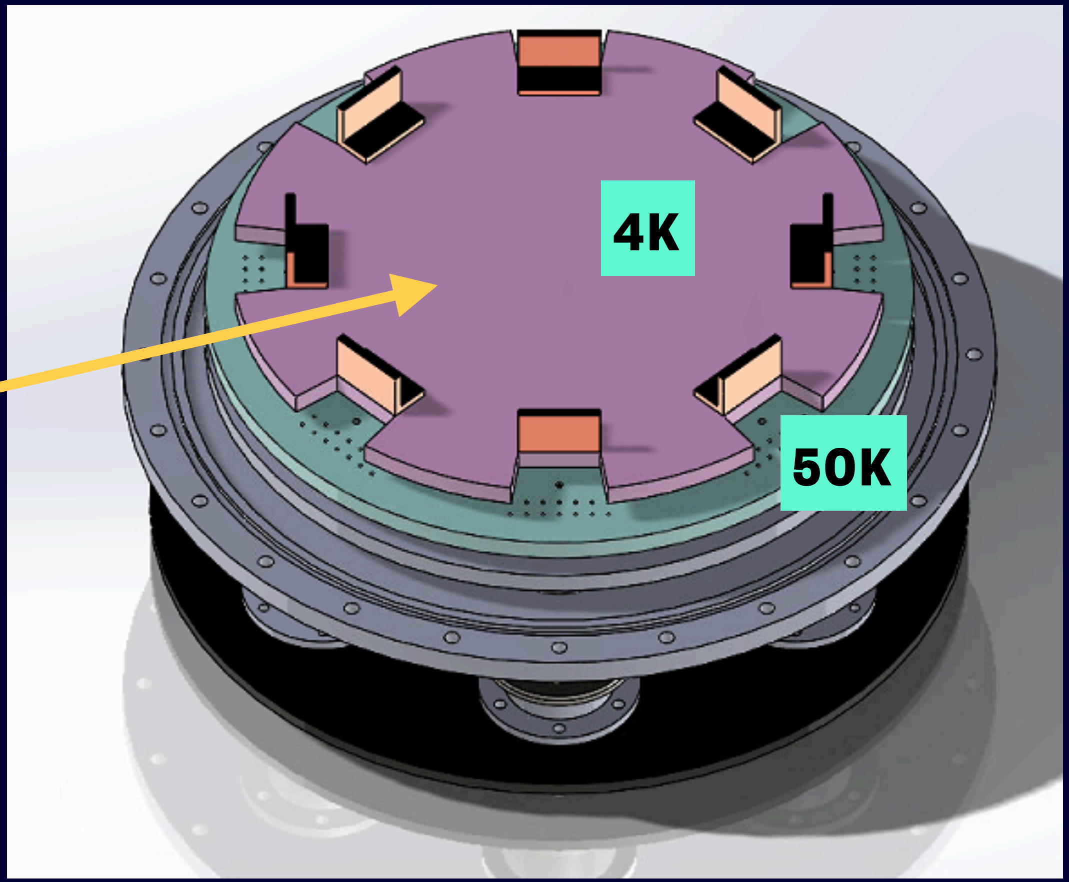


- Preparation of infrastructure to accept NCU interferometer at early 2023
- Development of cryogenic measurement environment with large chamber

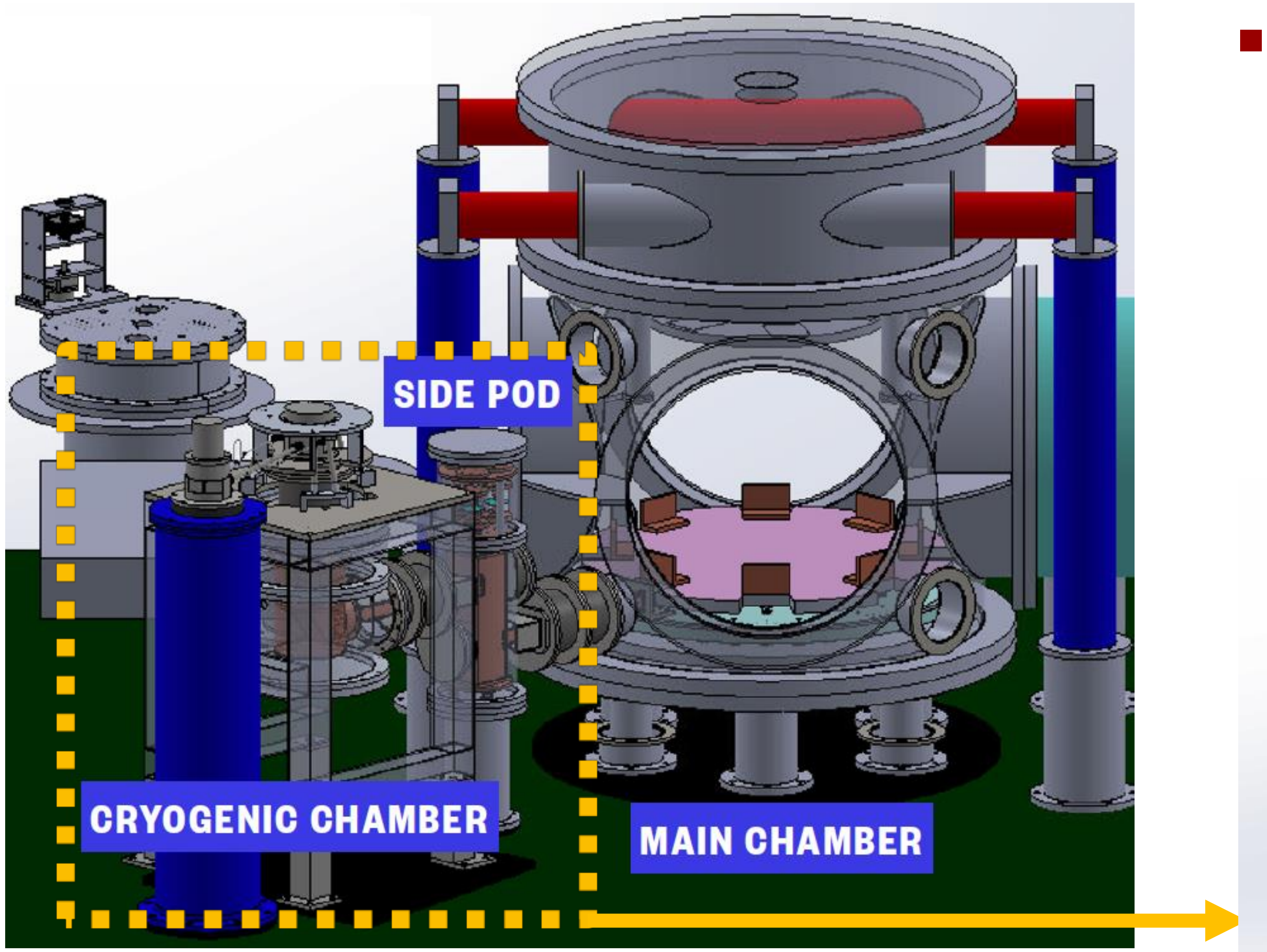
Temperature of large chamber

We need to achieve the 4K temperature at main stages. We need to reduce the thermal loading and establish the heatlink technology with pure aluminum wire.

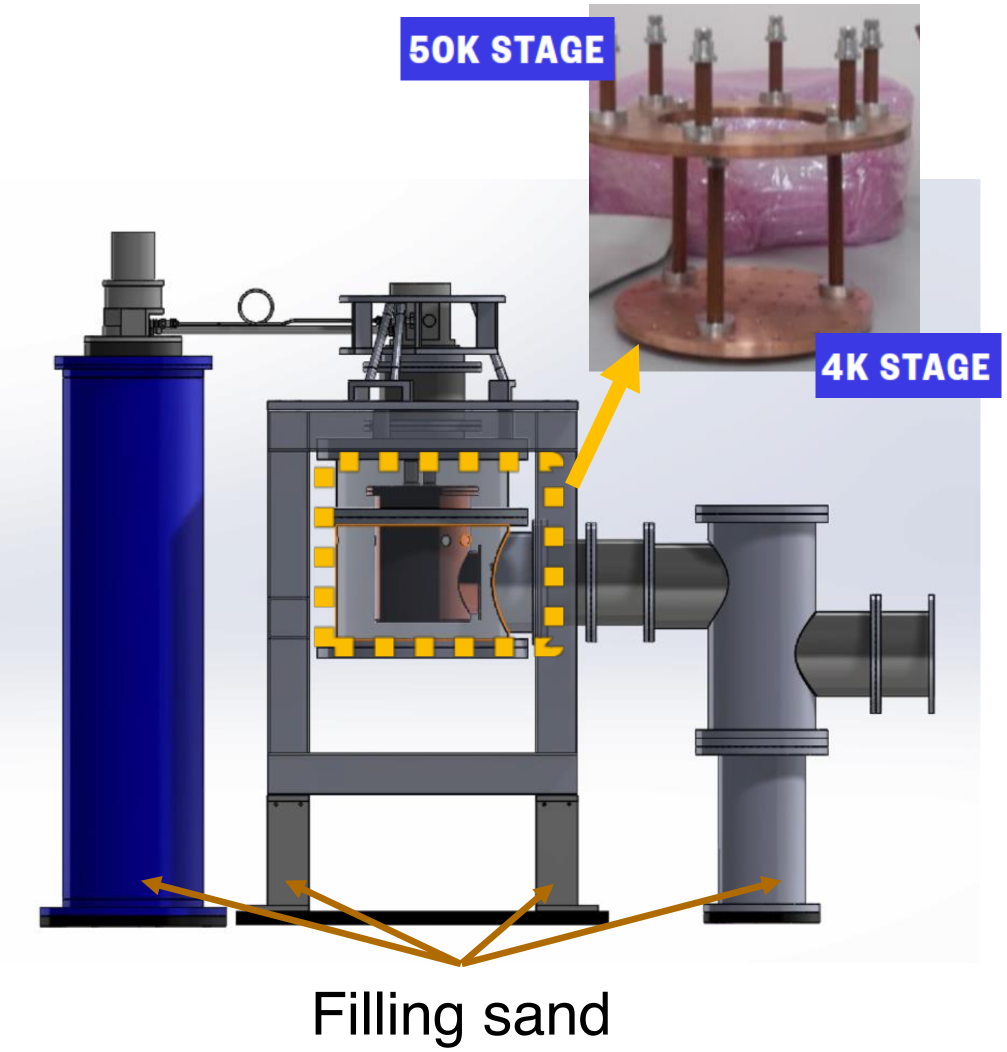




Overview of Cryogenic system



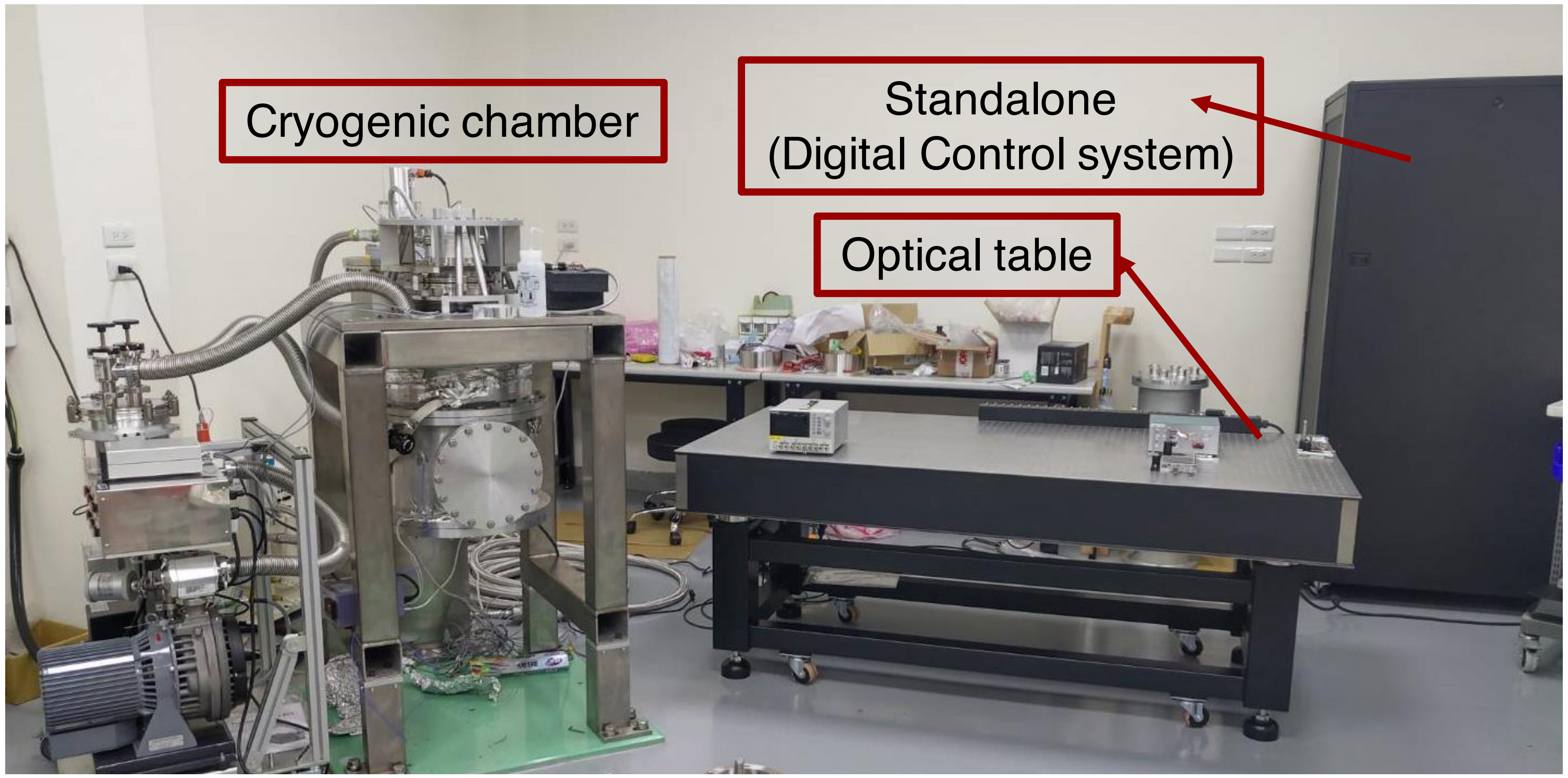
- **M**ultiple **A**pplications cryocooler system with **R**ealtime feedbacked **L**ow **E**nvironmental background (MARLE) consists of **3** chambers



- Cryocooler : 2-Stages pulse tube cooler
- Stages temp. : 50 K, 4 K
- CHRONOS requirement : 4K

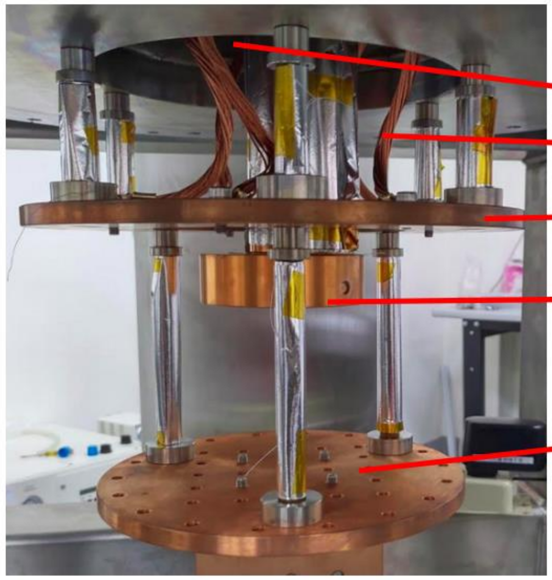
Setup of cryogenic system

- Optical table and standalone server are prepared



Compressor

Chiller(to be upgraded to be more powerful)



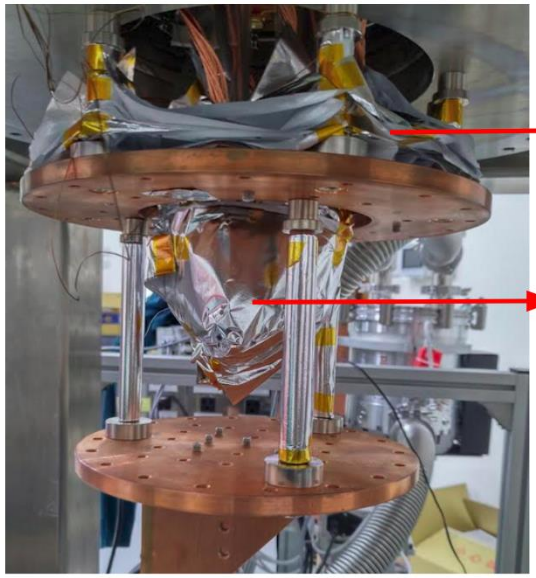
50K cooling head

heat links (50K)

Stage of 50K for testing

4K cooling head

Stage of 50K for testing (in Run002, we do not install the heat links for 4K)



50 layers MLI cover the 50K stage

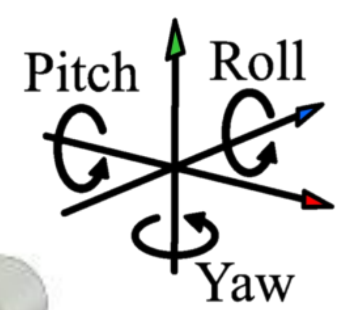
MLI cover the 4K cooling head

Feedback control system

- Feedback control :
  - Vibration noise almost large enough to swamp the signal we are looking for
  - Do more than barely make the instrument work : use feedback to control the relevant angles and positions

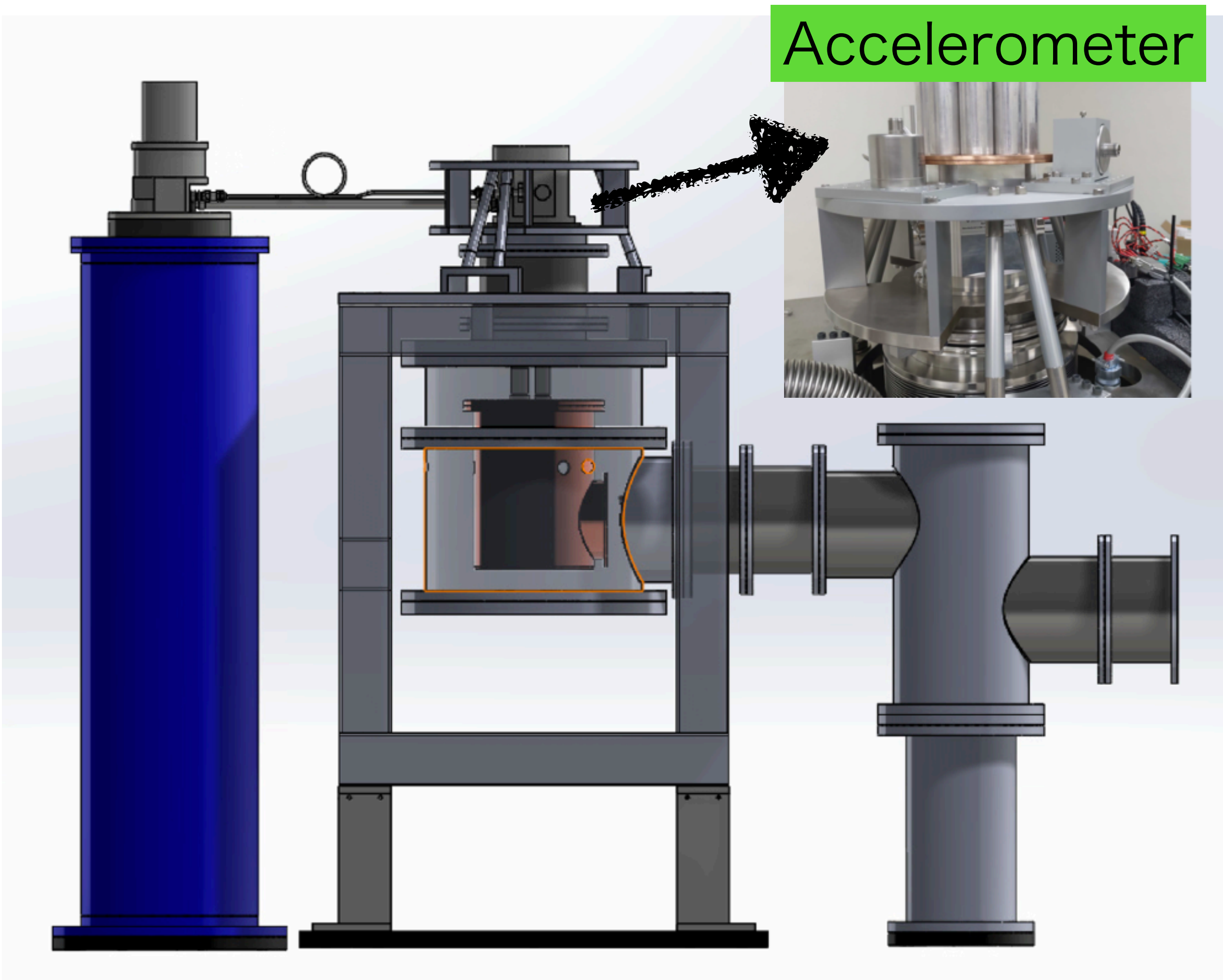
- 6 degree of freedom?
  - Translational vibration couples to the rotational motion

Accelerometer
(seimometer)

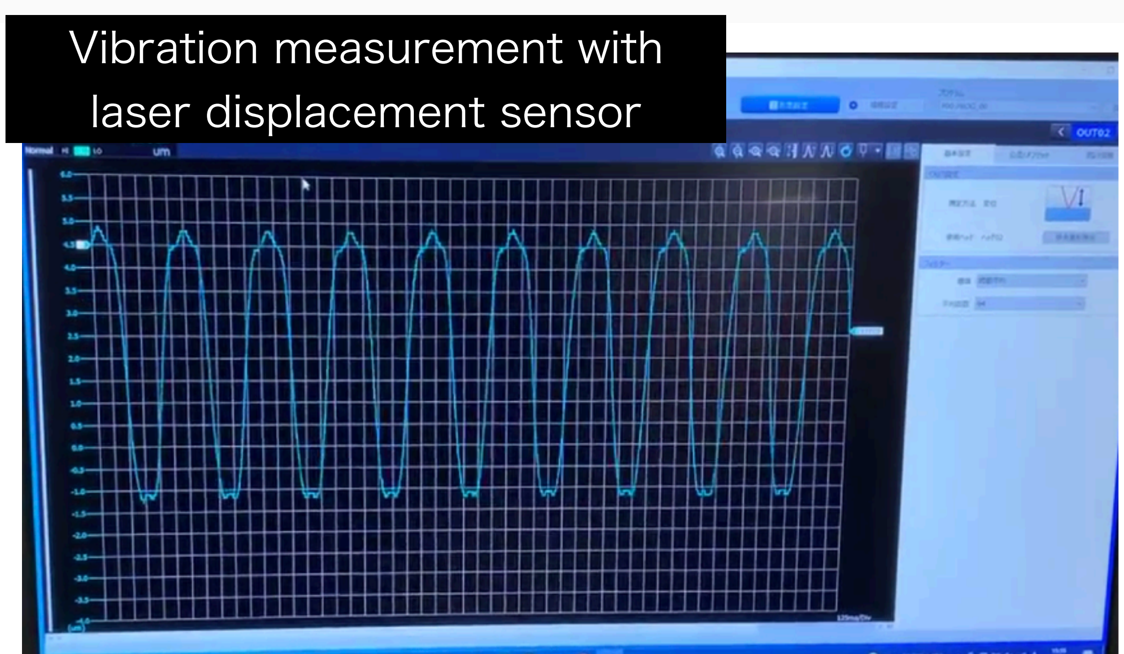


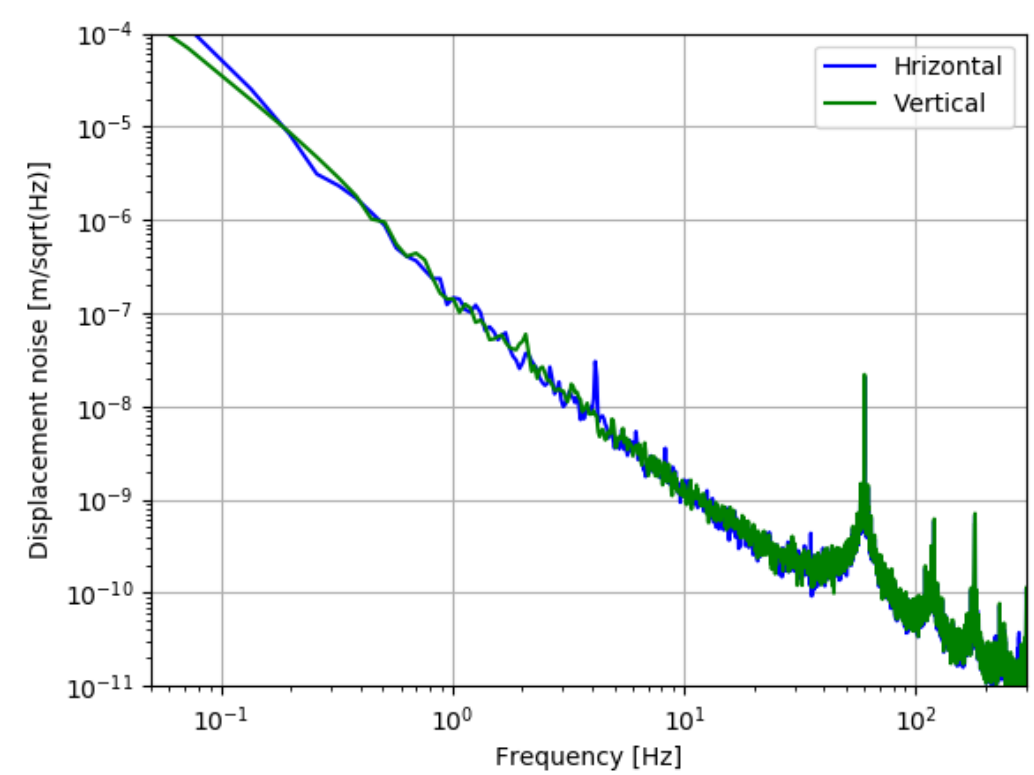
Piezo Flexure Actuator
P-844 Preloaded Piezo Actuators

Development of loss measurement system
- Characterization of Vibration-



- We measured the vibration from PTC
- To mitigate the periodic vibration from PTC (~10um), we are developing active damping vibration isolation system
- To make error signal for feedback, we start to install the accelerometer and photo sensors.
- We plan to finish the initial test within 1.5 month
- From May, we will start the optical test for loss characterization system with my students





3. Listing up the science and sensitivity

Astronomy →
- Intermediate Black hole
- Contentious Wave
- SMBH marger?

Test of Gravity →
- Black hole spectroscopy

Cosmology →
- Stochastic background
- Black hole binary with host galaxy

Geophysics →
- Earth quake in Taiwan

Exotic science →
- Hidden photon
- Axion
- Yukawa Gravity

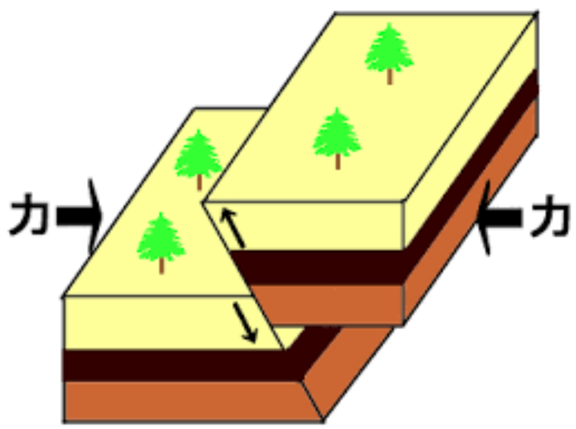
By collaborating with theorist, we need to list up all science possibility with sensitivity curves. We will discuss it in Theory session.

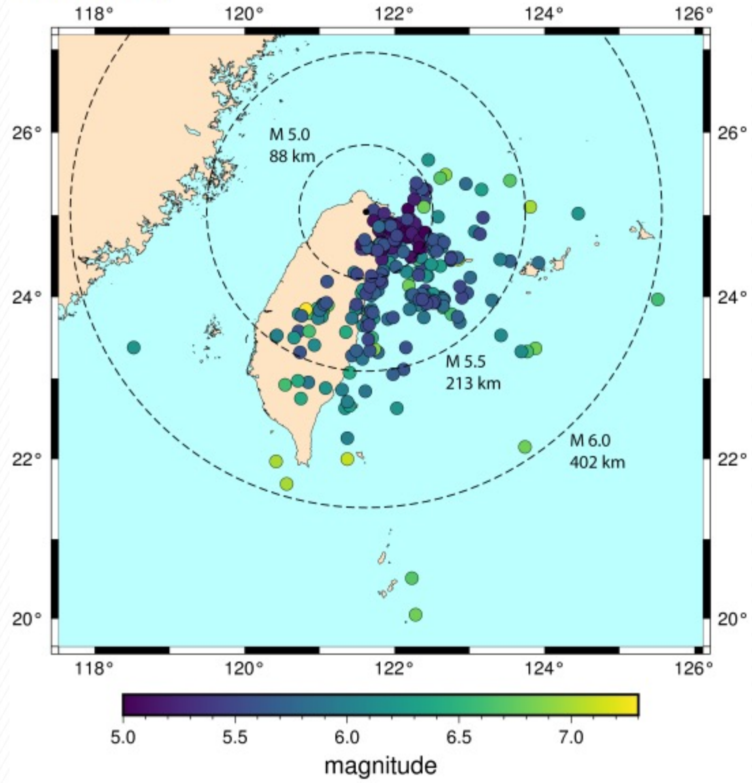
Earth quake measurement in Taiwan

- **Dynamical of mass** inside the earth surface **can generate a perturbation to gravitational potential** on the surface of the earth
- It can be observed by strainmeter throught **gravity strain**

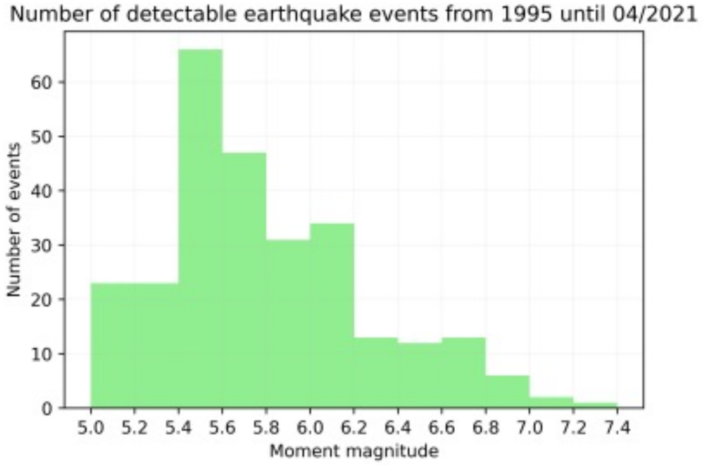
$$\mathbf{h}(\mathbf{r}, t) = \int_0^t d\tau' \int_0^{\tau'} d\tau \; \nabla \otimes \delta\mathbf{g}[\mathbf{r}, \tau].$$

- Harms (2016) provided a numerical calculation method to **compute the gravity strain signal by** solving the equation with double-couple source (symmetric **moment tensor**) in homogeneous half-space (the signal is sourced from the underground).



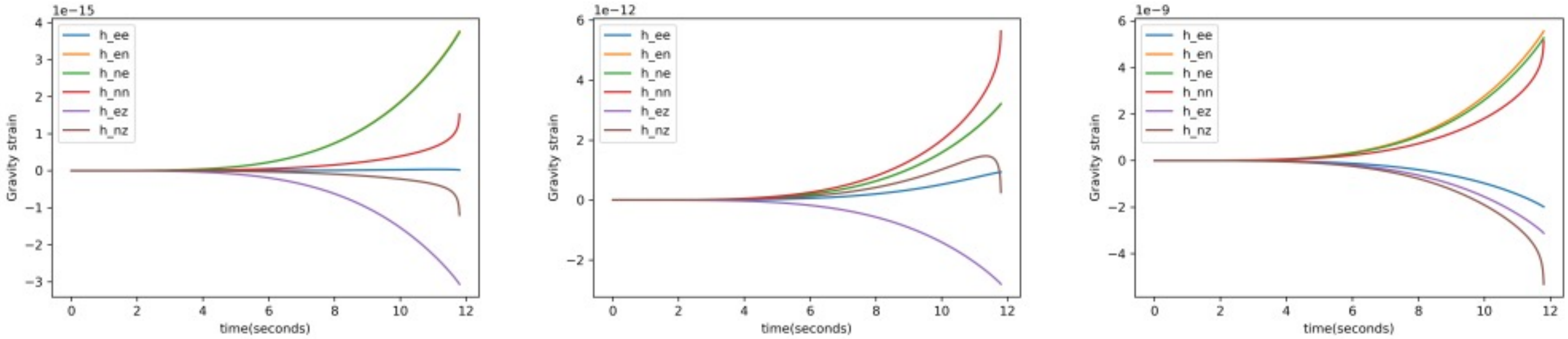


We can cover all Taiwan region for detecting earthquake around M 6.0



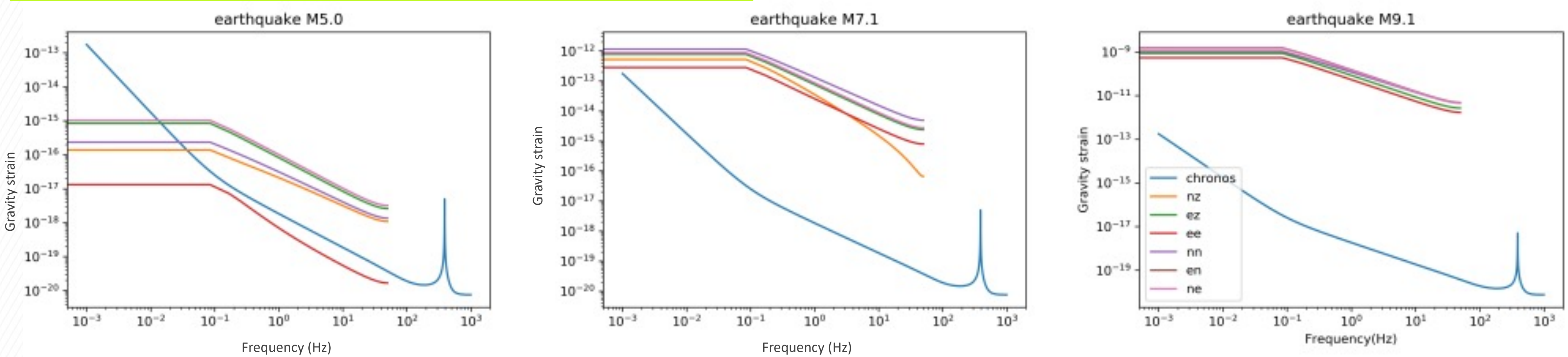
Simulation and Sensitivity

SIMULATED GRAVITY STRAIN FROM MOMENT TENSOR DATA IN TAIWAN



(a) M 5.0 (b) M 7.1 (c) M 9.1

SENSITIVITY OF CHRONOS AND TYPICAL SIGNAL



(a) M 5.0 (b) M 7.1 (c) M 9.1

Collaboration is very welcome!!

- Development of ASGRAF (Software / Hardware)
    - Vacuum, Electronics, Machining, and Cryogenic
- Application of active damping cryogenic system for other experiment (CMB, Dark matter, ..)
- Astronomical research for Intermediate black hole generation process
- Study for Stochastic back ground
- GEO science and analysis with ASGRAF data

Summary

- Gravitational wave was detected by LIGO. Nowadays, we can observe gravitational wave every ten days.

- AS-NCU-NRHU group start the LIGO study from 2021. We focus on calibration and coating study.

- Construction of ASGRAF is ongoing. We will test the new technology for future R&D. We would like to apply our facility as one of the test facility of LIGO in the future.

- R&D of Taiwanese GW experiment, CHRONOS, is ongoing. We are testing key technology in NCU and Academia Sinica.