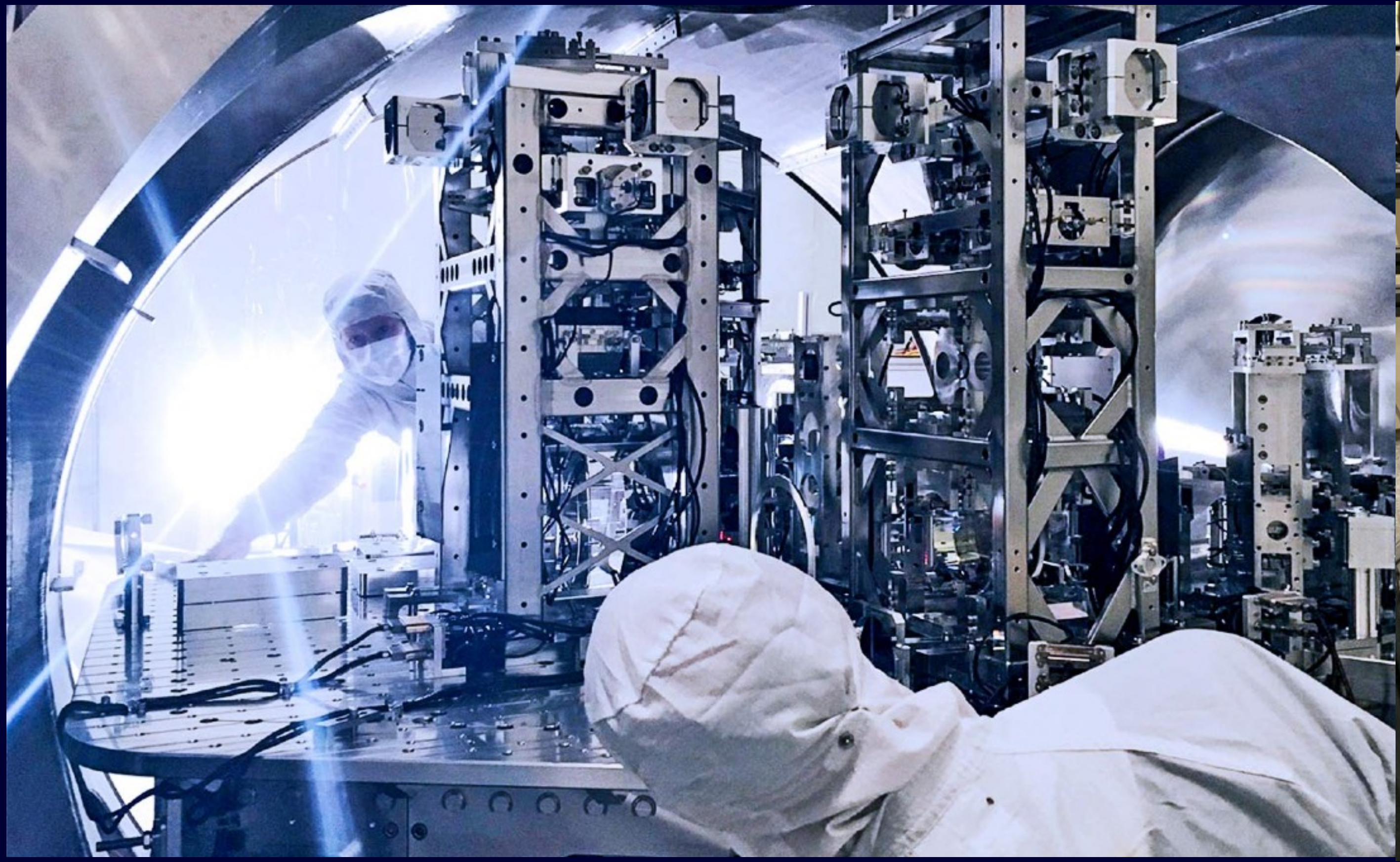

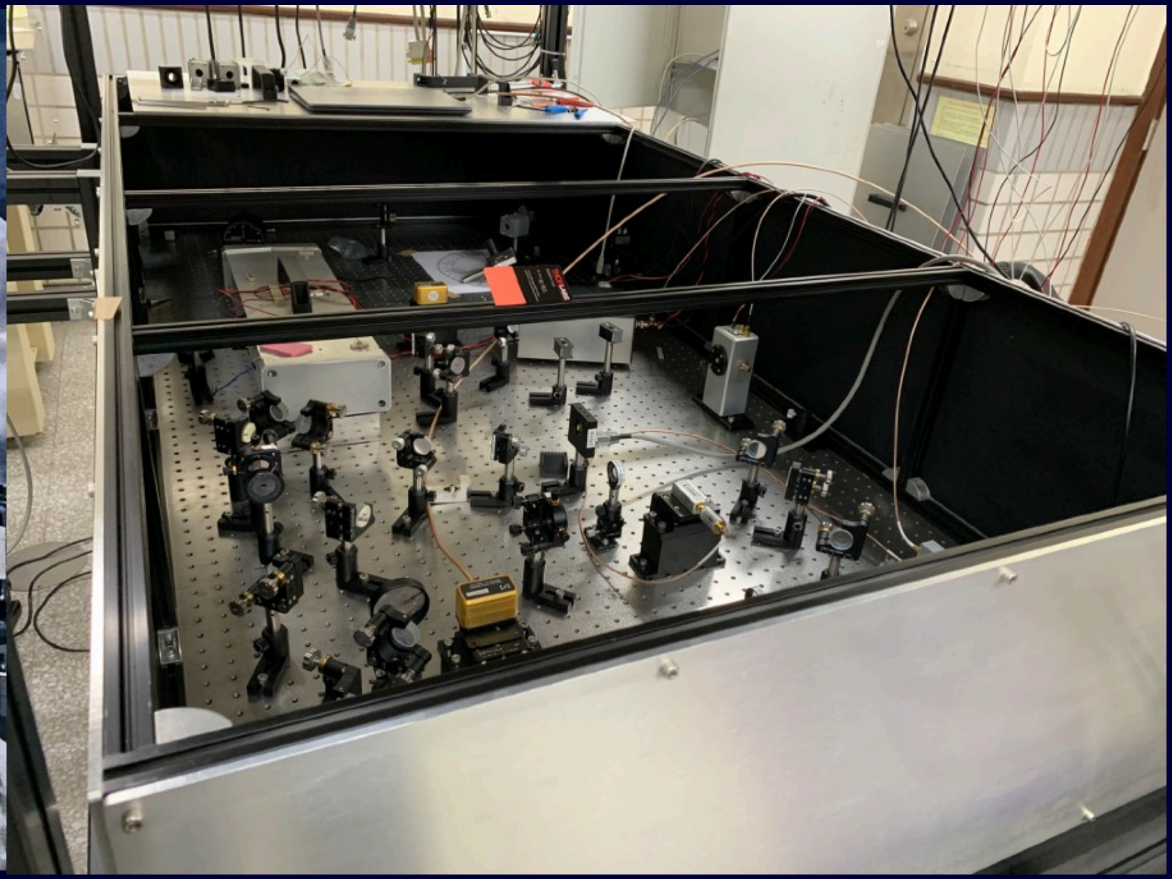

Progress of Gravitational wave study in LIGO

National Central University and Academia Sinica
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GSROC LSC

NTU 20211013

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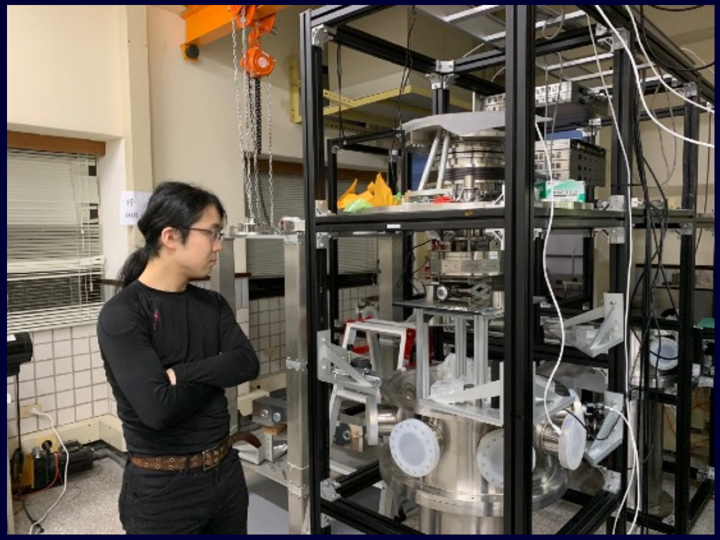
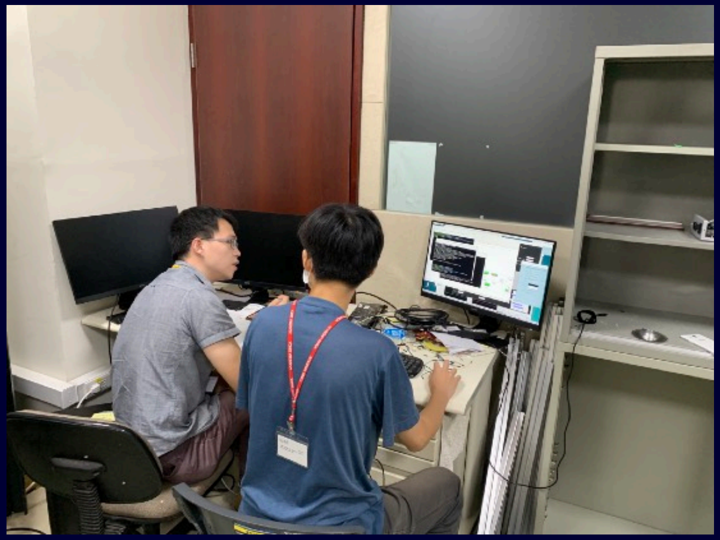
Hsiang-Chieh Hsu(NCKU)
Afif Ismail

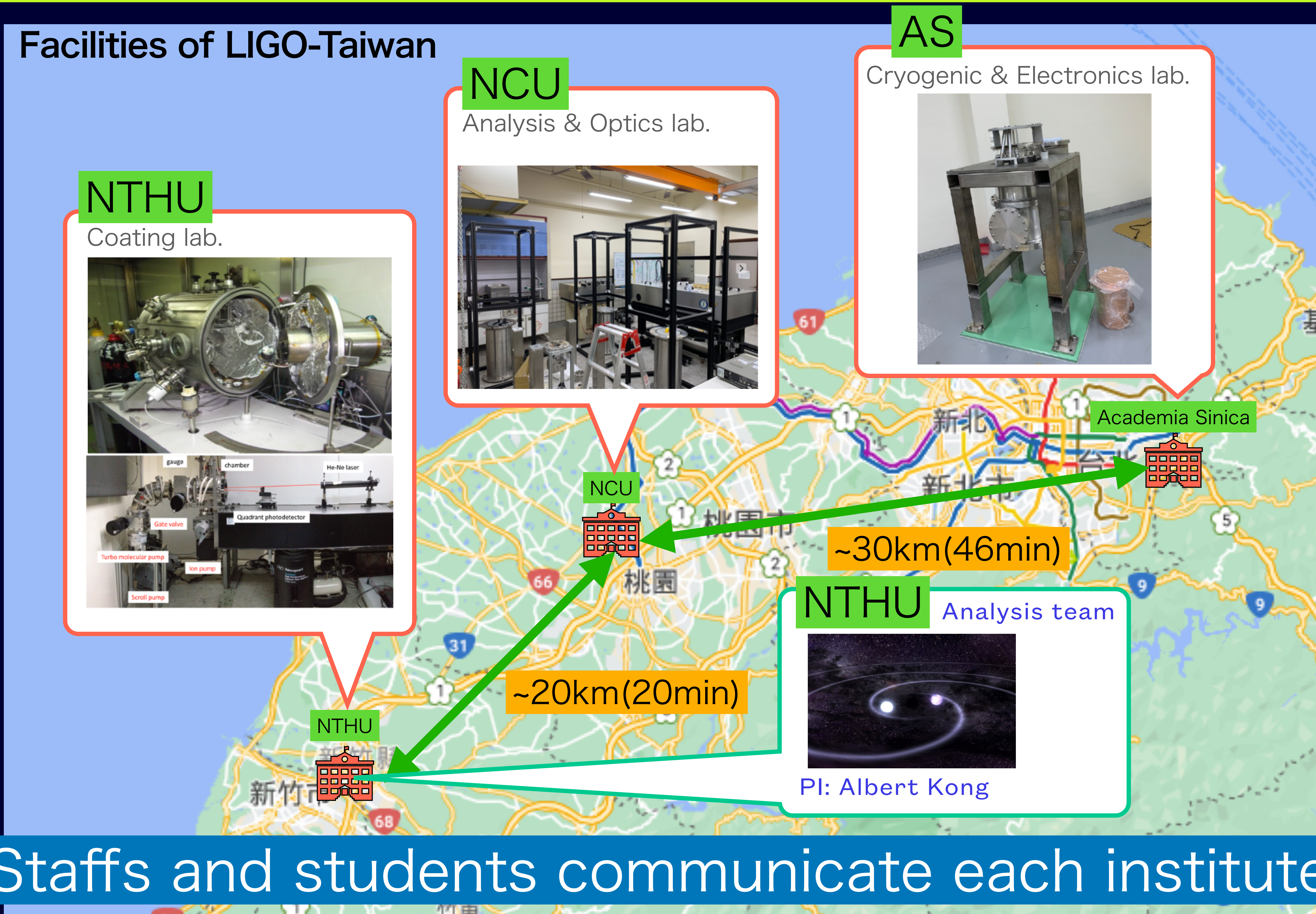
National Tsing Hua University

Shiuh Chao





Facilities of LIGO-Taiwan

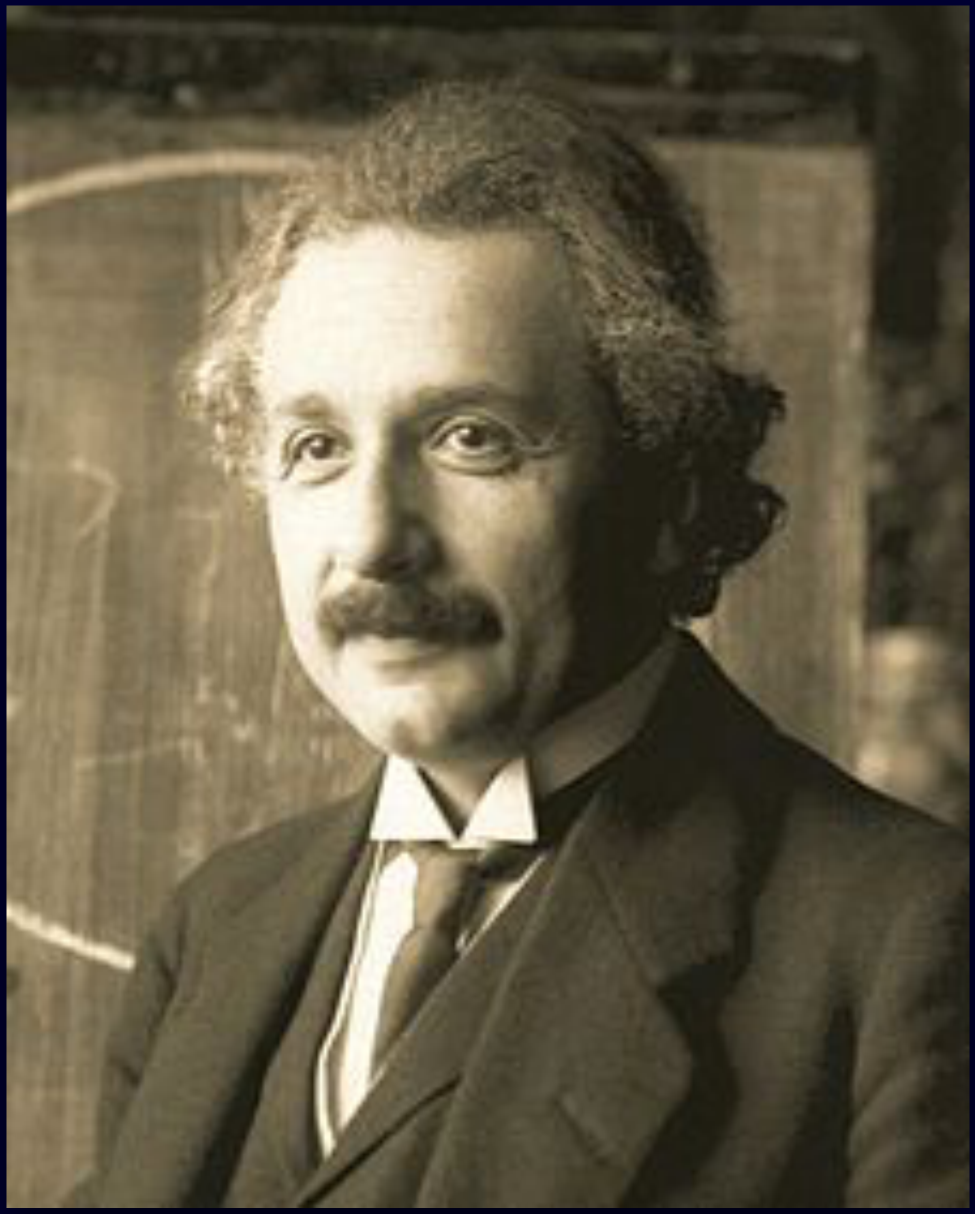


Staffs and students communicate each institute.

Outline

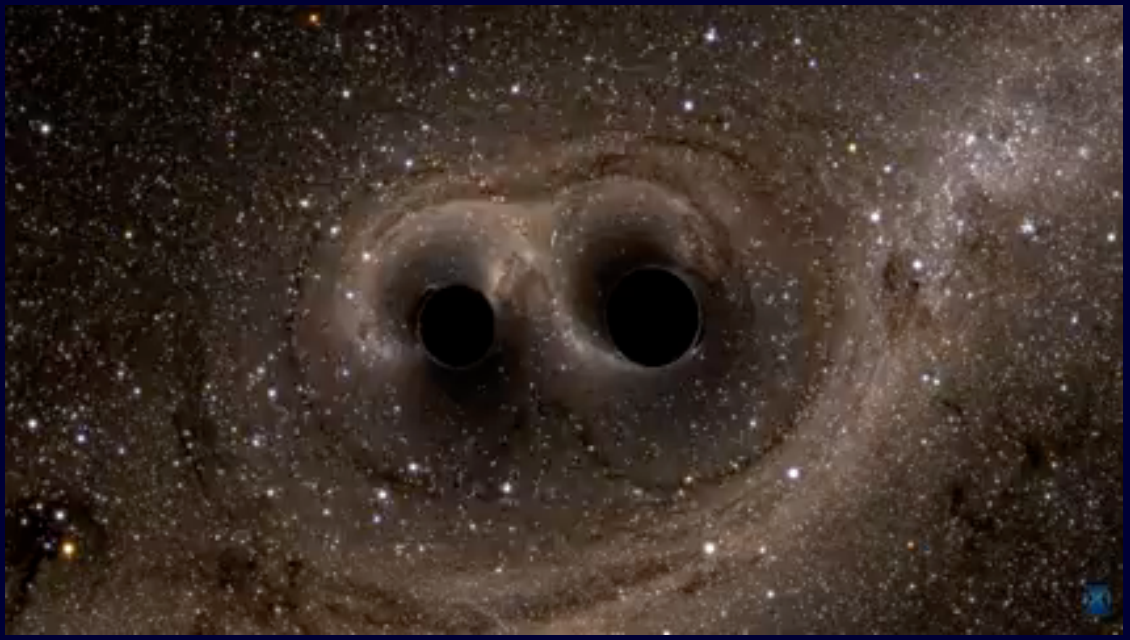
- Introduction
- GW source
- LIGO
- Future R&D
- Summary

Introduction



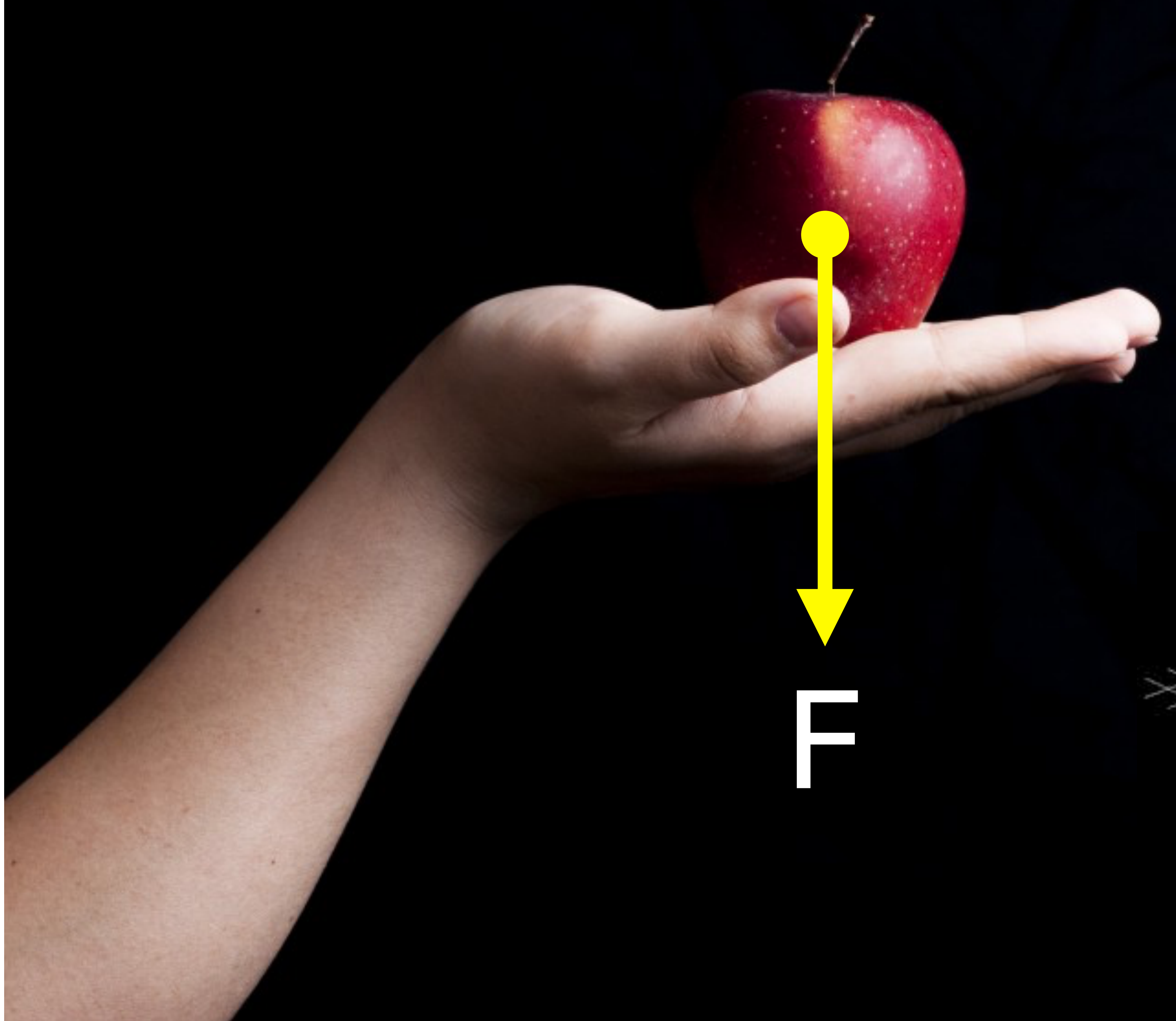
- Albert Einstein
- 1916 General Relativity
  - 'Distortion of Space and Time'
- One of the most important predictions:

Gravitational Wave!

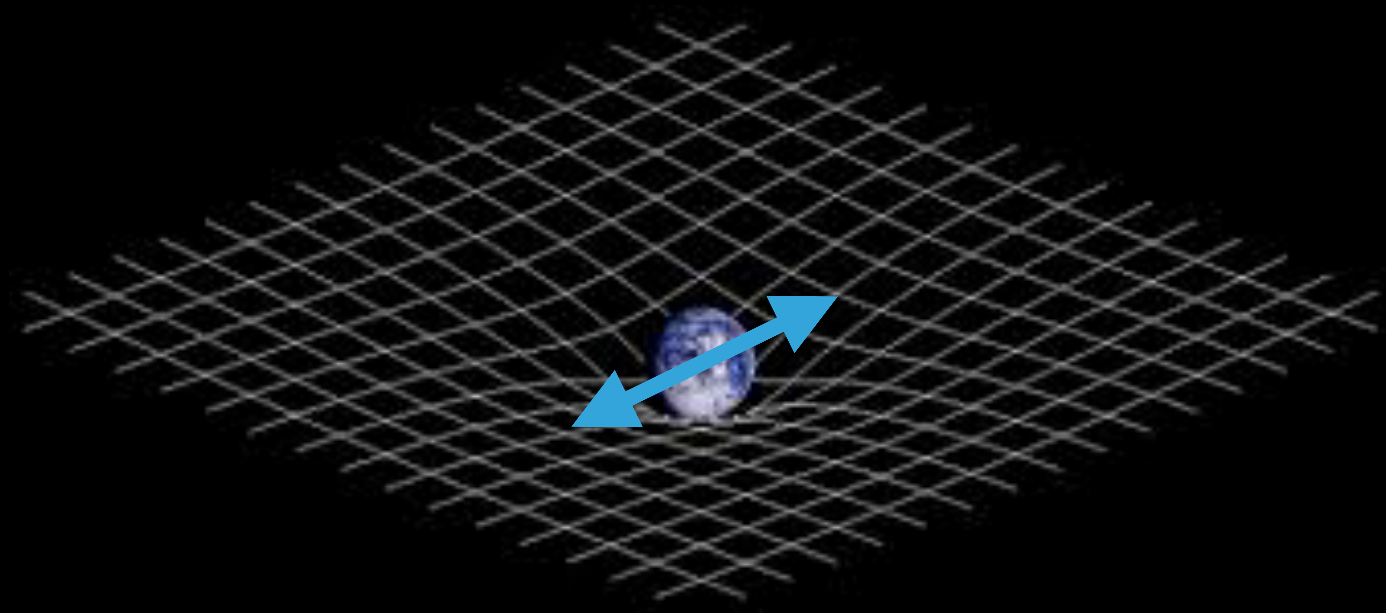


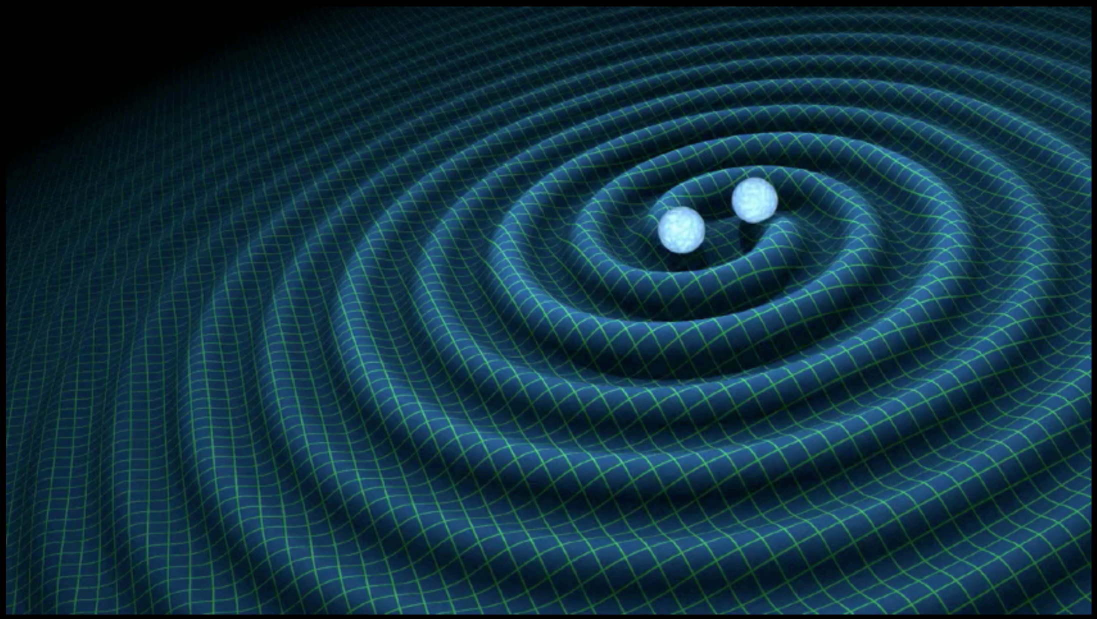
Nowadays, GW is observable target to know the astronomical phenomena.

APPLE ON THE EARTH



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

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

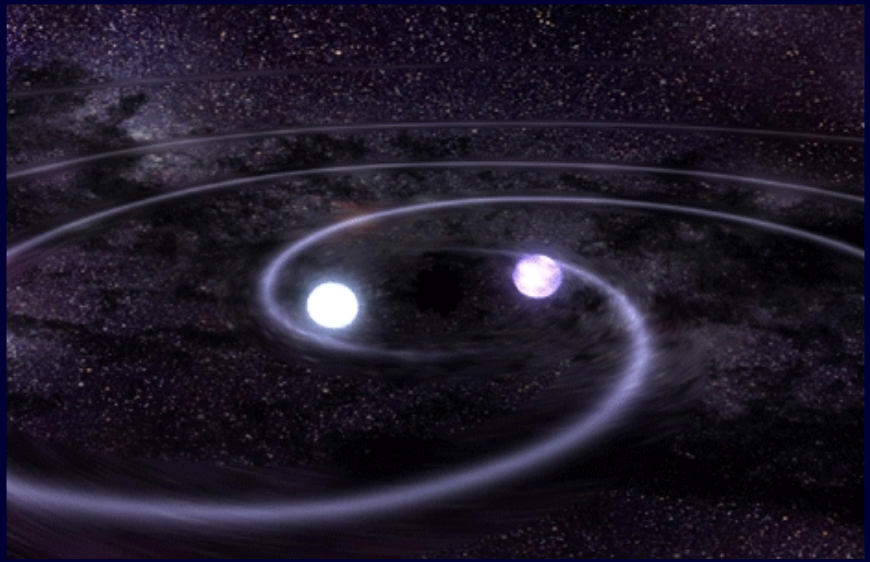
$$h_{ij} = A_{ij} \times \exp\left[\mathrm{i}(\omega t - kz)\right]$$

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

Gravitational wave source

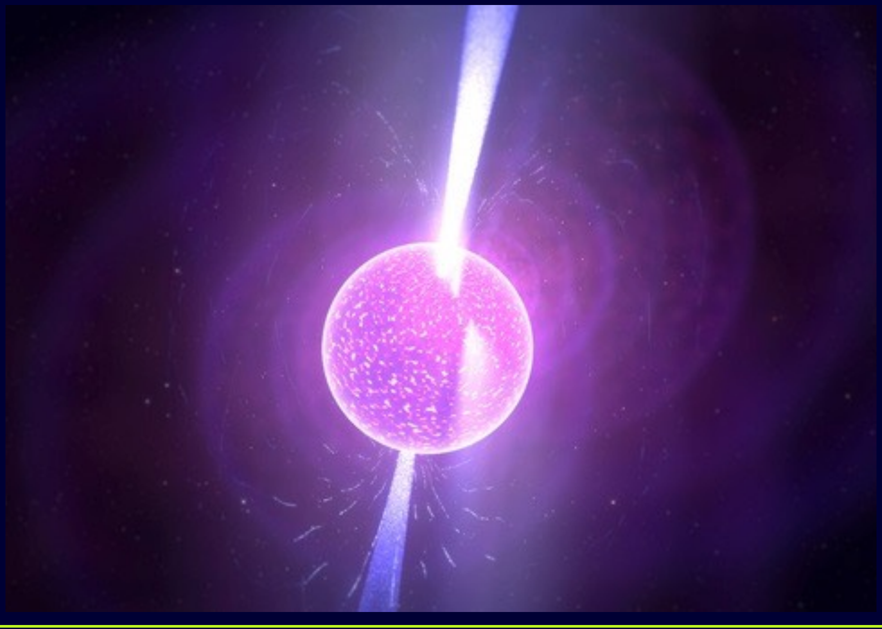
Gravitational wave source

BINARY SYSTEMS

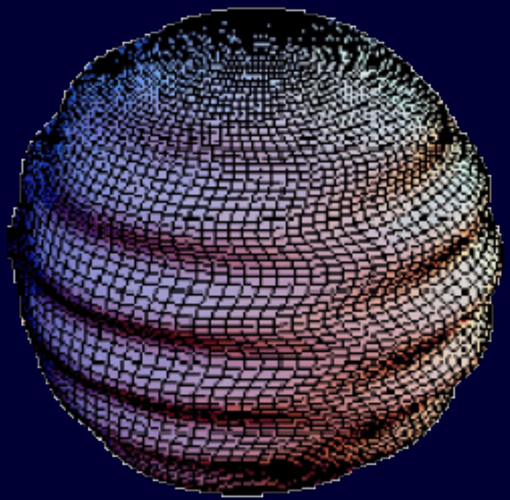


SUPER NOVA

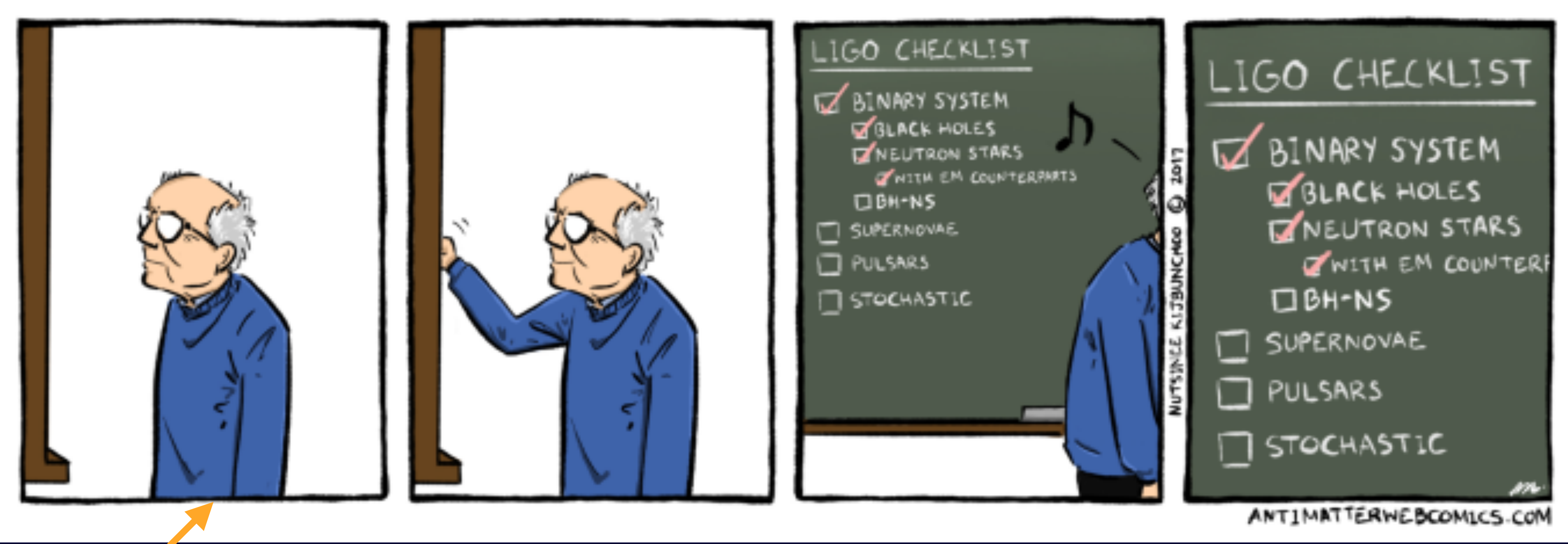
PULSER



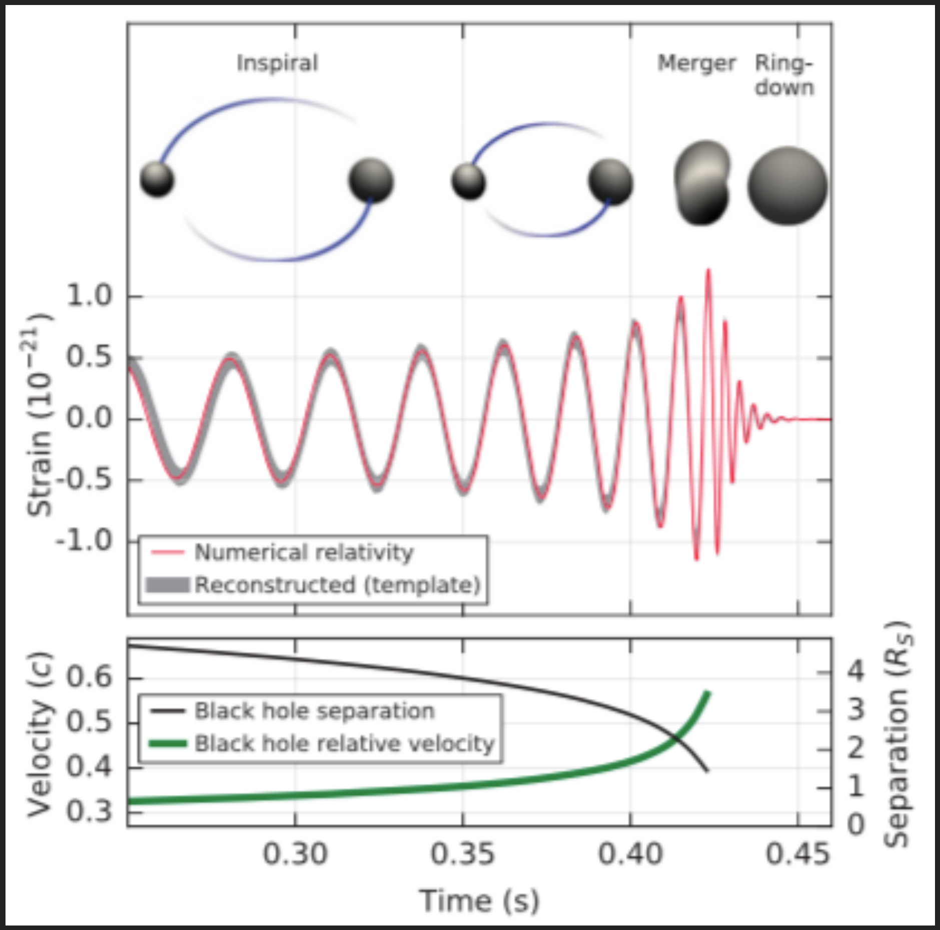
STOCHASTIC BACKGROUND

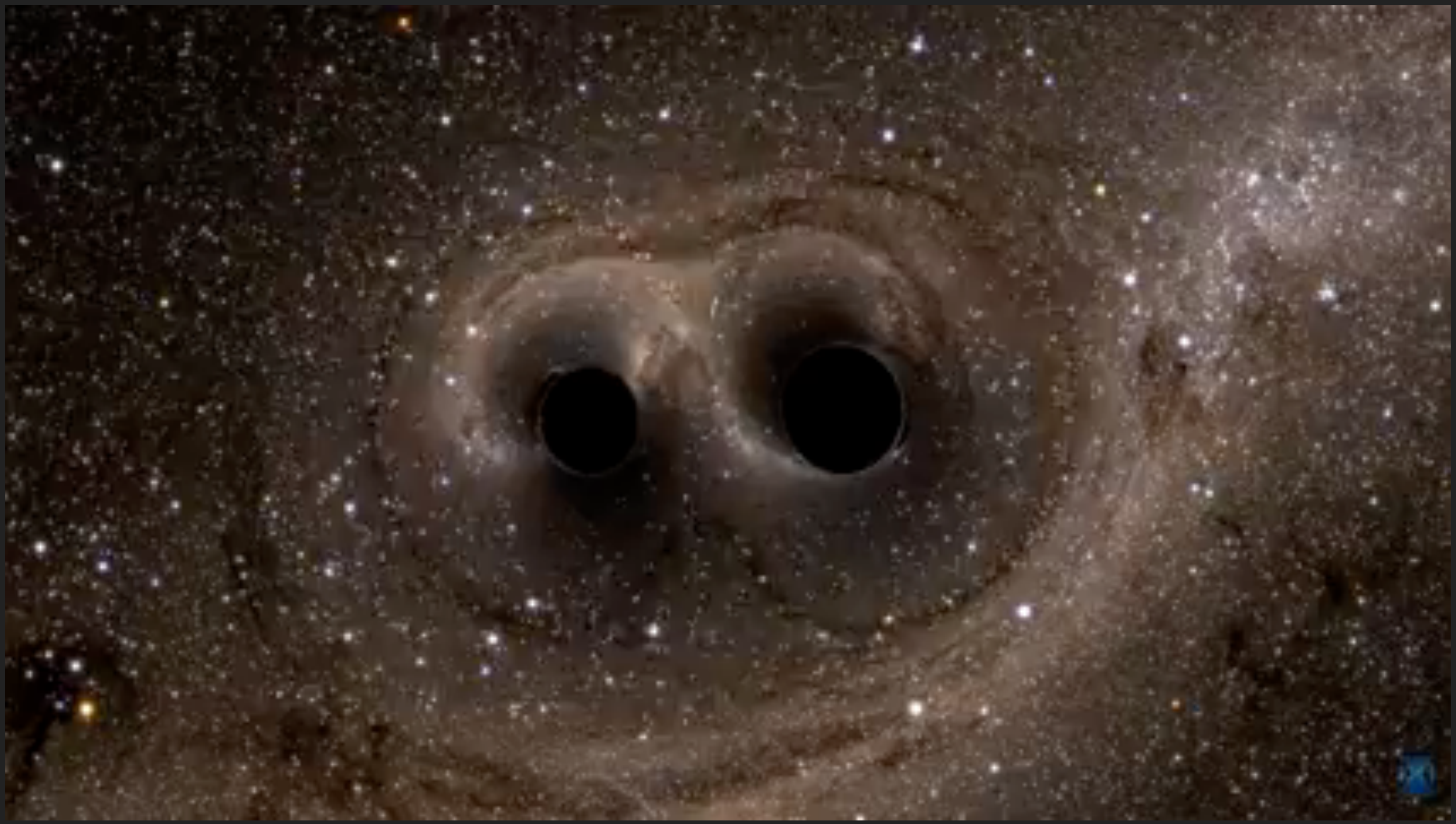


Scientific Goal (Before O3)



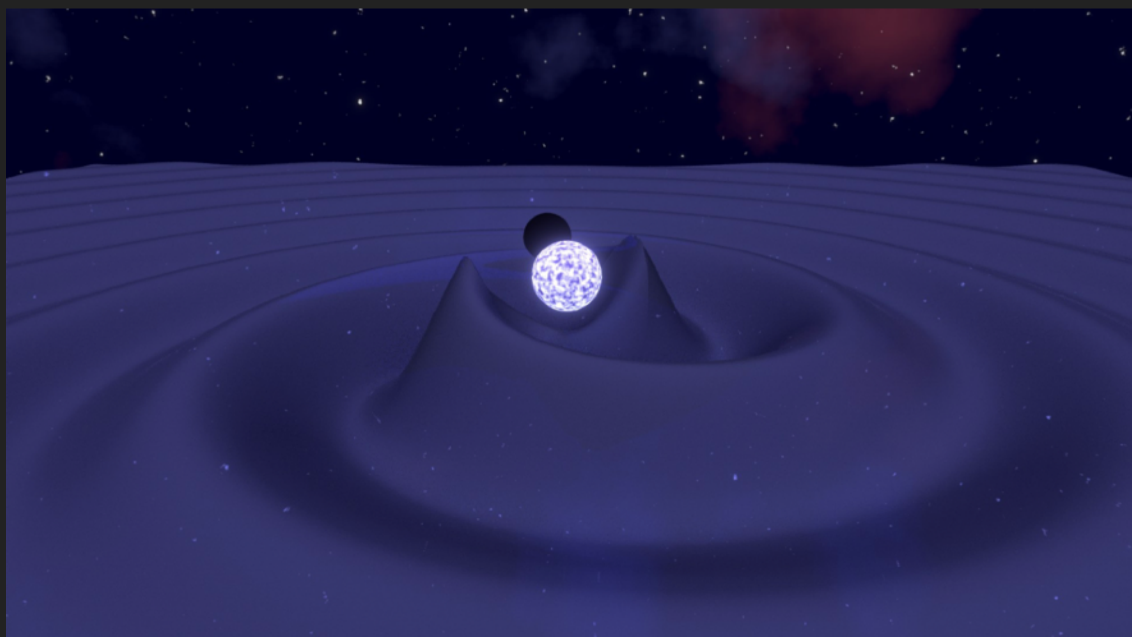
COMPACT BINARY COALESCENCE





- BH-BH, BH-NS, NS-NS (BH = Black hole, NS = Neutron Star)
- LIGO and VIRGO observe it every 10 days.

BLACK HOLE – NEUTRON STAR



THE ASTROPHYSICAL JOURNAL LETTERS

OPEN ACCESS

Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences

R. Abbott[1], T. D. Abbott[2], S. Abraham[3], F. Acernese[4,5], K. Ackley[6], A. Adams[7], C. Adams[8], R. X. Adhikari[1], V. B. Adya[9], C. Affeldt[10,11]

+ Show full author list

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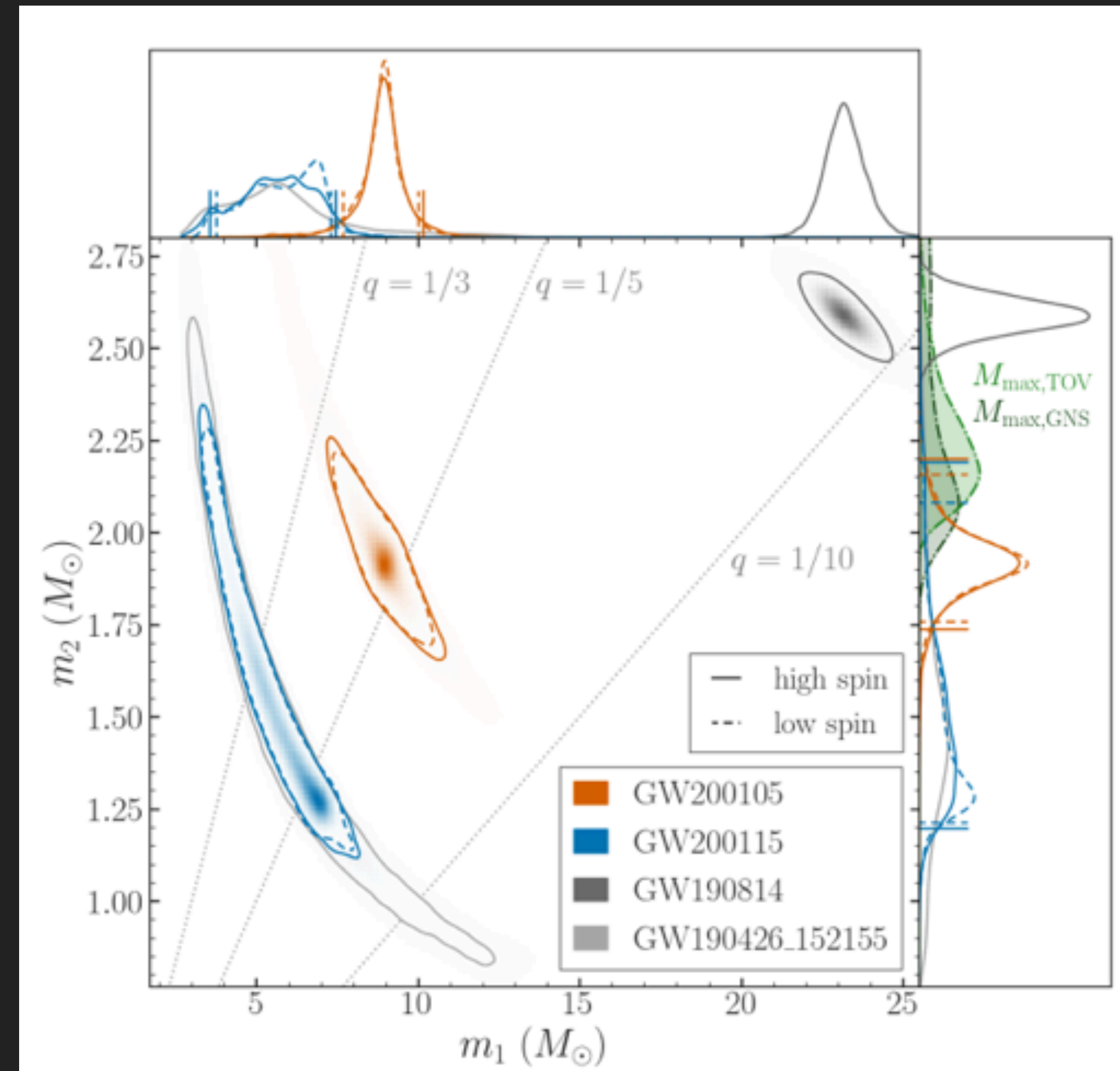
The Astrophysical Journal Letters, Volume 915, Number 1

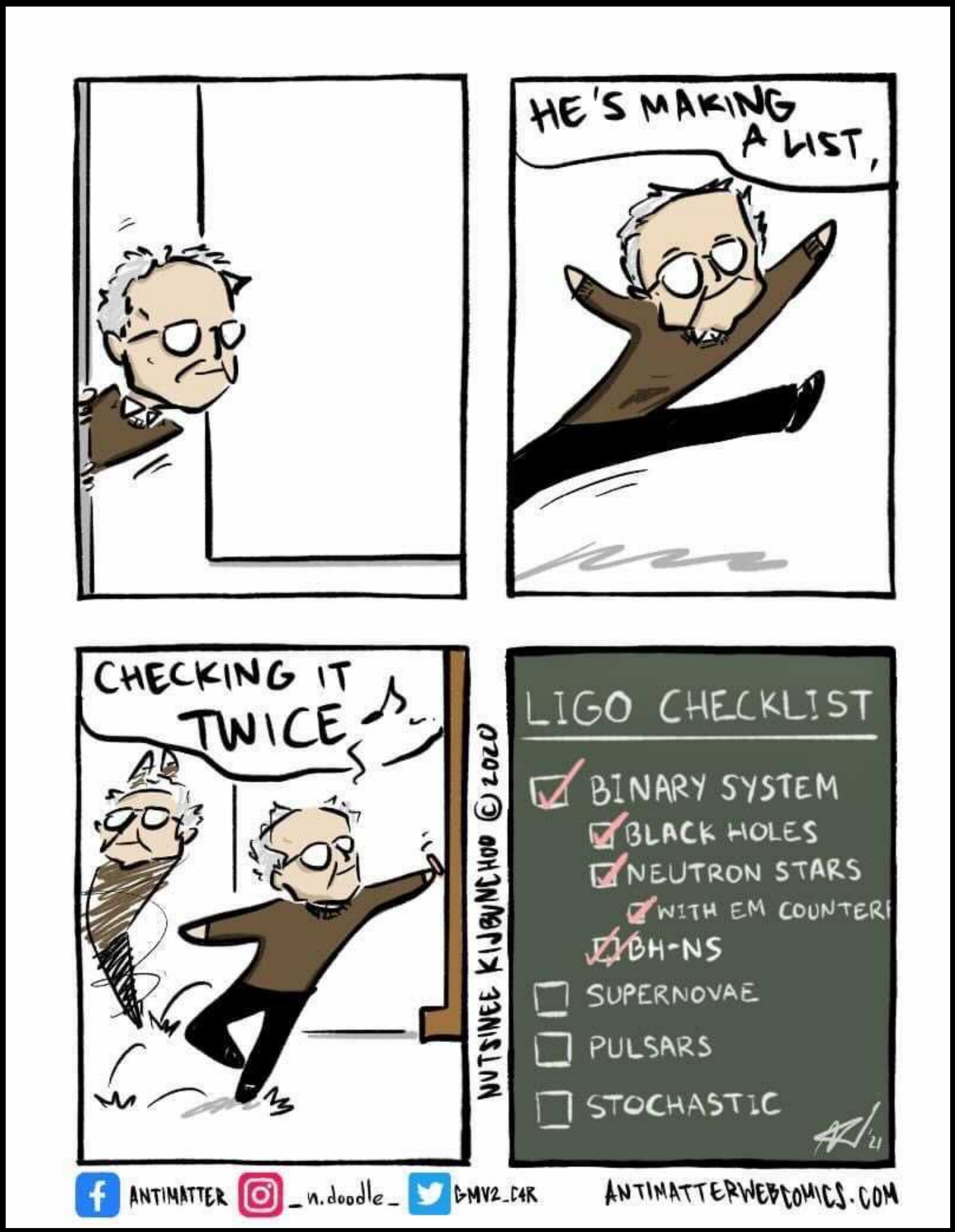
Citation R. Abbott *et al* 2021 *ApJL* **915** L5



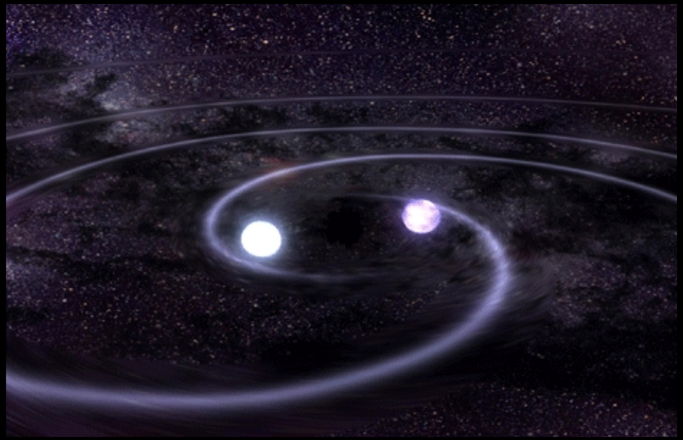
Source Properties of GW200105 and GW200115

	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
Mass ratio q	$0.21^{+0.06}_{-0.04}$	$0.22^{+0.08}_{-0.04}$	$0.24^{+0.31}_{-0.08}$	$0.26^{+0.35}_{-0.10}$
Total mass $M/M_\odot$	$10.8^{+0.9}_{-1.0}$	$10.9^{+1.1}_{-1.2}$	$7.3^{+1.2}_{-1.5}$	$7.1^{+1.5}_{-1.4}$
Chirp mass $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$3.619^{+0.006}_{-0.006}$	$3.619^{+0.007}_{-0.008}$	$2.580^{+0.006}_{-0.007}$	$2.579^{+0.007}_{-0.007}$
Primary spin magnitude χ_1	$0.09^{+0.18}_{-0.08}$	$0.08^{+0.22}_{-0.08}$	$0.31^{+0.52}_{-0.29}$	$0.33^{+0.48}_{-0.29}$
Effective inspiral spin parameter χ_{eff}	$-0.01^{+0.08}_{-0.12}$	$-0.01^{+0.11}_{-0.15}$	$-0.14^{+0.17}_{-0.34}$	$-0.19^{+0.23}_{-0.35}$
Effective precession spin parameter χ_p	$0.07^{+0.15}_{-0.06}$	$0.09^{+0.14}_{-0.07}$	$0.19^{+0.28}_{-0.17}$	$0.21^{+0.30}_{-0.17}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

Next goal after O3

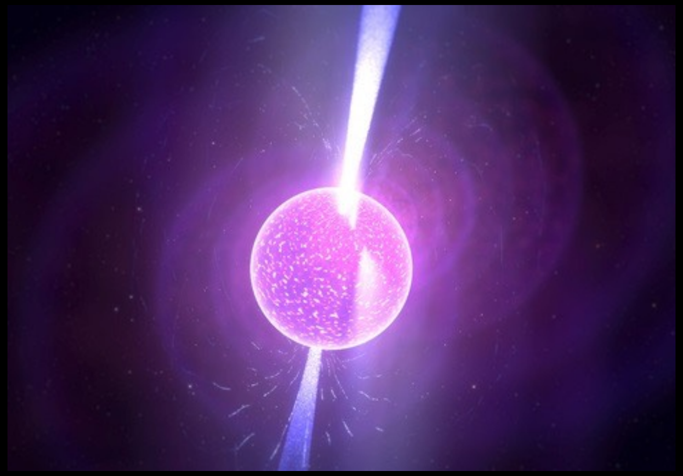


BINARY SYSTEMS

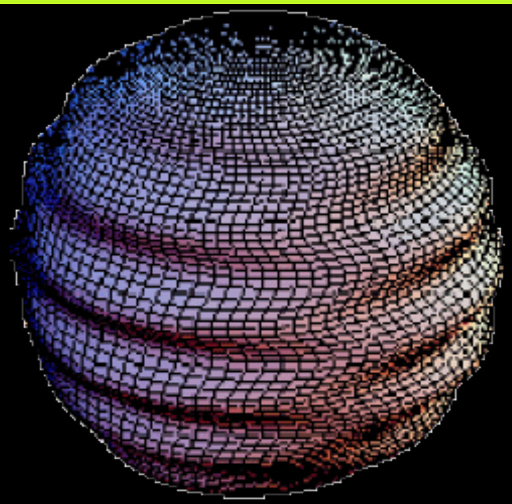


SUPER NOVA

PULSER

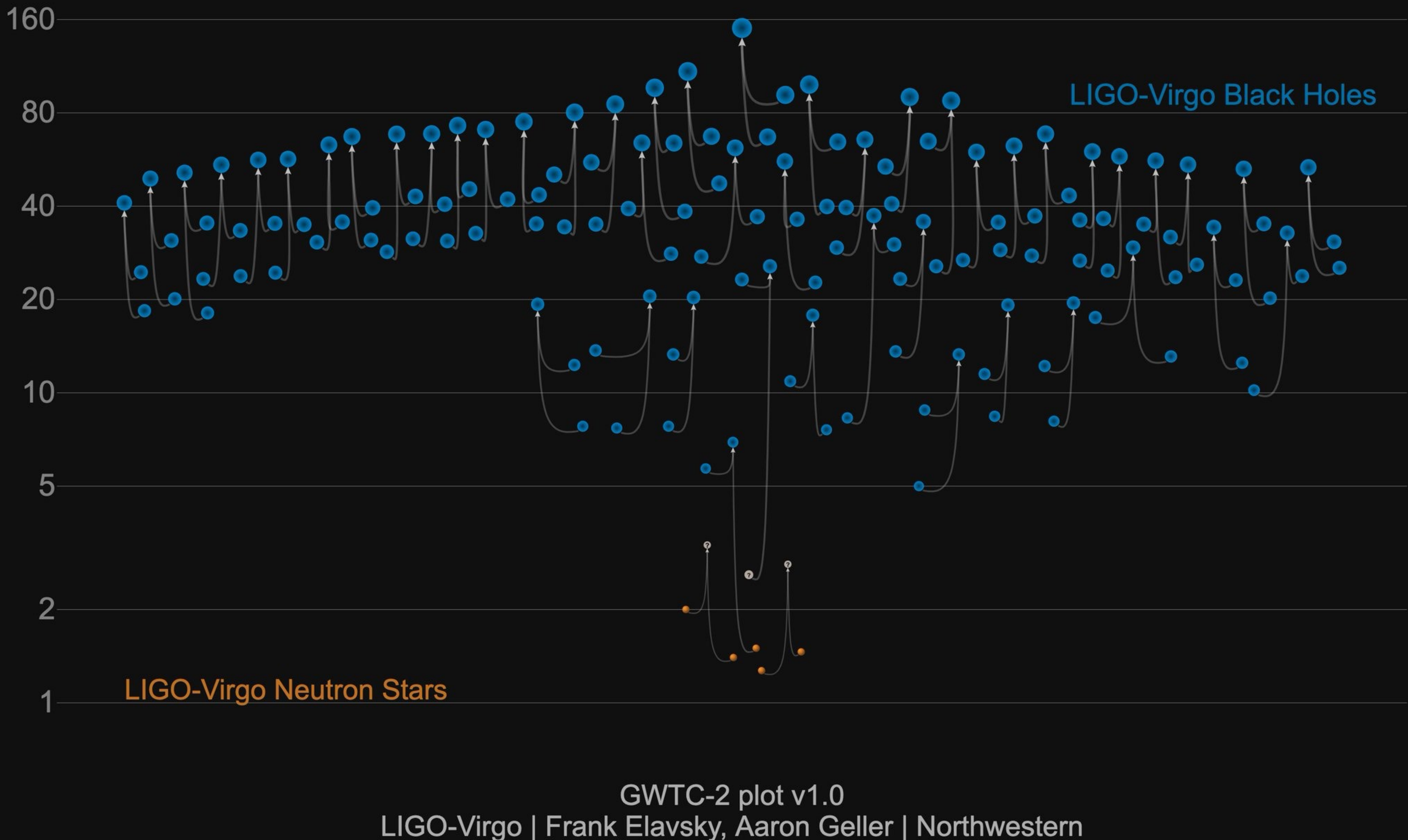


STOCHASTIC BACKGROUND

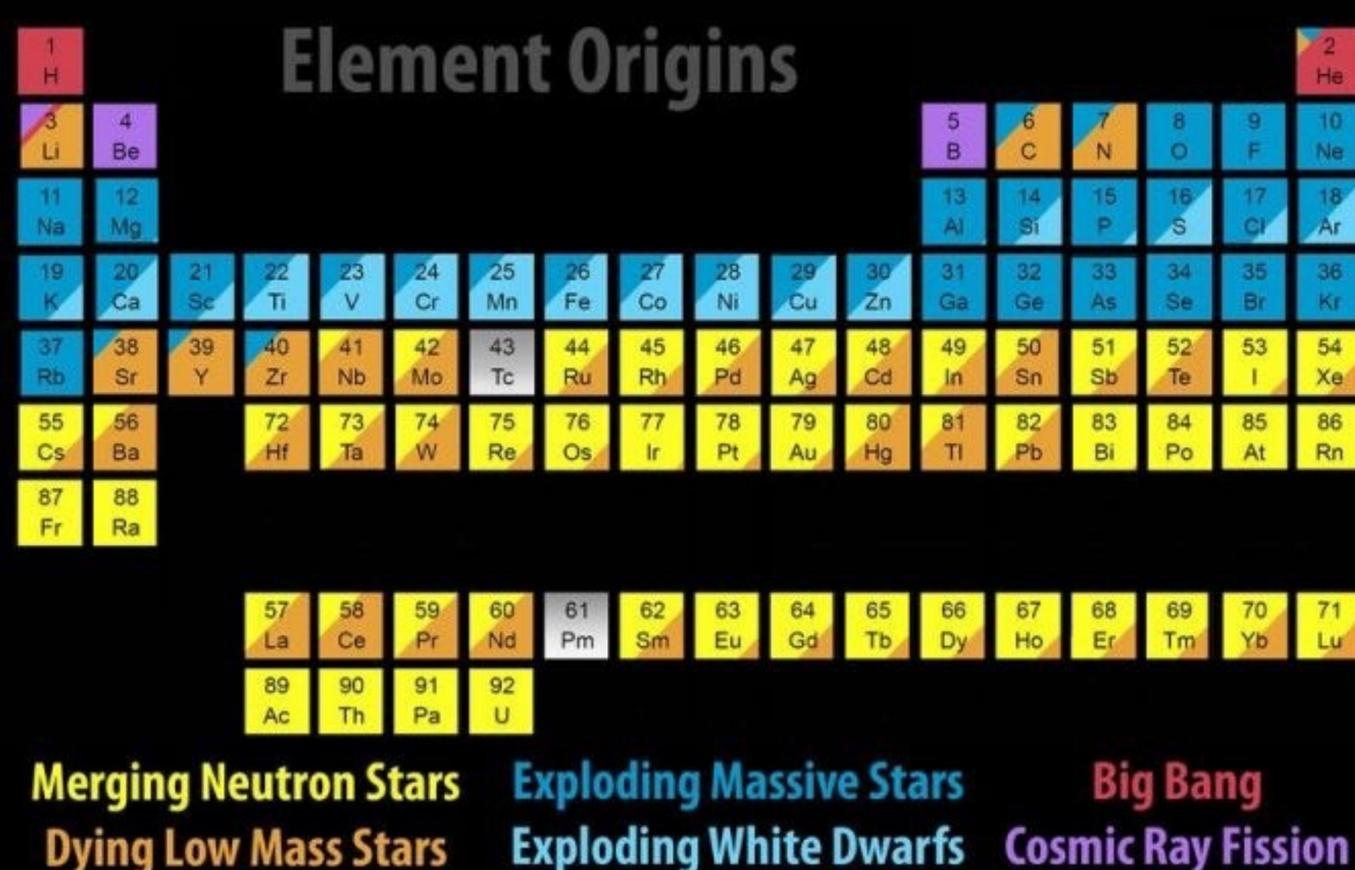


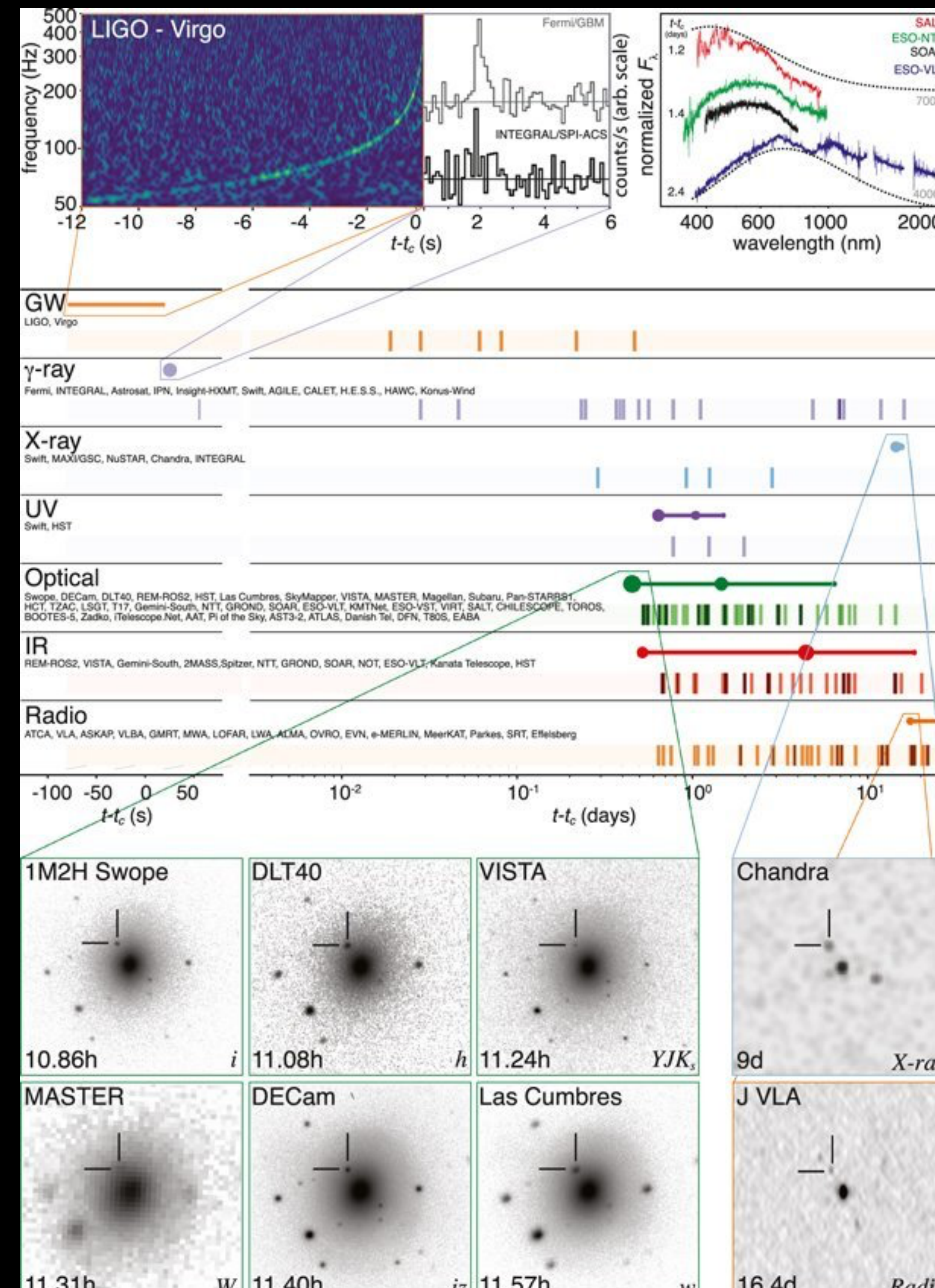
Masses in the Stellar Graveyard

in Solar Masses



Multimessenger astronomy





Parameter of Chirp signal

Source parameters

Chirp mass: $\mathcal{M} = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$

Mass ratio: $\eta = (m_1 m_2)/(m_1 + m_2)^2$

Marger time: t_0

Detector Geometry

Luminosity distance: D_L

Inclination angle: ι

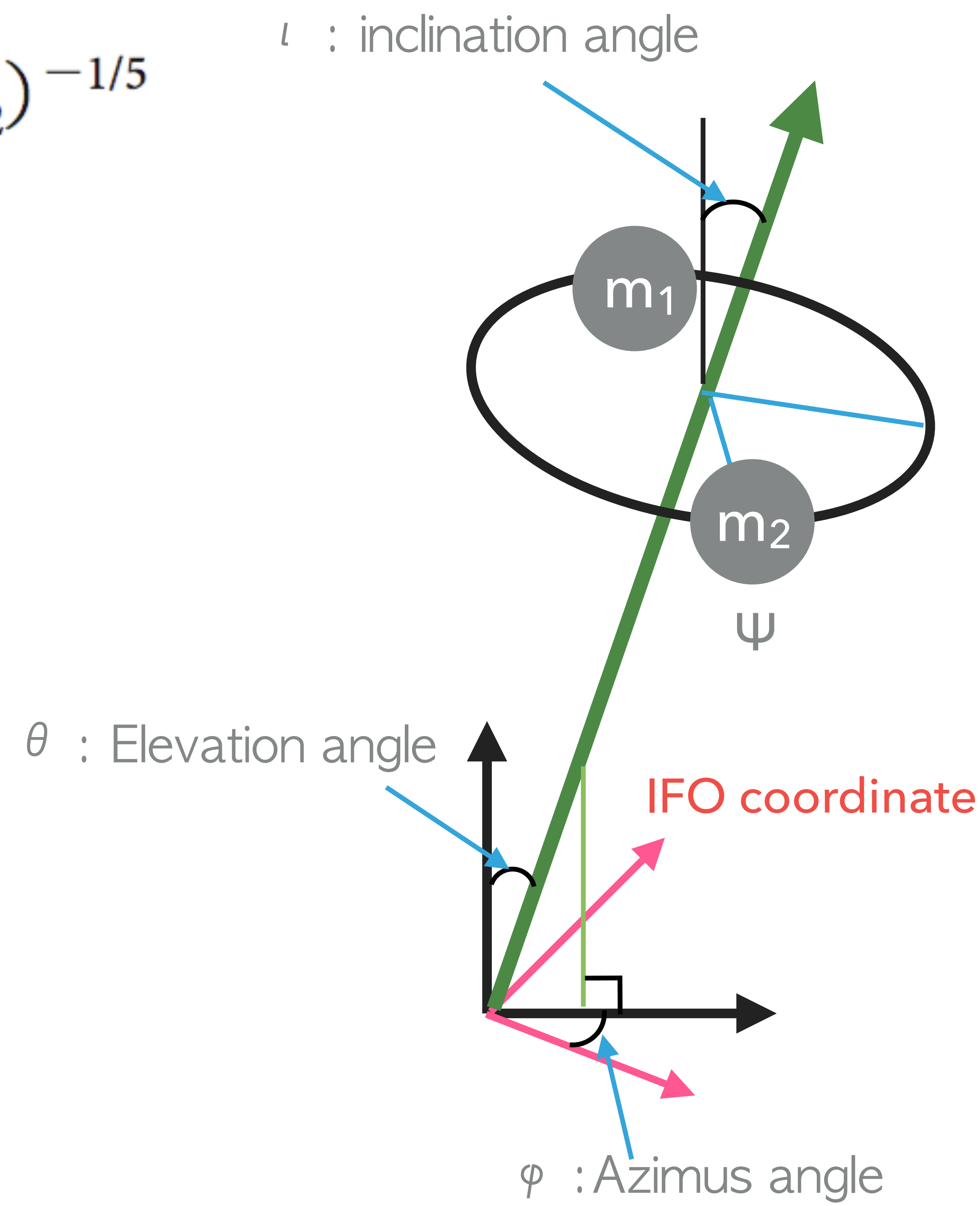
El. and Az. angles: (θ, φ)

Polarization angles: ψ

Observation parameters

Initial phase: ϕ_0

Initial freq.: f_0



Polarization

5 unknown parameters

$$h(t)=F_{+}(\theta,\varphi,\psi)h_{+}(t)+F_{x}(\theta,\varphi,\psi)h_{x}(t)$$

Polarization	Localization	Polarization angle
$h_{+}(t)$ $h_{x}(t)$	(θ,φ)	ψ

$h_{+}(t) \propto (1+\cos^2\iota)/d_L$ $h_{x}(t) \propto \cos\iota/d_L$

Observable parameters

- 1 detector: $h(t)$
- 2detectors: $h_1(t),h_2(t),\tau_{12}$
- 3detectors: $h_1(t),h_2(t),h_3(t),\tau_{13},\tau_{12}$

Gravitational wave detector

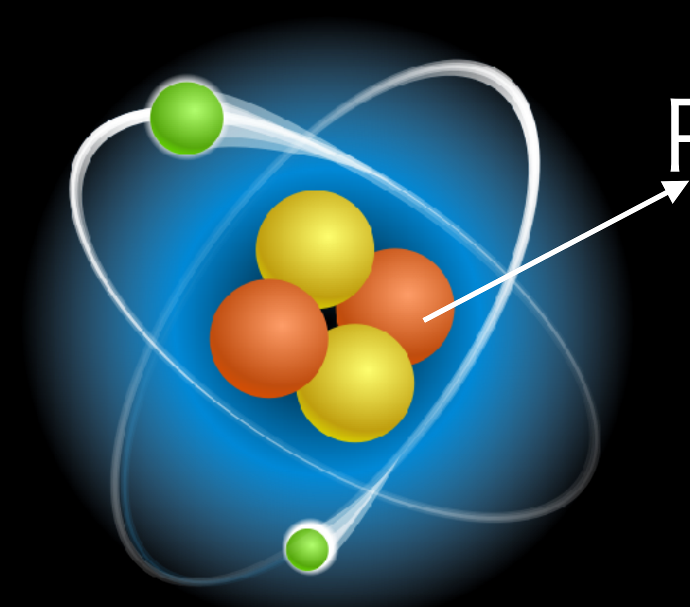
Typical gravitational wave strain sensitivity

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

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

→ $h \sim \delta L/L \sim 10^{-21}$

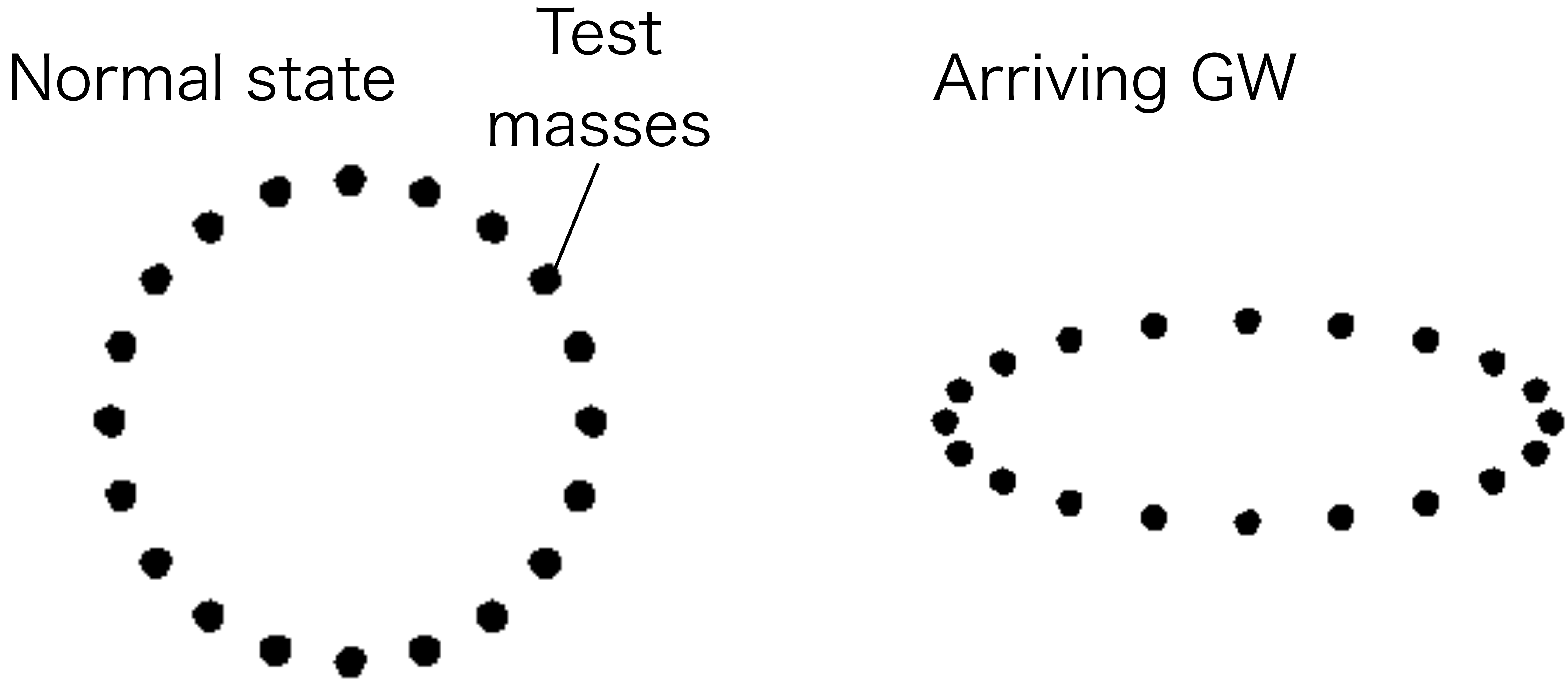
$\delta L \sim 2000\text{km} \times 10^{-21}$
$\sim 10^{-15}\text{m} \sim 1\text{fm}$



Proton radius

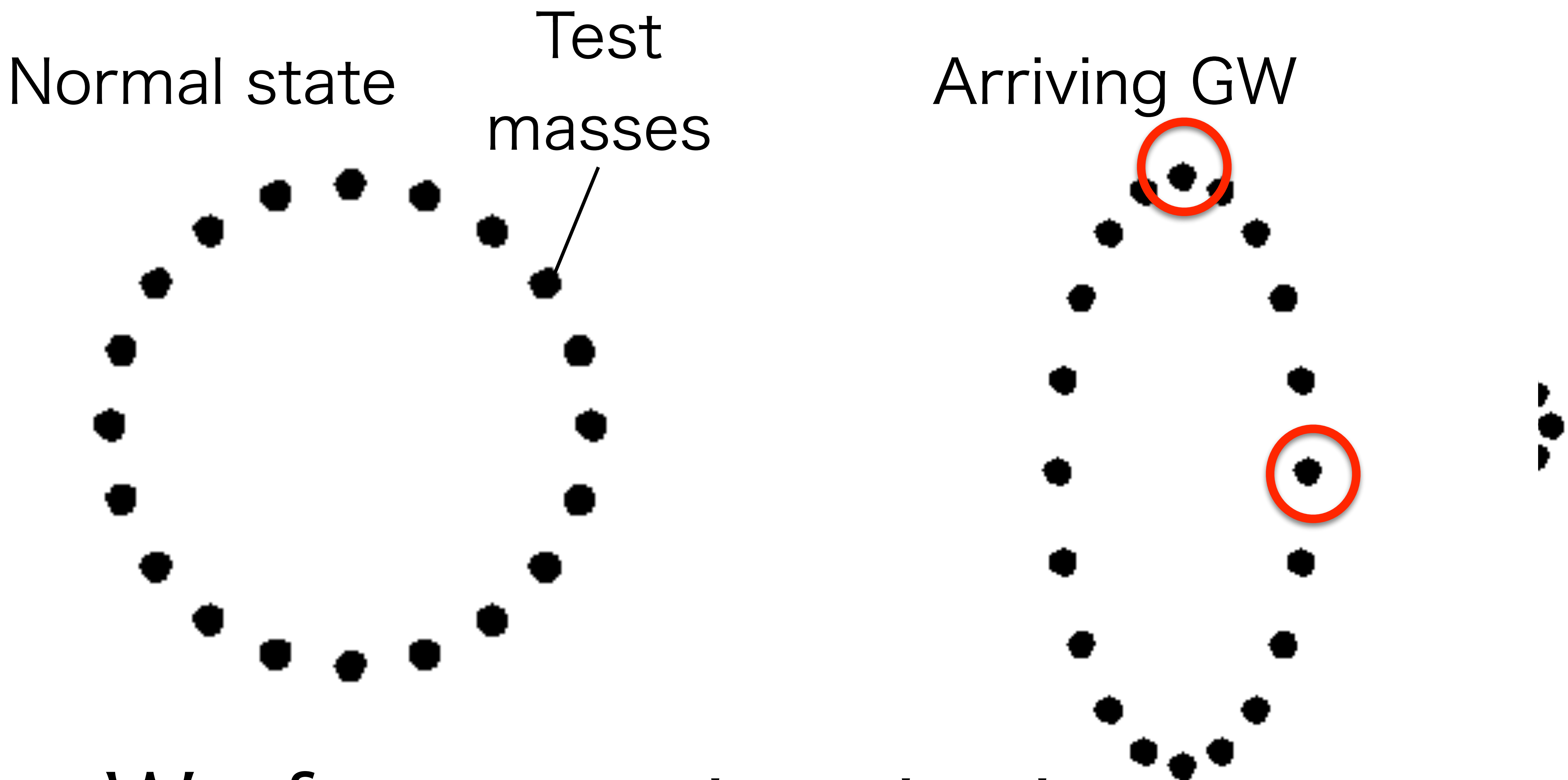
Amplitude of GW is very tiny

Principle of Observation



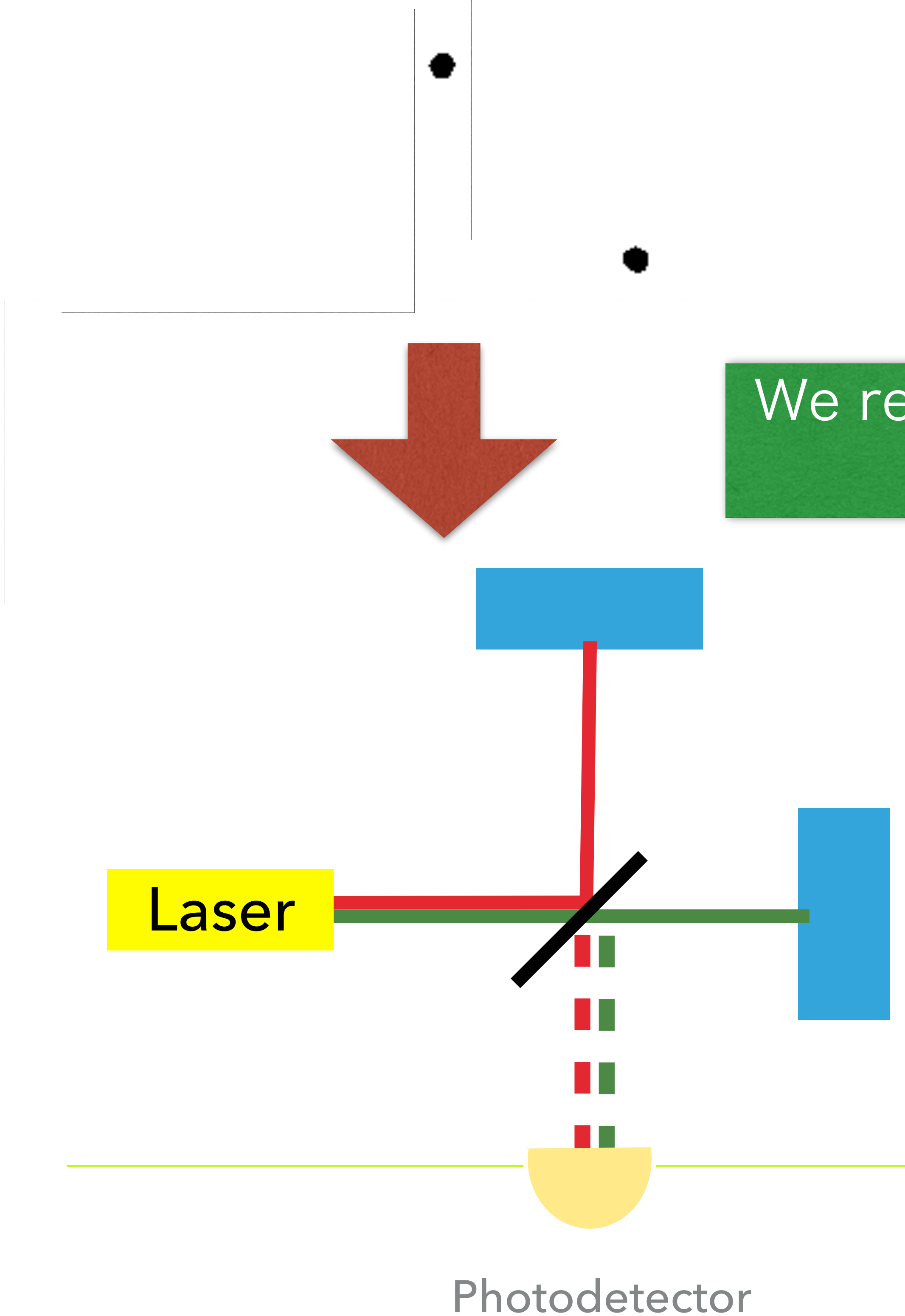
Test masses are moved by GWs.

Principle of Observation

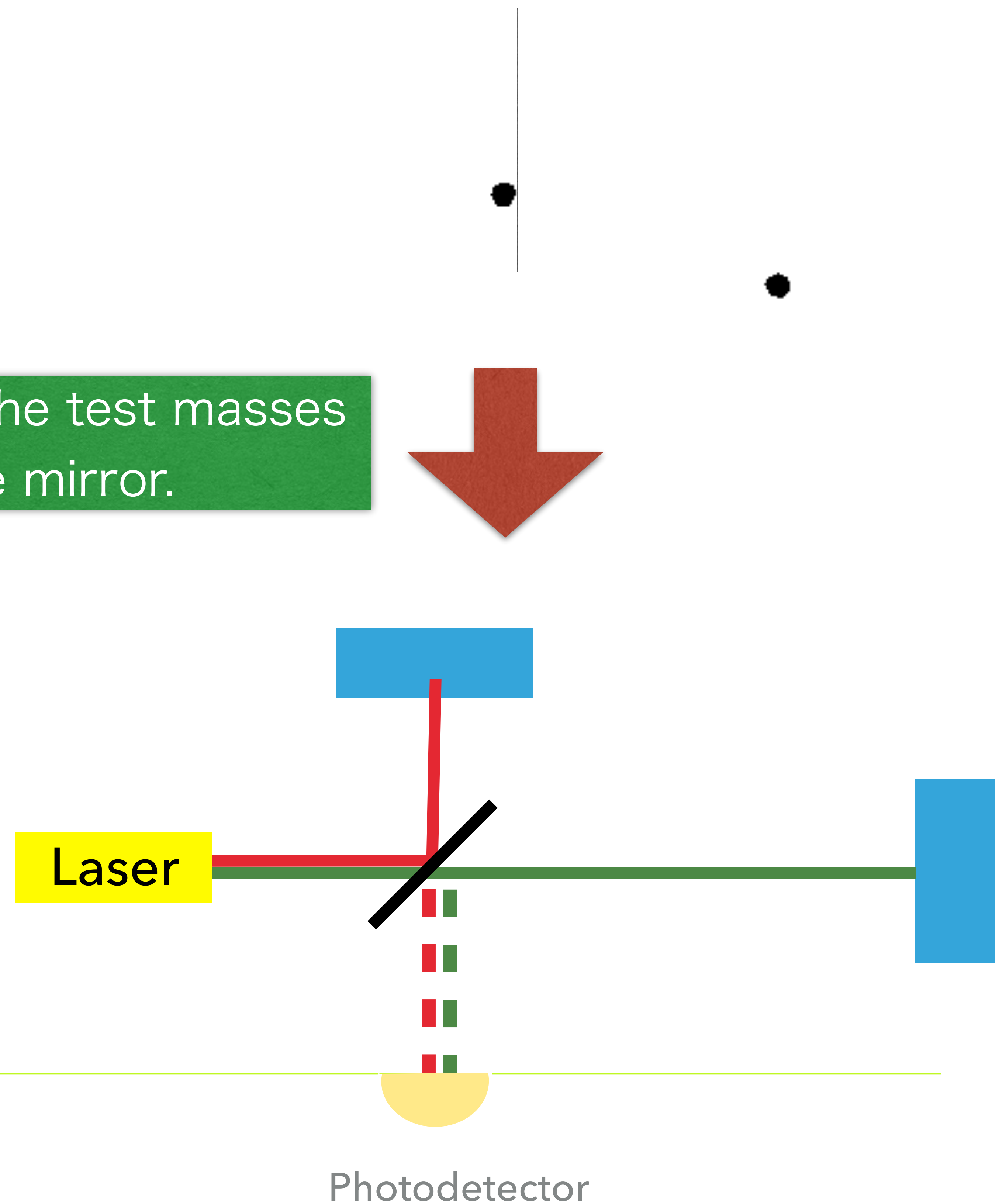


We focus on two test masses.

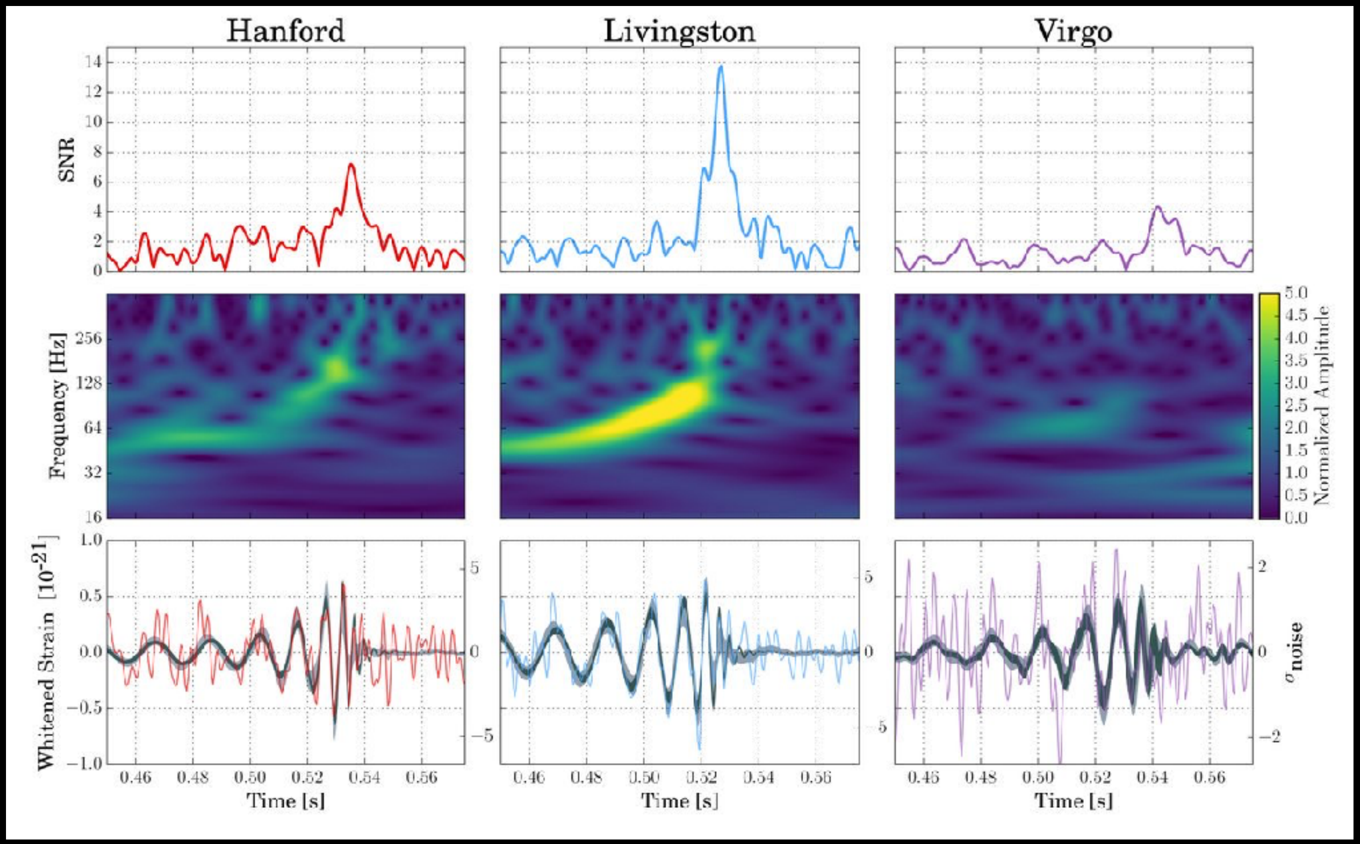
Principle of Observation

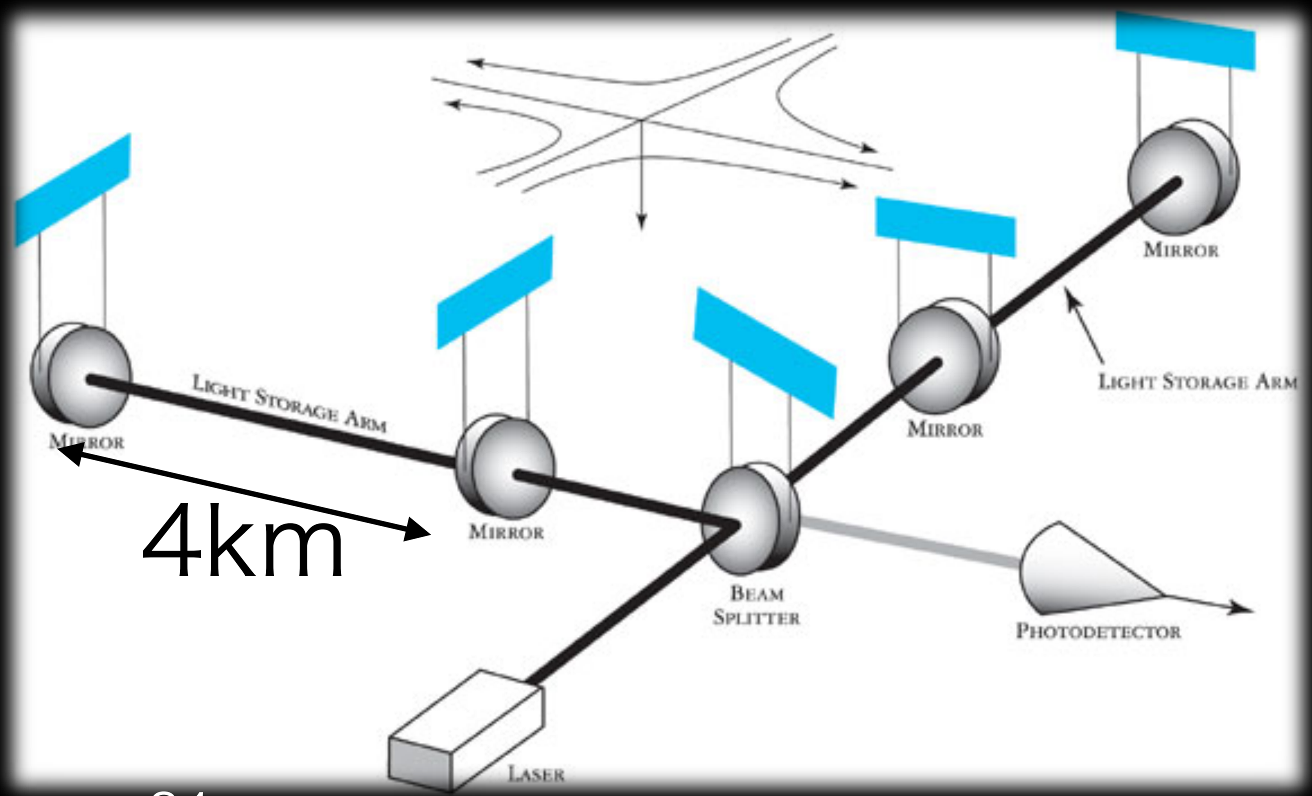


We replace the test masses to the mirror.



LIGO and Virgo

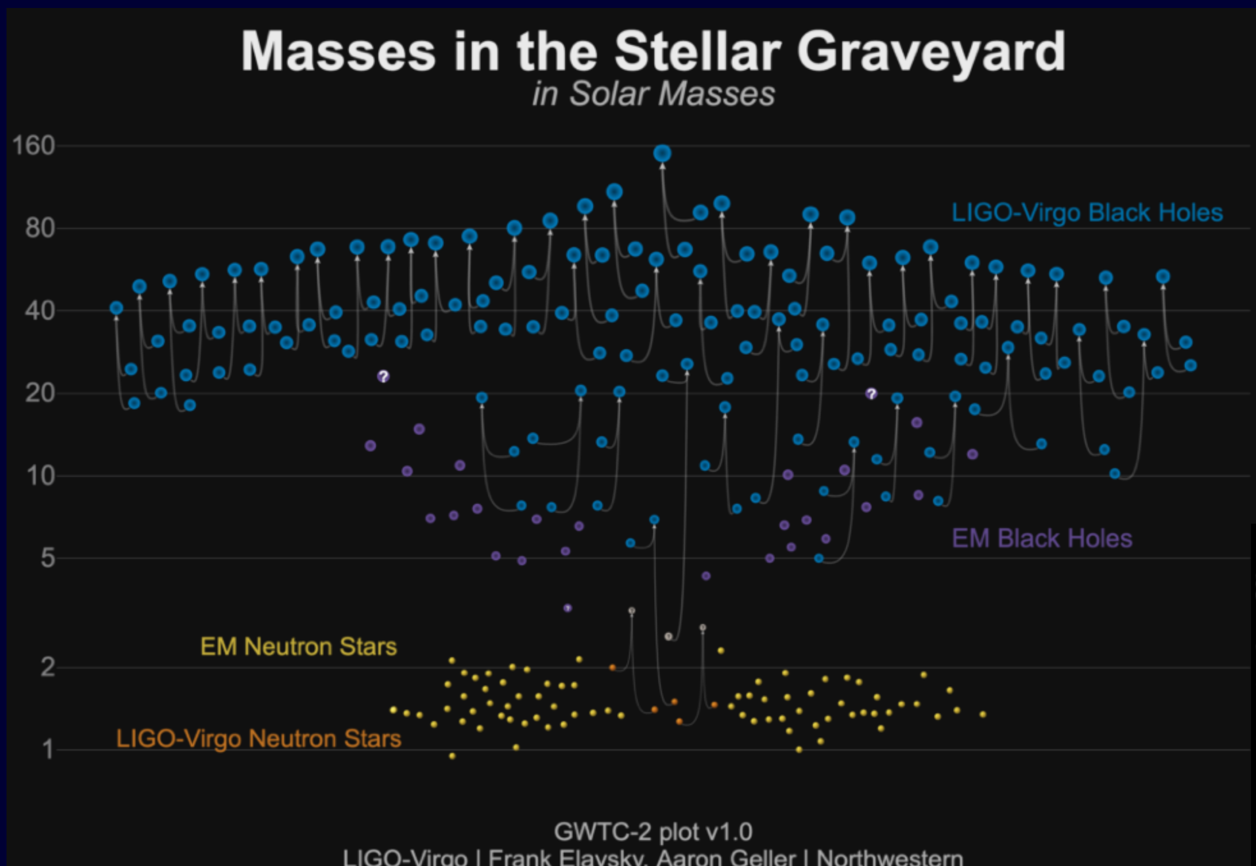


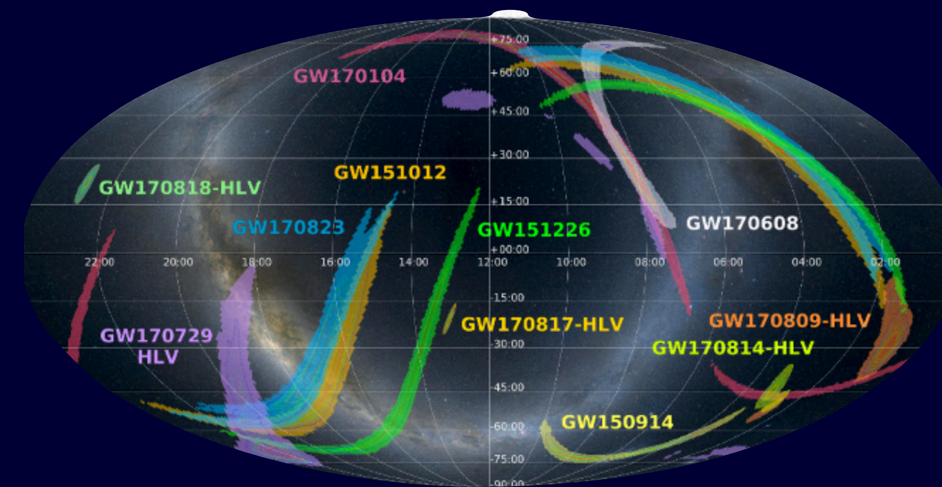


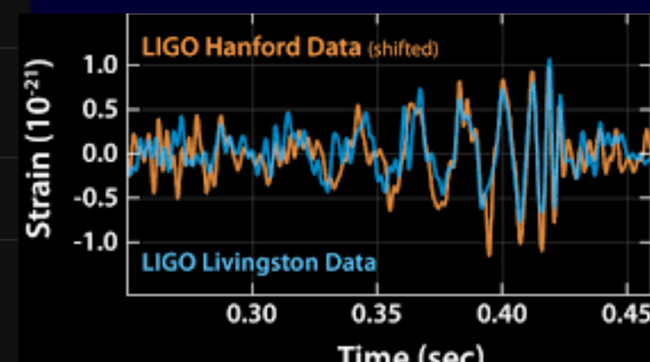
Overview of LIGO

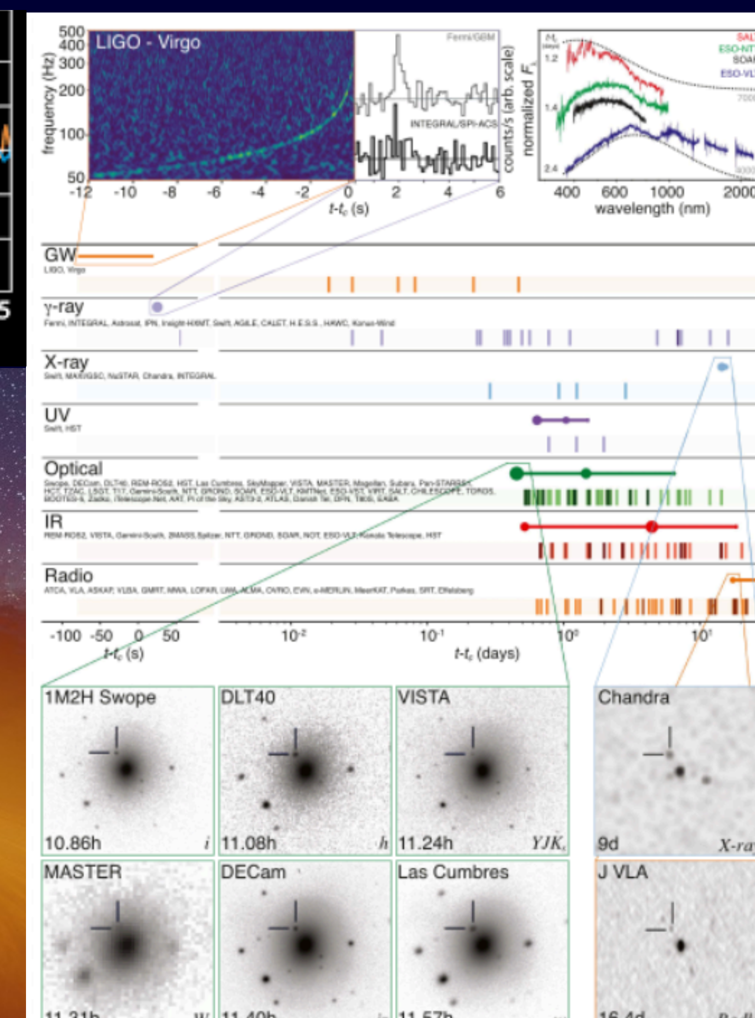
- LIGO is 2nd generation gravitational wave detector.
- They have two detector systems in Hanford and Livingston.
- 4km arm length interferometer

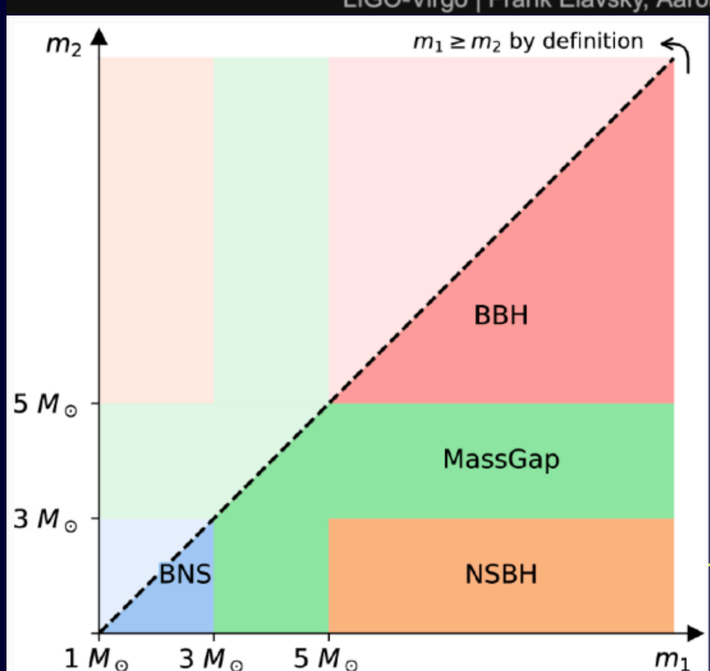
Science of LIGO

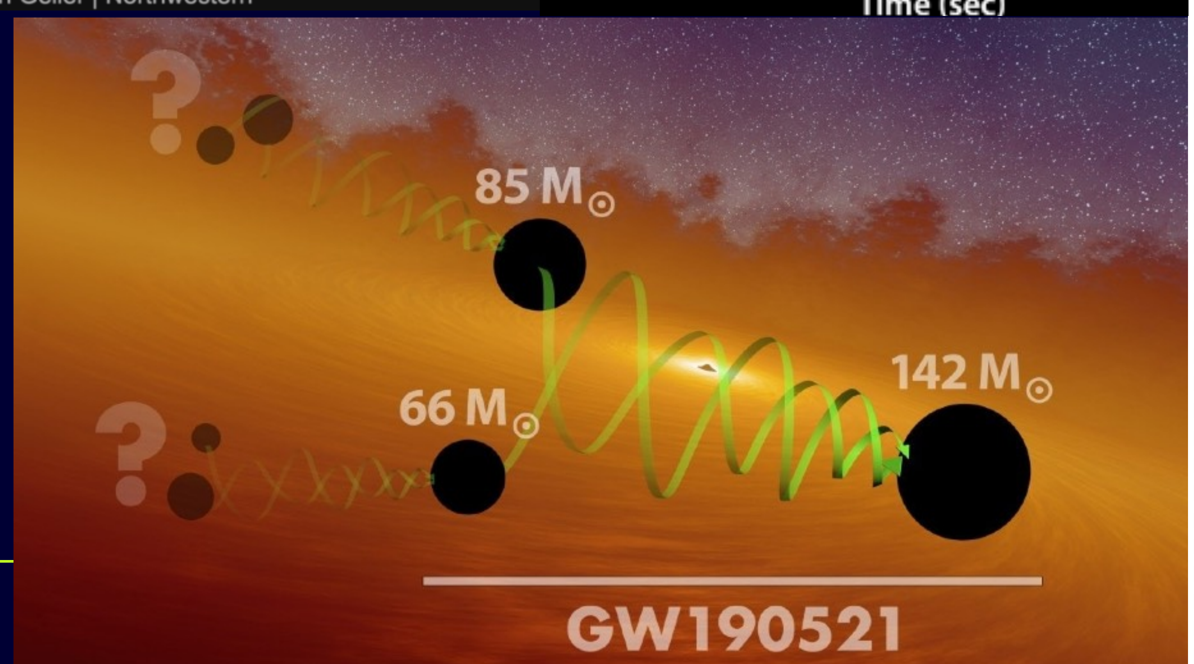




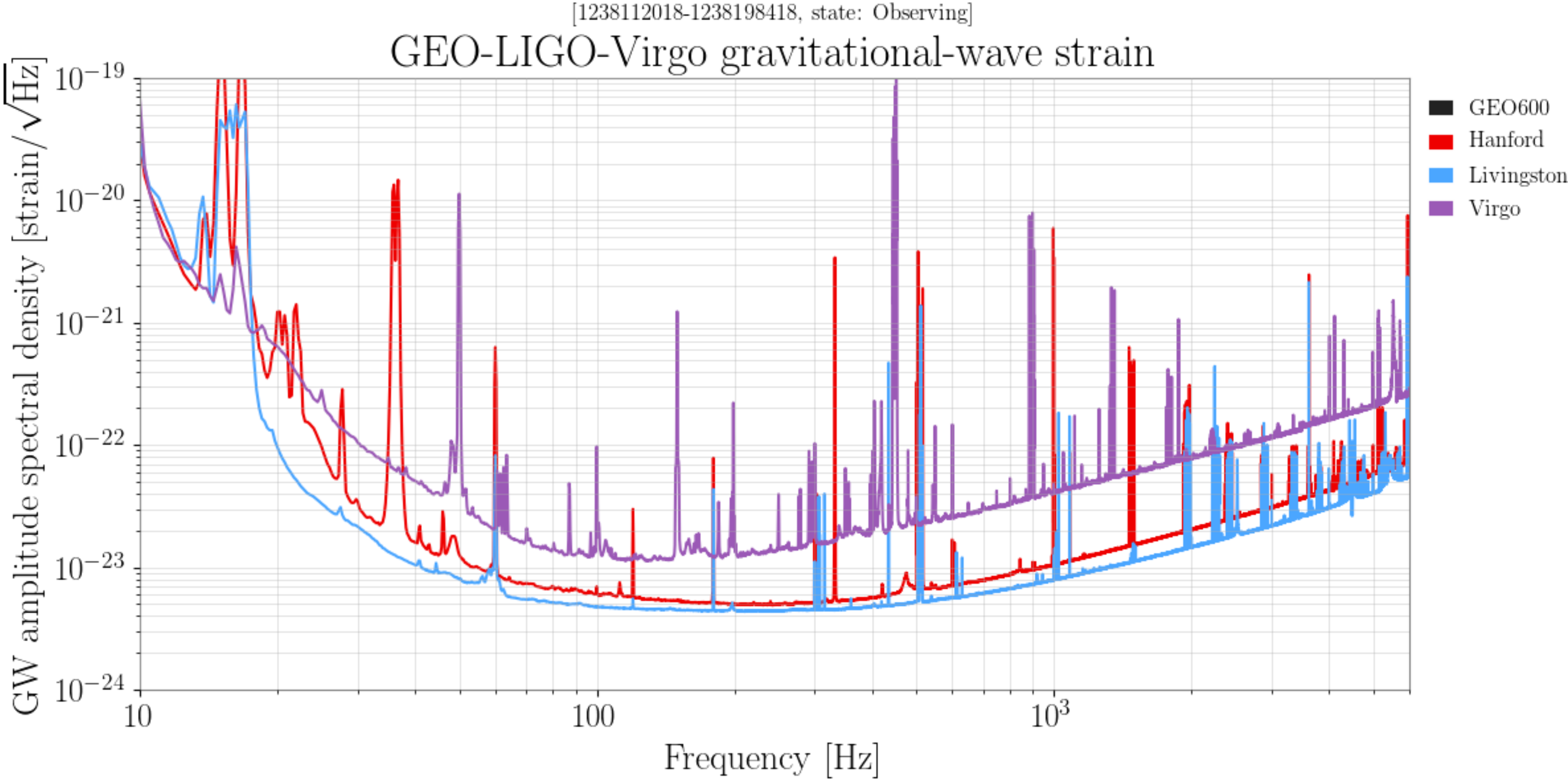




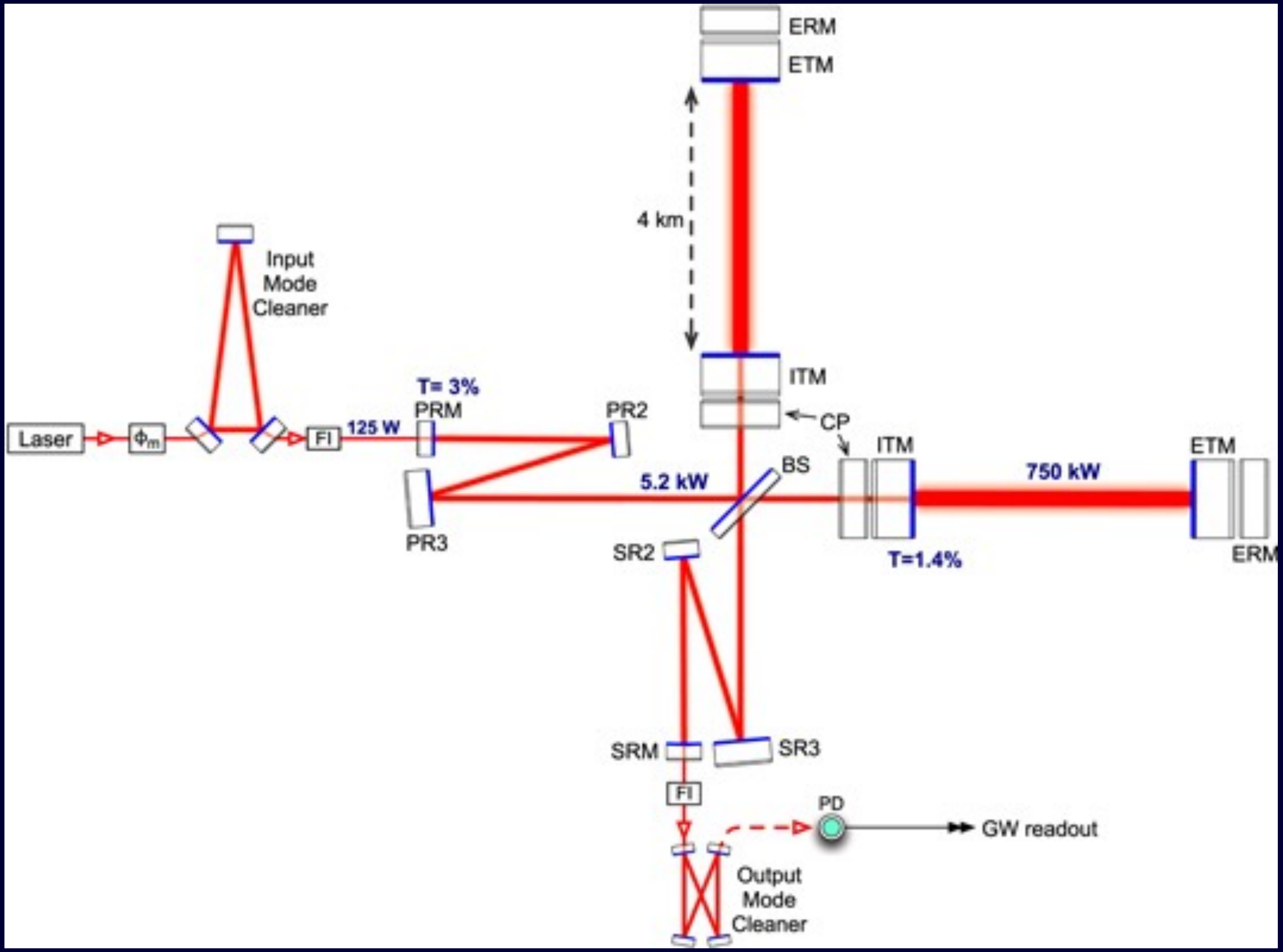




Sensitivity

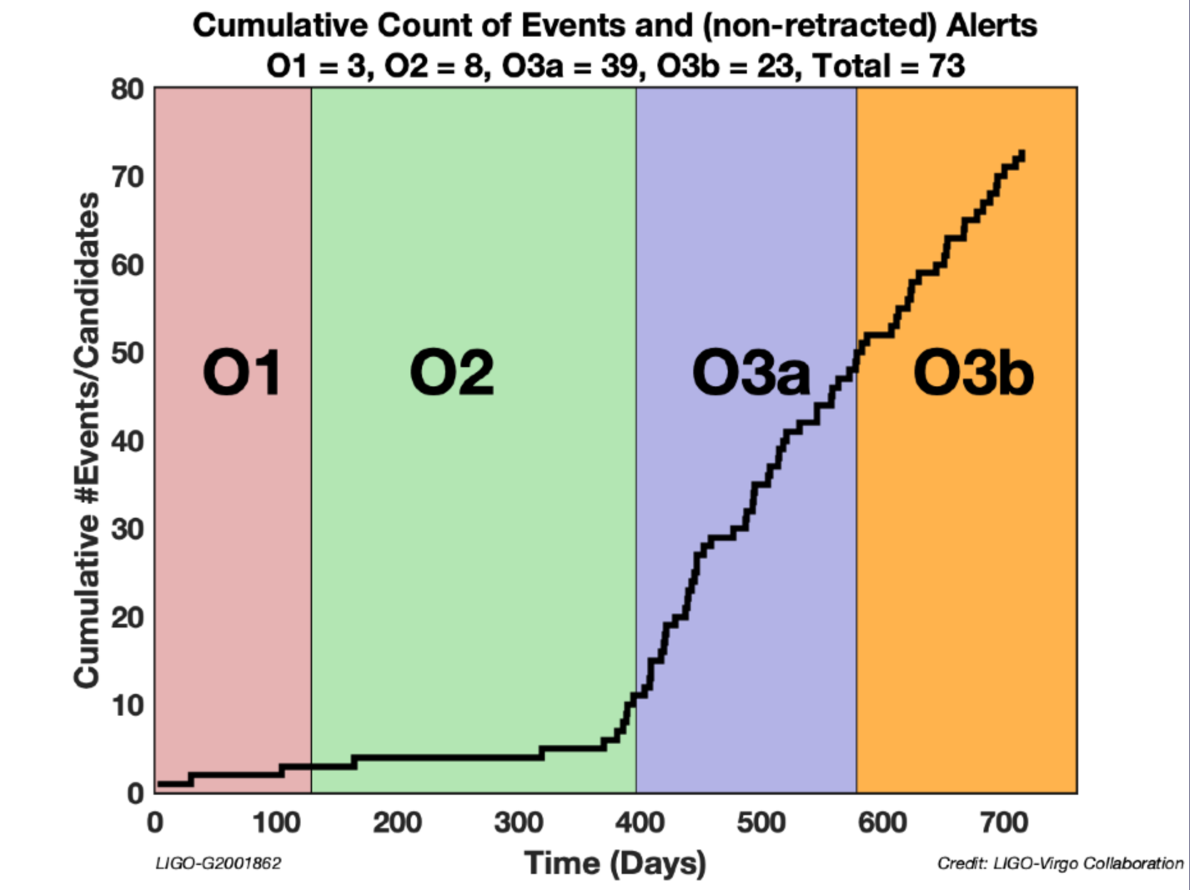


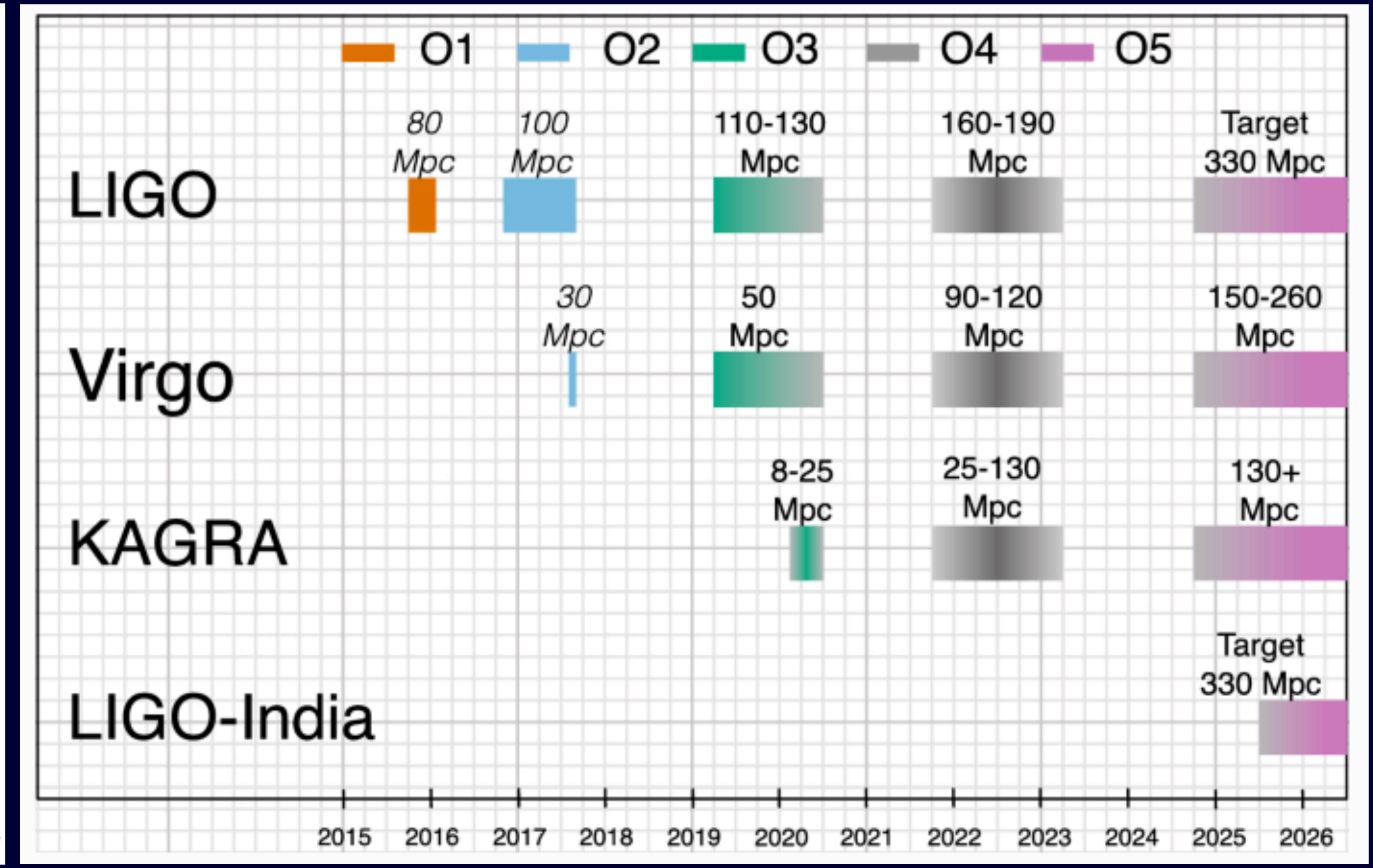
Interferometer



- Dual recycling Fabry Perot Michelson Interferometer

Observation history

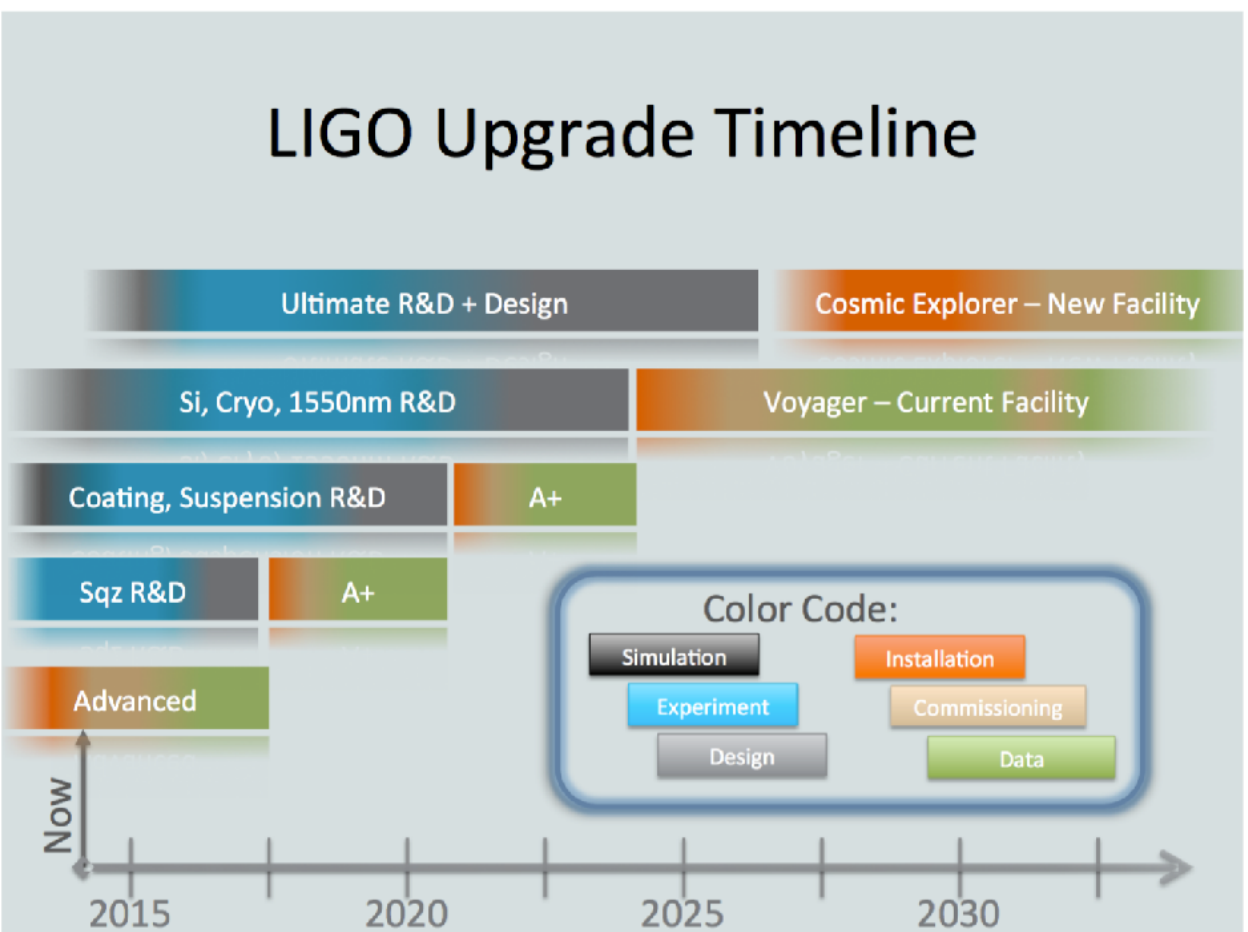


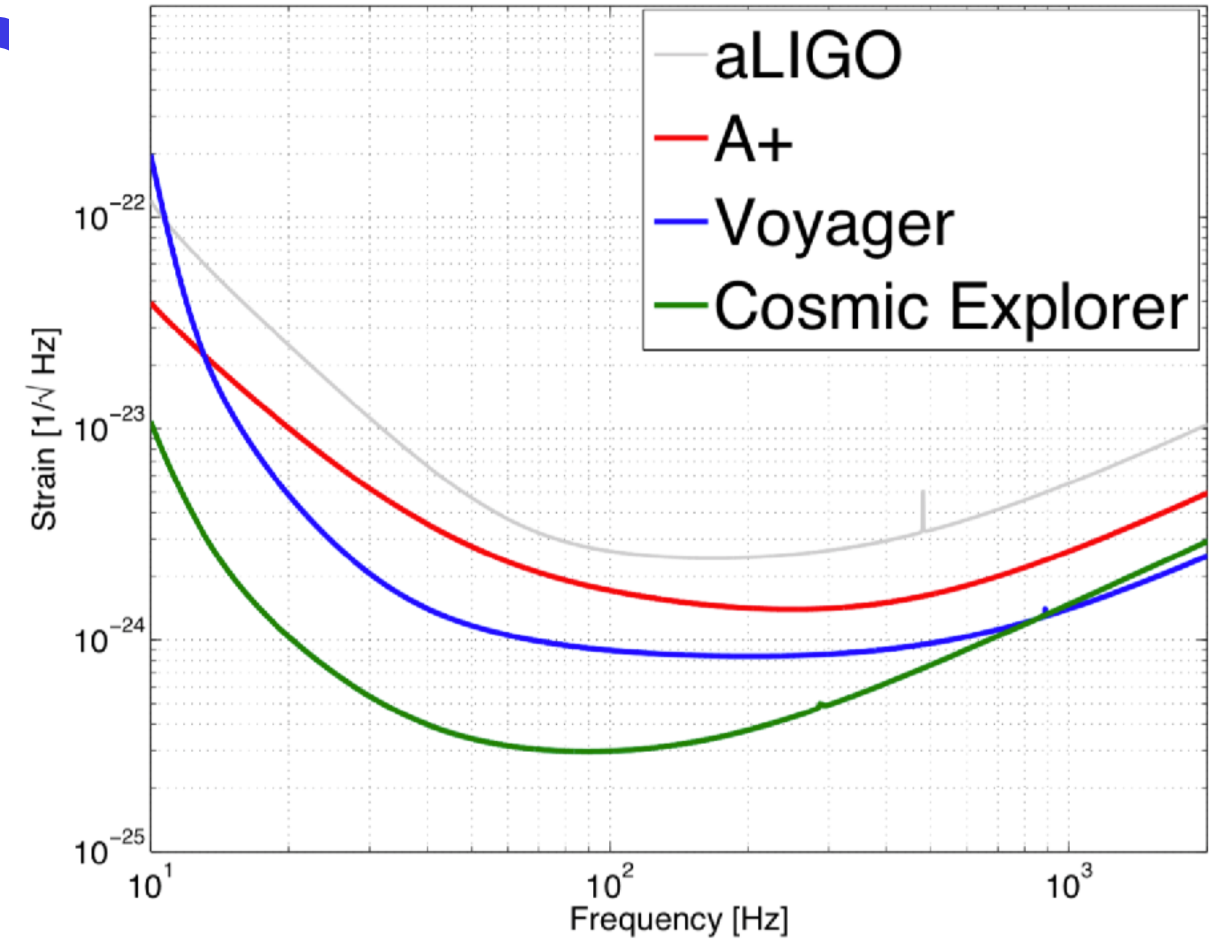


- Now is upgrade period for next observation
- Observation 4 will start from just one years later.

LIGO Voyager

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



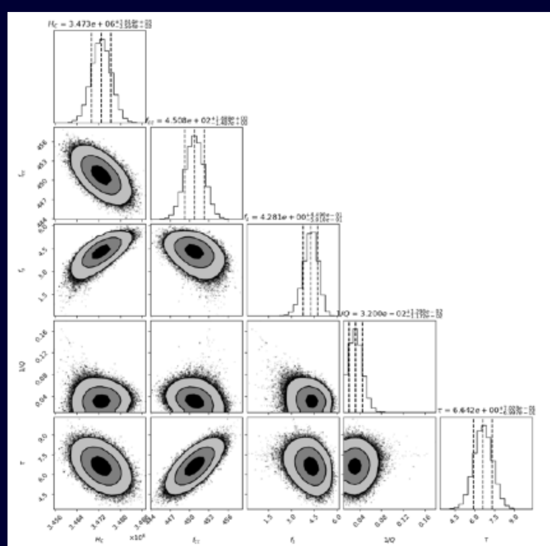


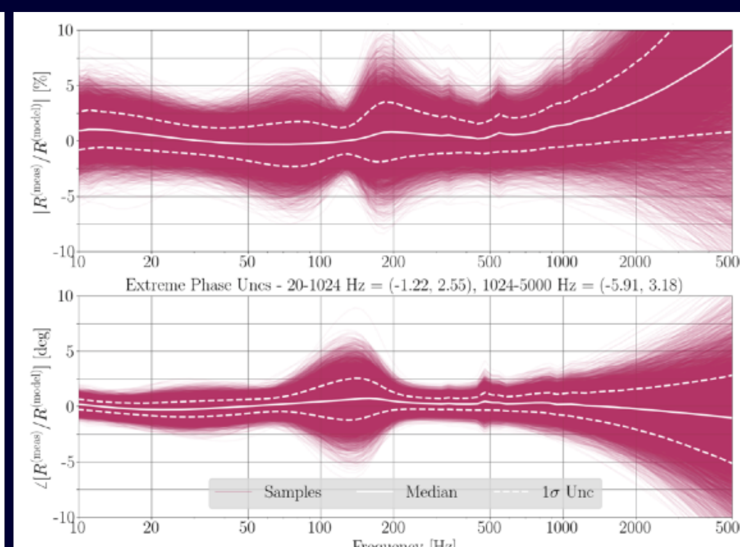
IFO Cases	aLIGO	A+	Voyager	Cosmic Explorer
Mirror Mass [kg]	40	80	160	80
Mirror Material	Silica	Silica	Silicon	Silica
Mirror Temp [K]	295	295	120	295
Sus Temp [K]	295	295	120	295
Sus Fiber	0.6m SiO_2	0.8m SiO_2	0.6m Si	0.8m SiO_2
Fiber Type	Fiber	Fiber	Ribbon	Fiber
Input Power [W]	125	125	450	125
Arm 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

Our Contributions

CALIBRATION FOR OBSERVATION 4

$$`h(t) + \sigma_h'$$



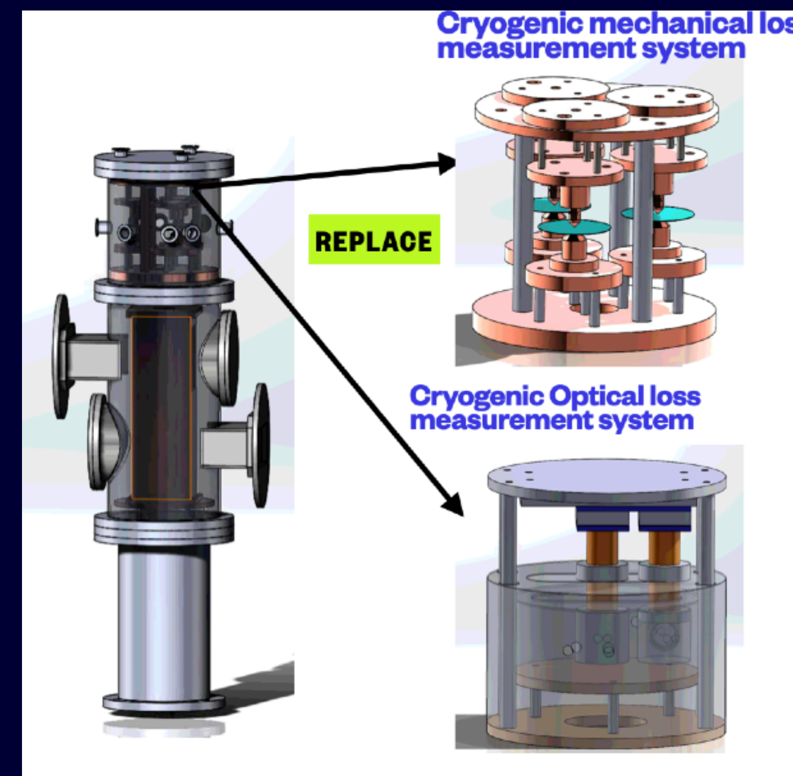


Contribute calibration of interferometer and reconstruction of h(t).

Development of error estimation pipeline.

Will provide hourly systematic error for all corroborators.

COATING FOR LIGO VOYAGER

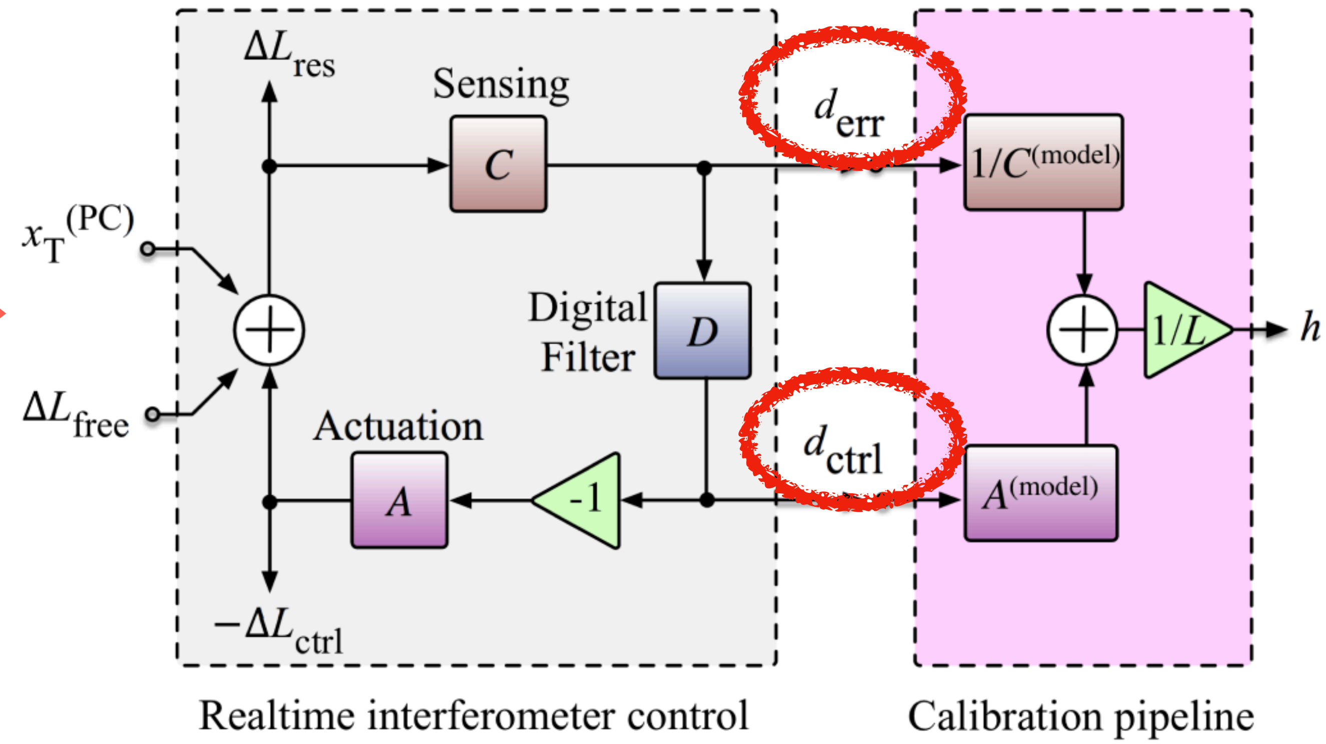


Coating properties are strongly depends on the sensitivity of detector.

But, LIGO need to prepare the cryogenic characterization system.

AS is developing new system with cryogenic technology.

Modeling of Interferometer



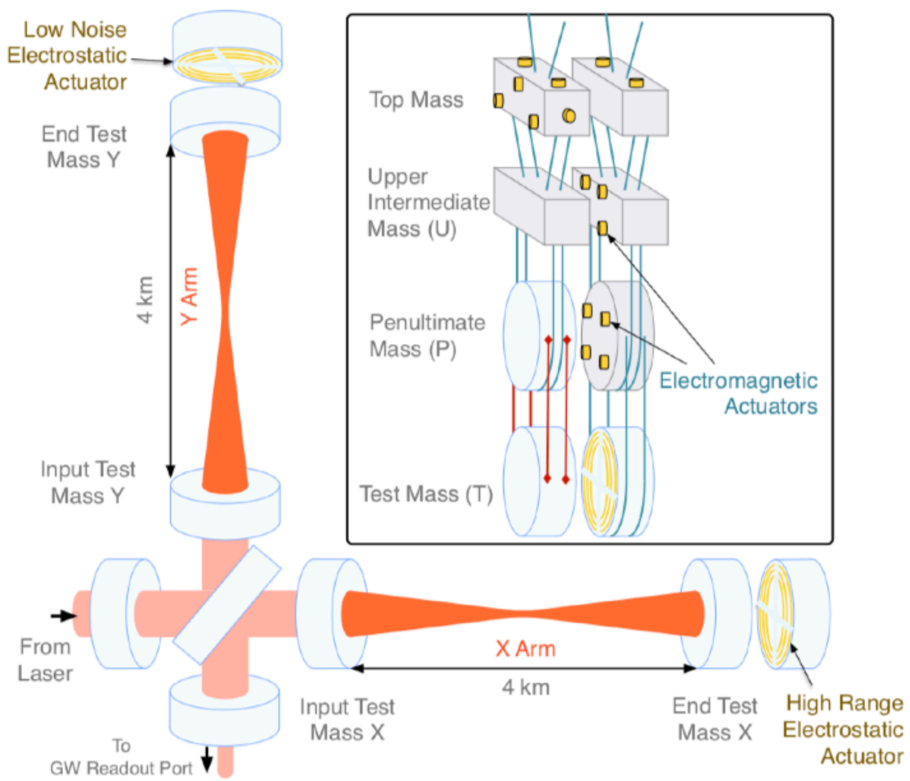
Changes of arm length are measured between Actuator and Detector

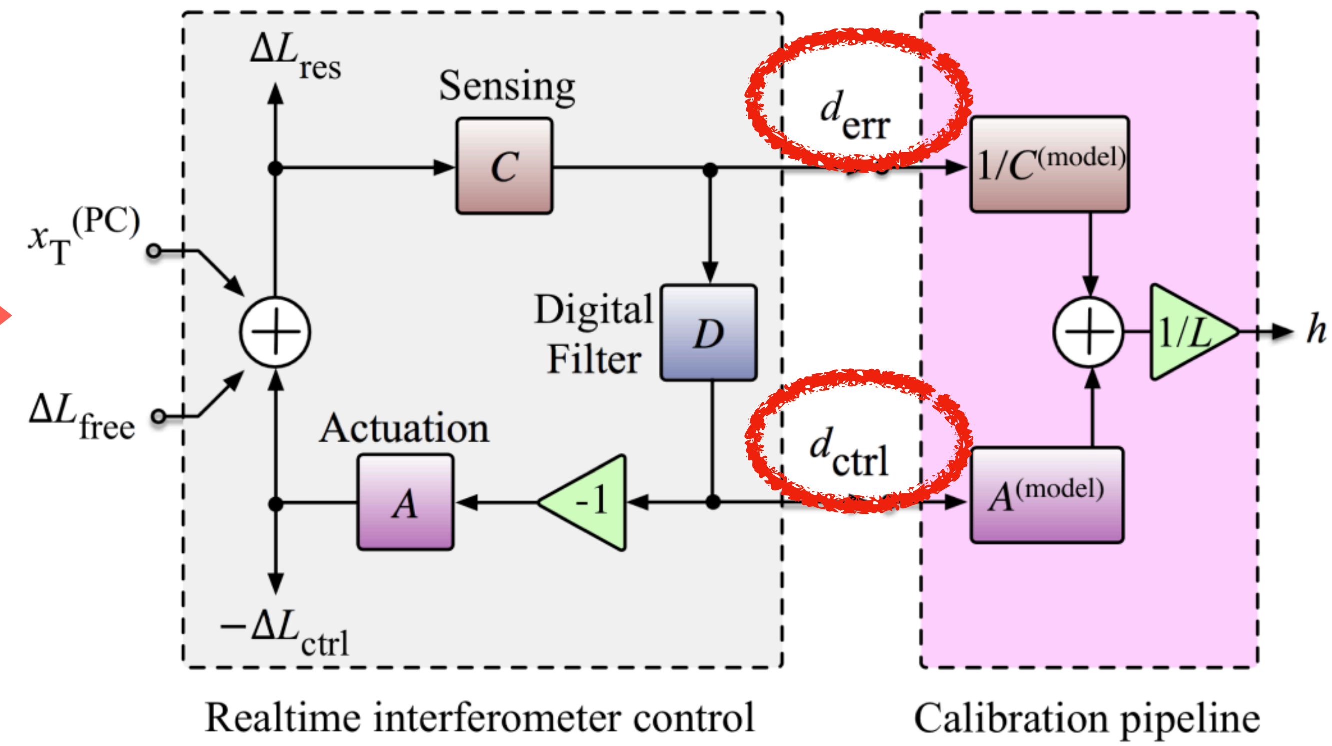
So, we can separate A and C part by estimation accurate model of A and C

→ Definition of Calibration：Parameter estimation of A and C

→ Definition of Reconstruction：Calculation from interferometer response

Modeling of Interferometer





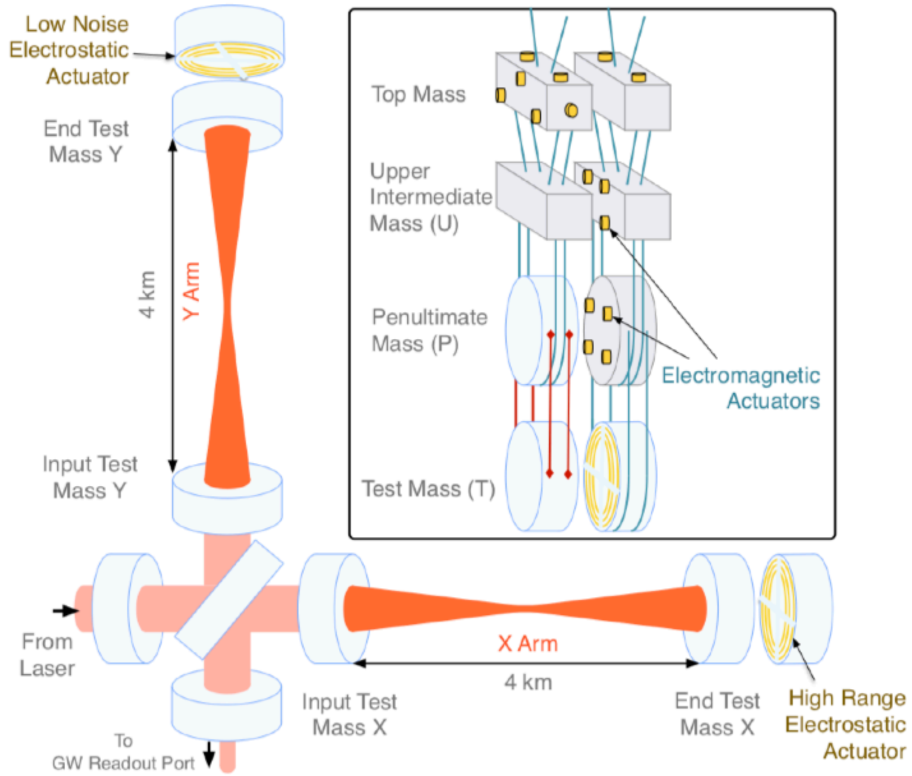
Changes of arm length are measured between Actuator and Detector

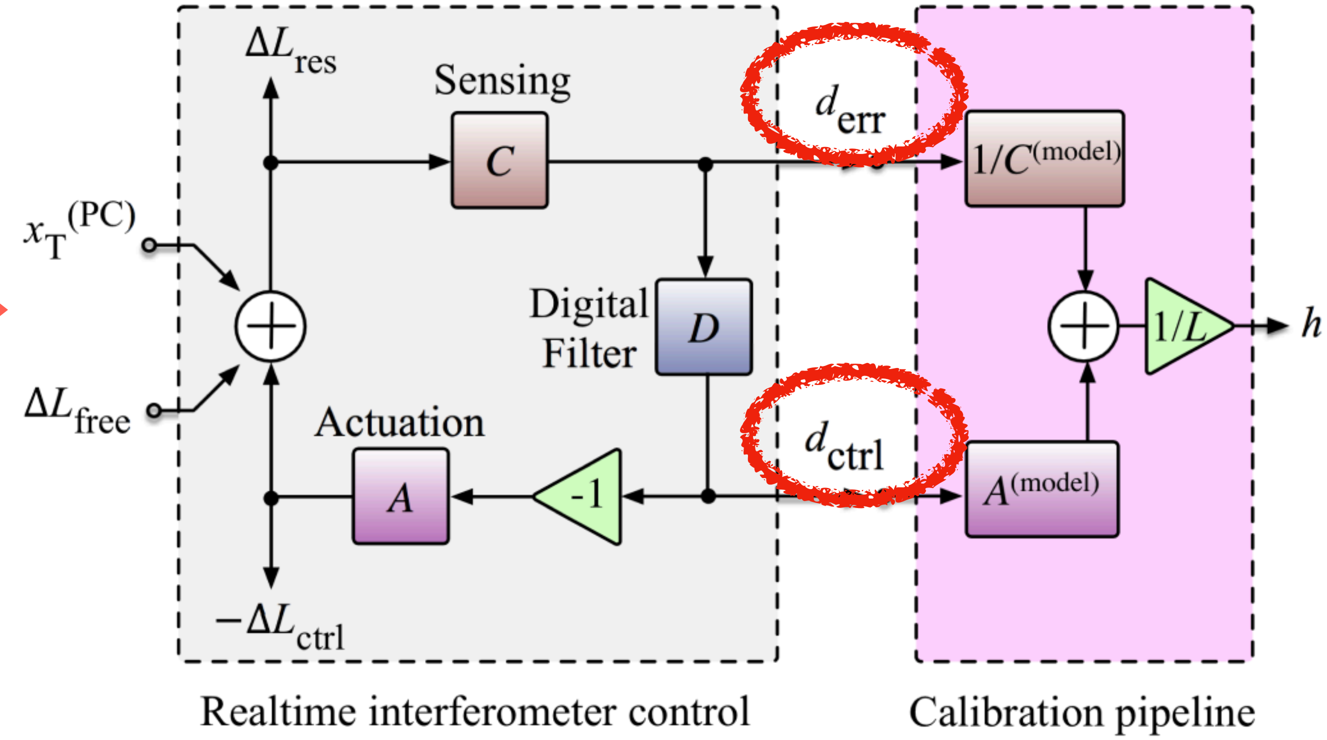
So, we can separate A and C part by estimation accurate model of A and C

→ Definition of Calibration : Parameter estimation of A and C

→ Definition of Reconstruction : Calculation from interferometer response

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

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

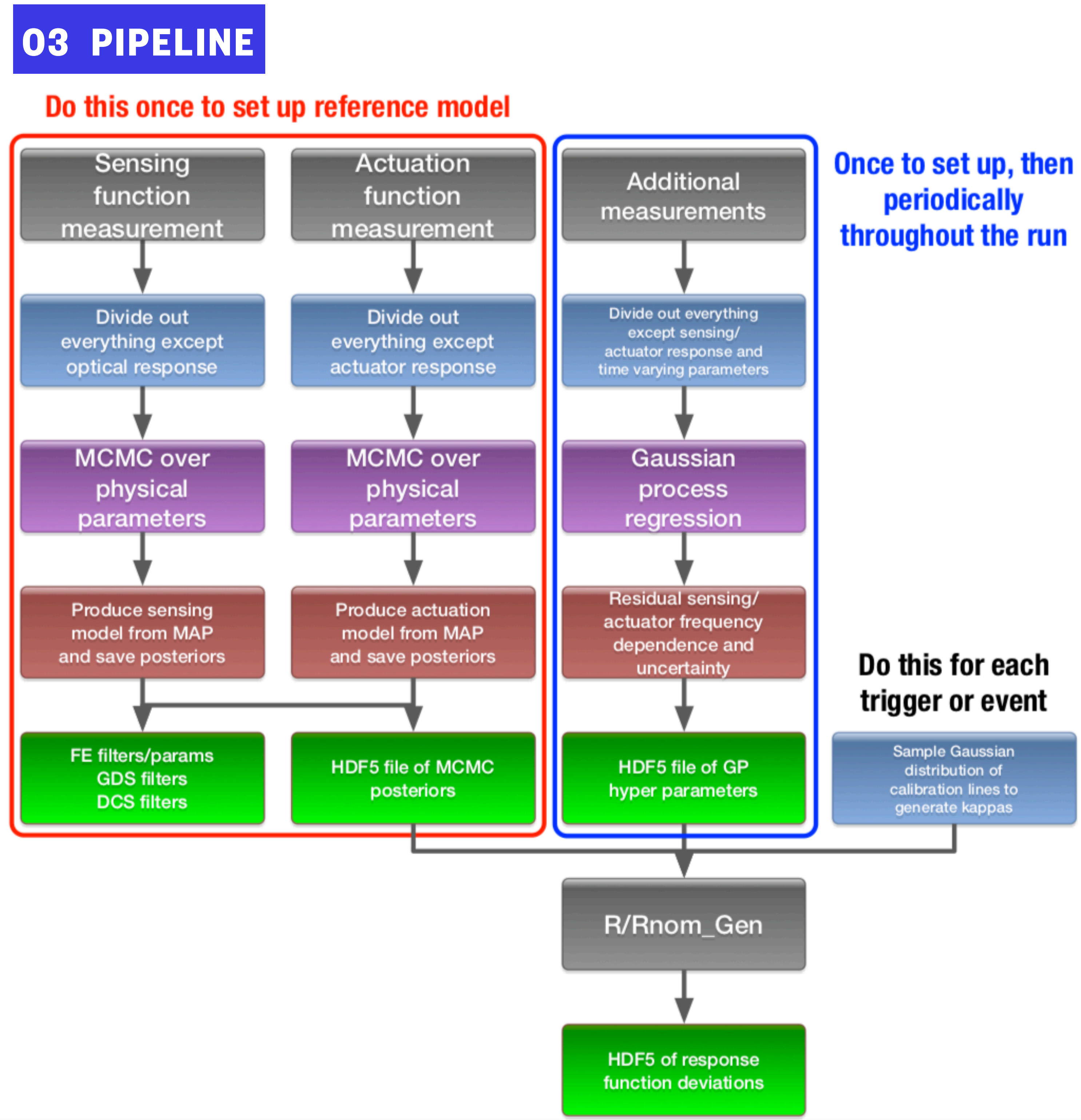
h(t) Reconstruction Pipeline

- “Control room calibration”
  - IIR filter
  - No-delay
- Low-latency (LIGO calls this C00)
  - IIR+FIR filter
  - 10sec delay
- Offline (high-latency, C01+)
  - Full FIR filter
  - several month delay

Development of pyDARM

pyDARM

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

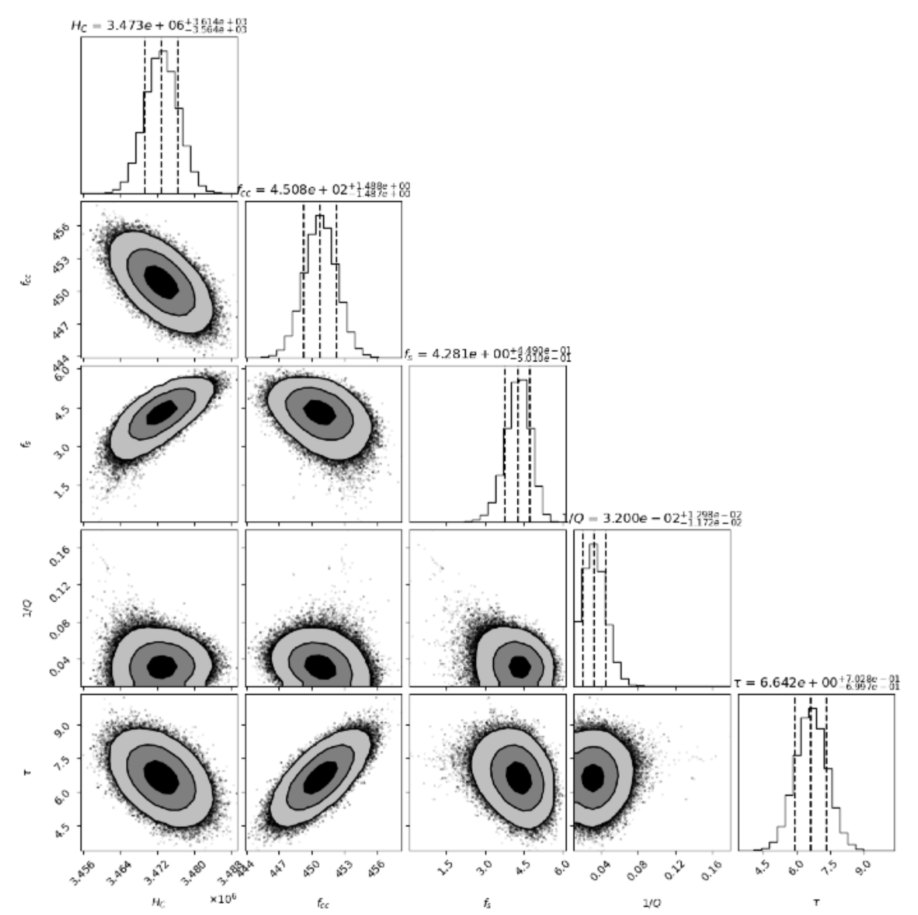


History of pyDARM

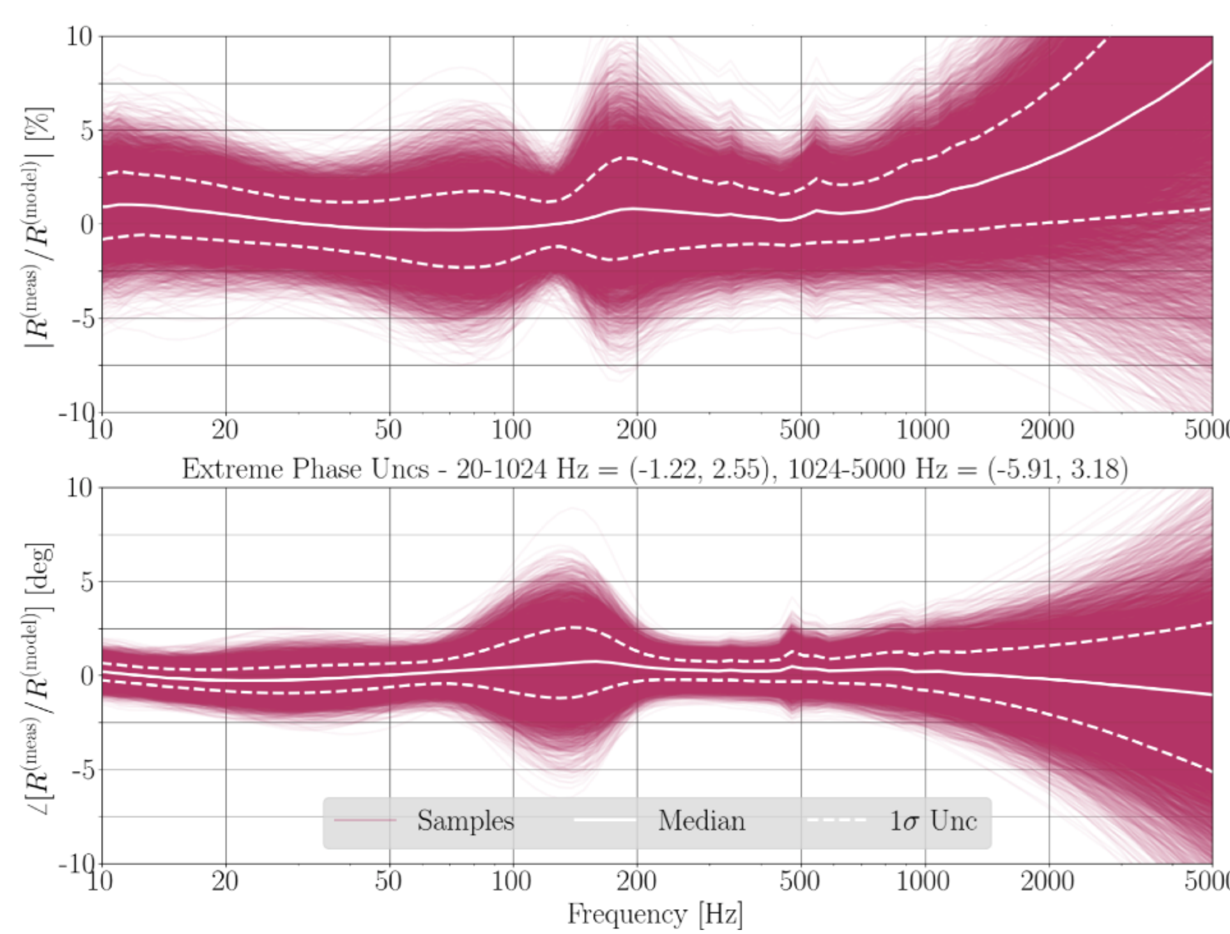
- O1: Matlab model only, simplified error analysis
- O2: Combination of Matlab and python codes used for modeling, filter generation, error/uncertainty (Bayesian) estimation
- O3: pure python codebase, but awkward to use (not modular, not easily extendable, doesn't integrate well, etc.)
- Plan for O4: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

Calibration error envelop

CALIBRATION PARAMETER ESTIMATION

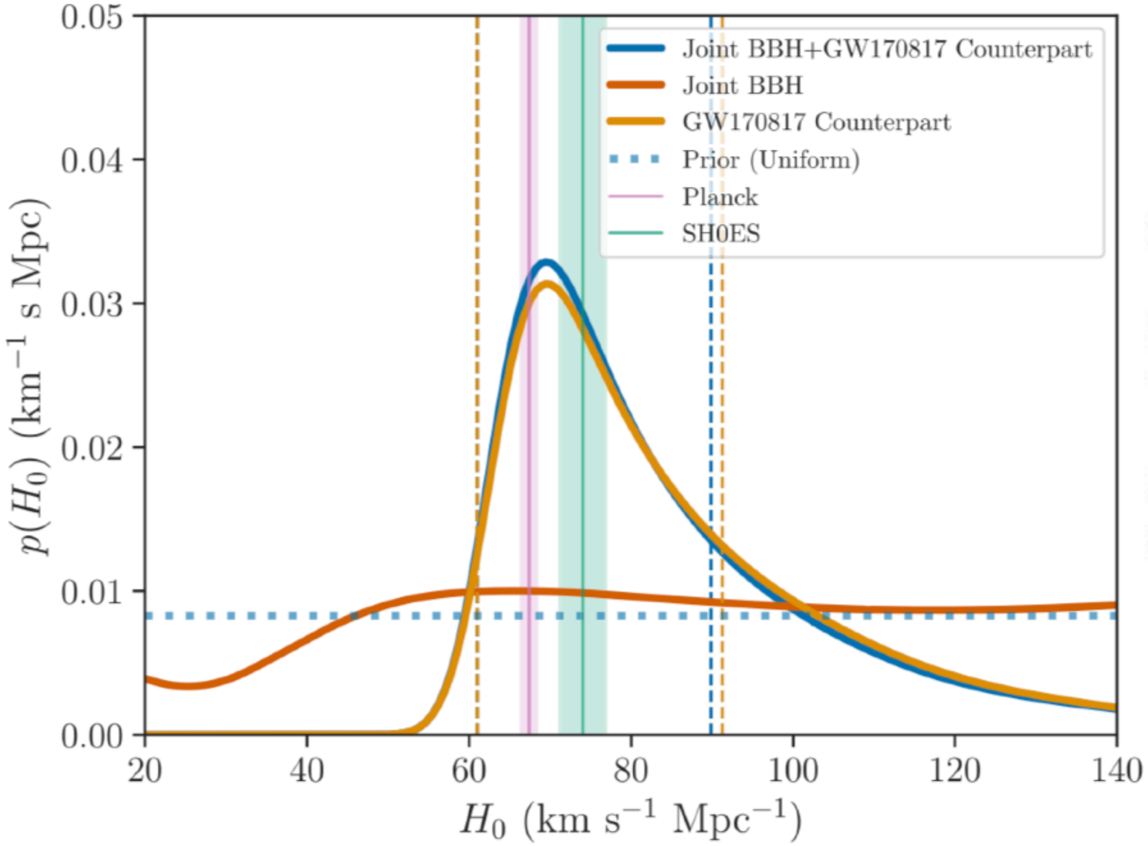


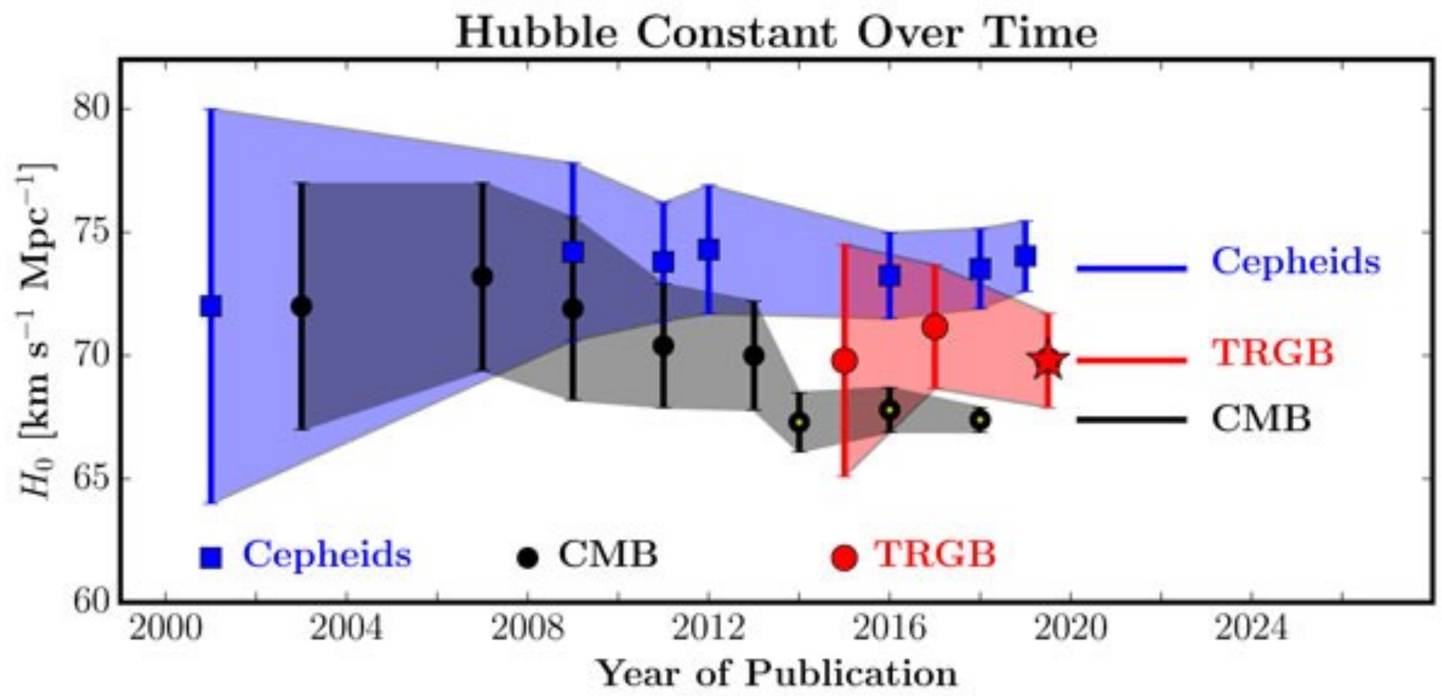
CALIBRATION ERROR OF STRAIN SENSITIVITY



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

Impact for cosmology





- Absolute amplitude uncertainty of h(t) corresponds to Distance uncertainty.
- To reduce the absolute uncertainty, we need to reduce the uncertainty of calibrator.
- We employ gravity and photon pressure method to cross check the systematic uncertainty.
-

https://arxiv.org/abs/1907.09897

https://arxiv.org/pdf/2009.10193.pdf

Procedure of technical demonstration in LIGO

TEST FACILITYIES

US

CAHTECH 40M

EU

GEO600

GLASGOW 10M

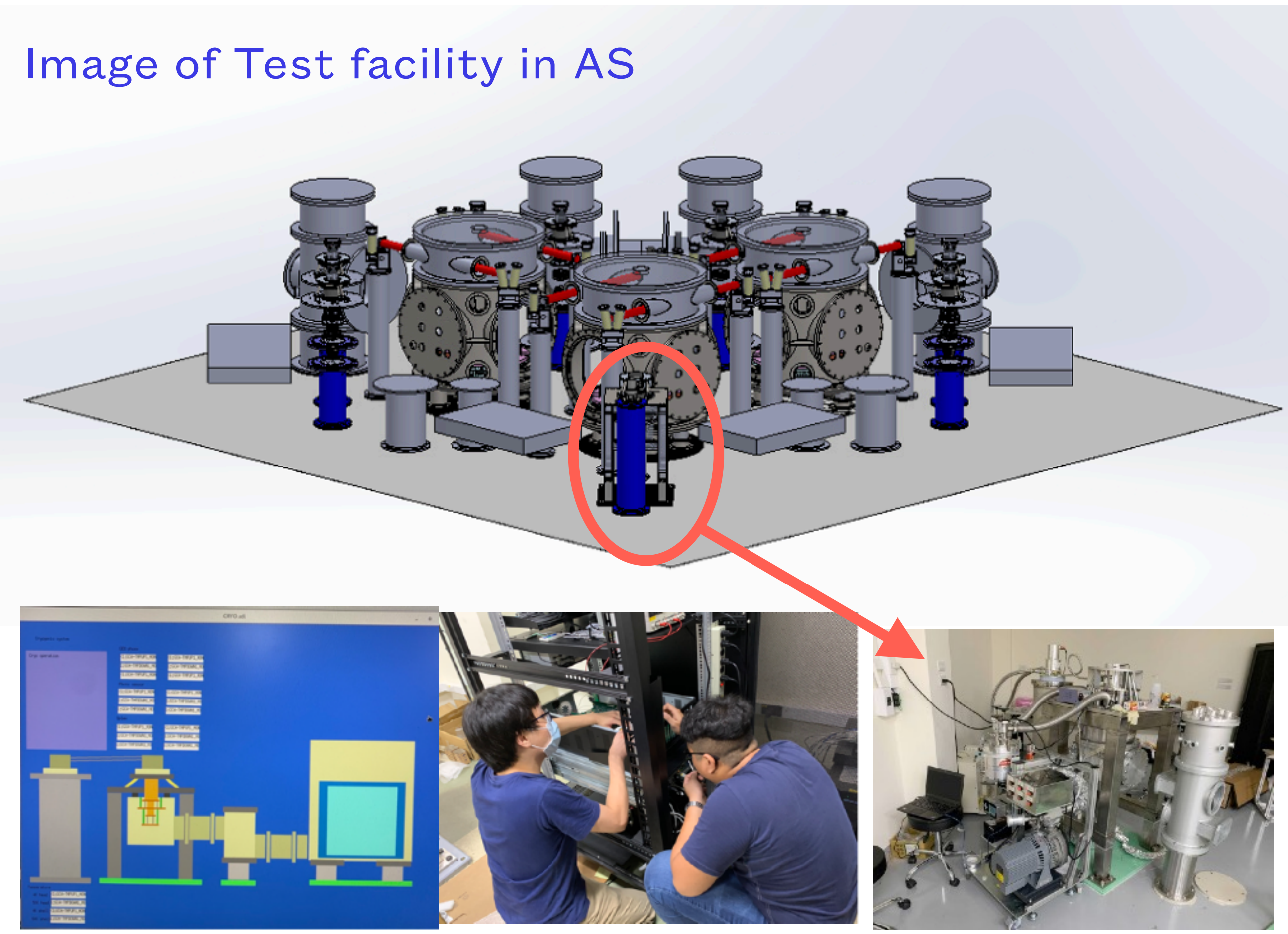
ASIA

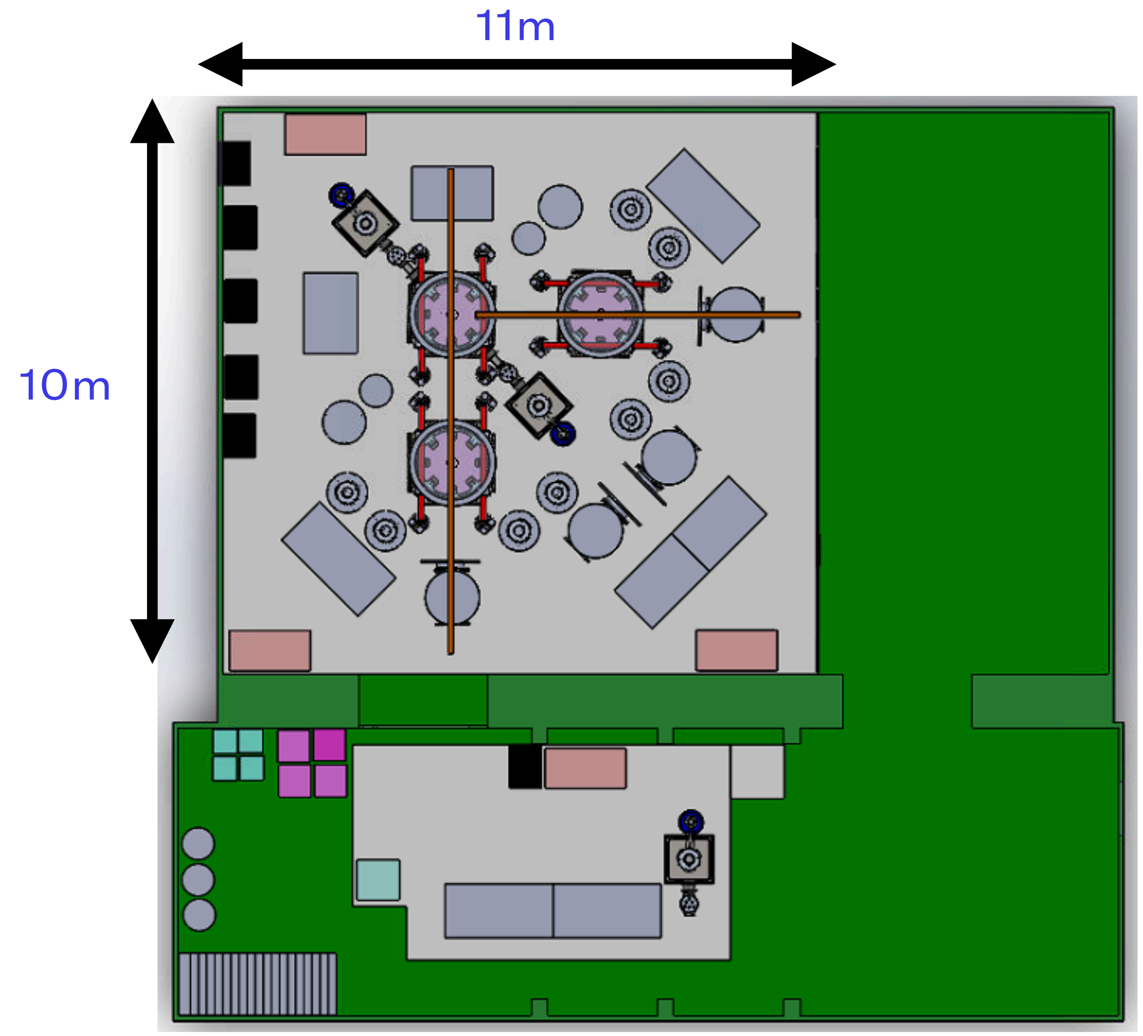
There is no test facility of LIGO in Asia for the test of technology!

LIGO HANFORD OBSERVATORY

LIGO LIVINGSTON OBSERVATORY

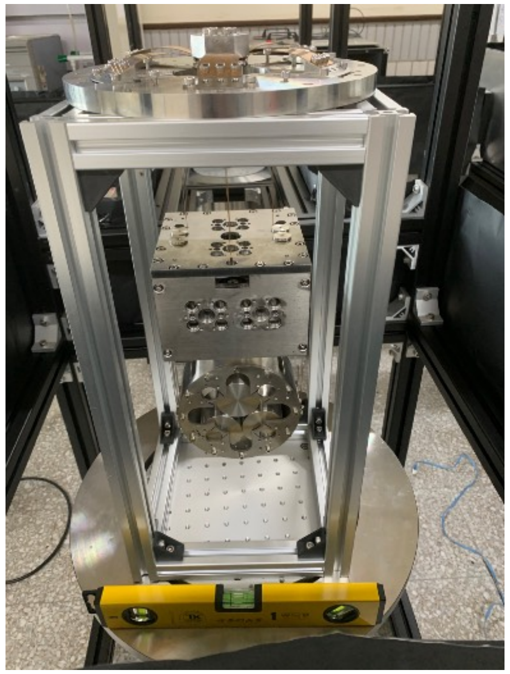
B1 - Test facility construction in ASIoP

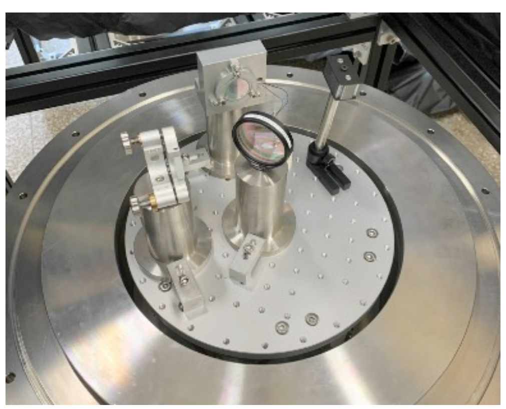




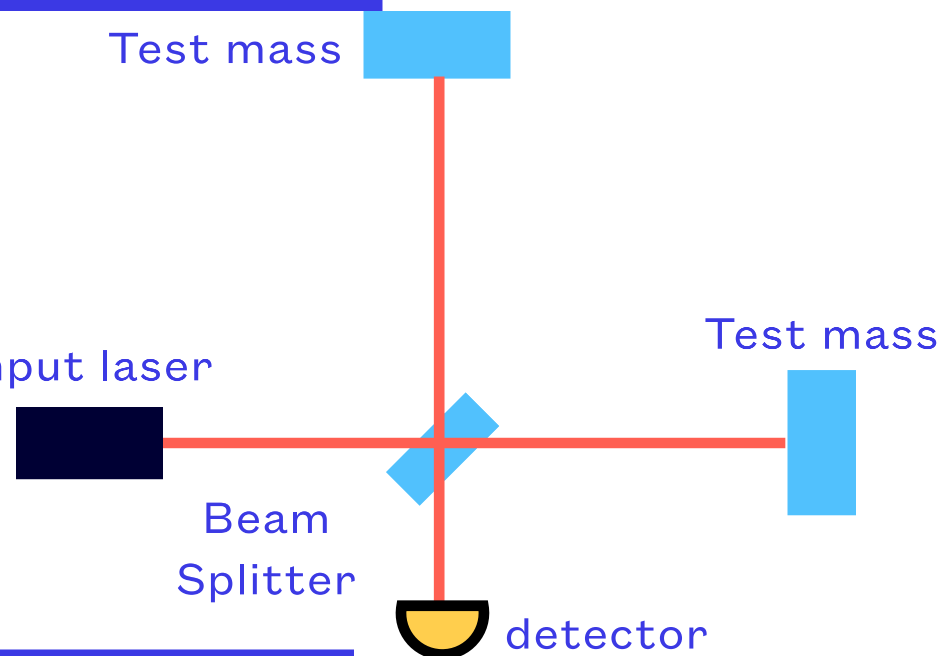
- To test the principle of new technology and principle of exotic science, we are developing small interferometer system in Academia Sinica
- Designing and Testing of Cryogenic system + O(10 m) size interferometer
- Clean room
- Main purpose is the verification of future technologies (Supported by Vanguard program in MOST).
- Construction proposal was approved in ASIOP. We will build it from next Spring.

Interferometer in NCU

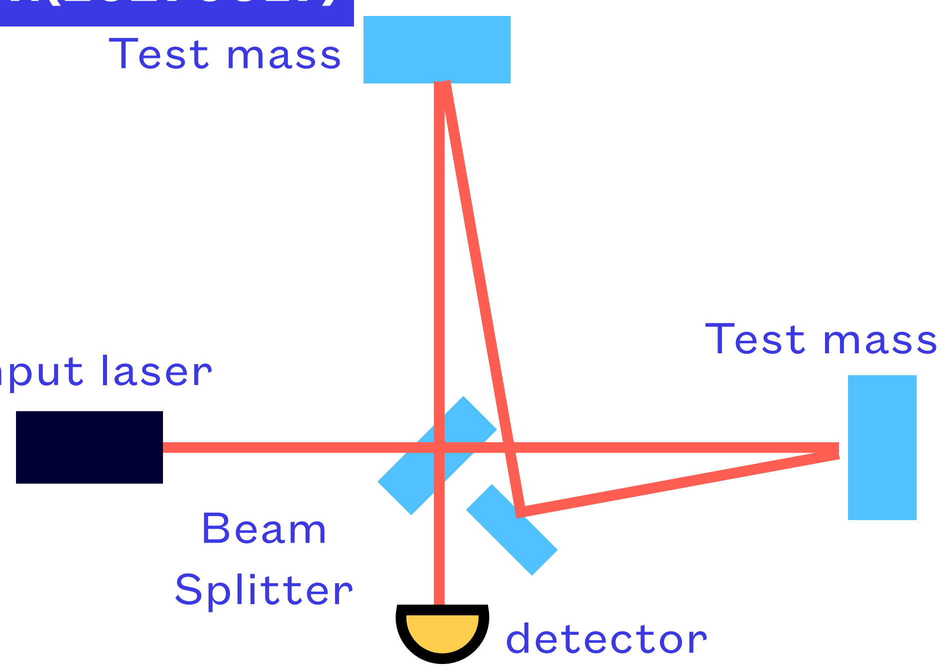


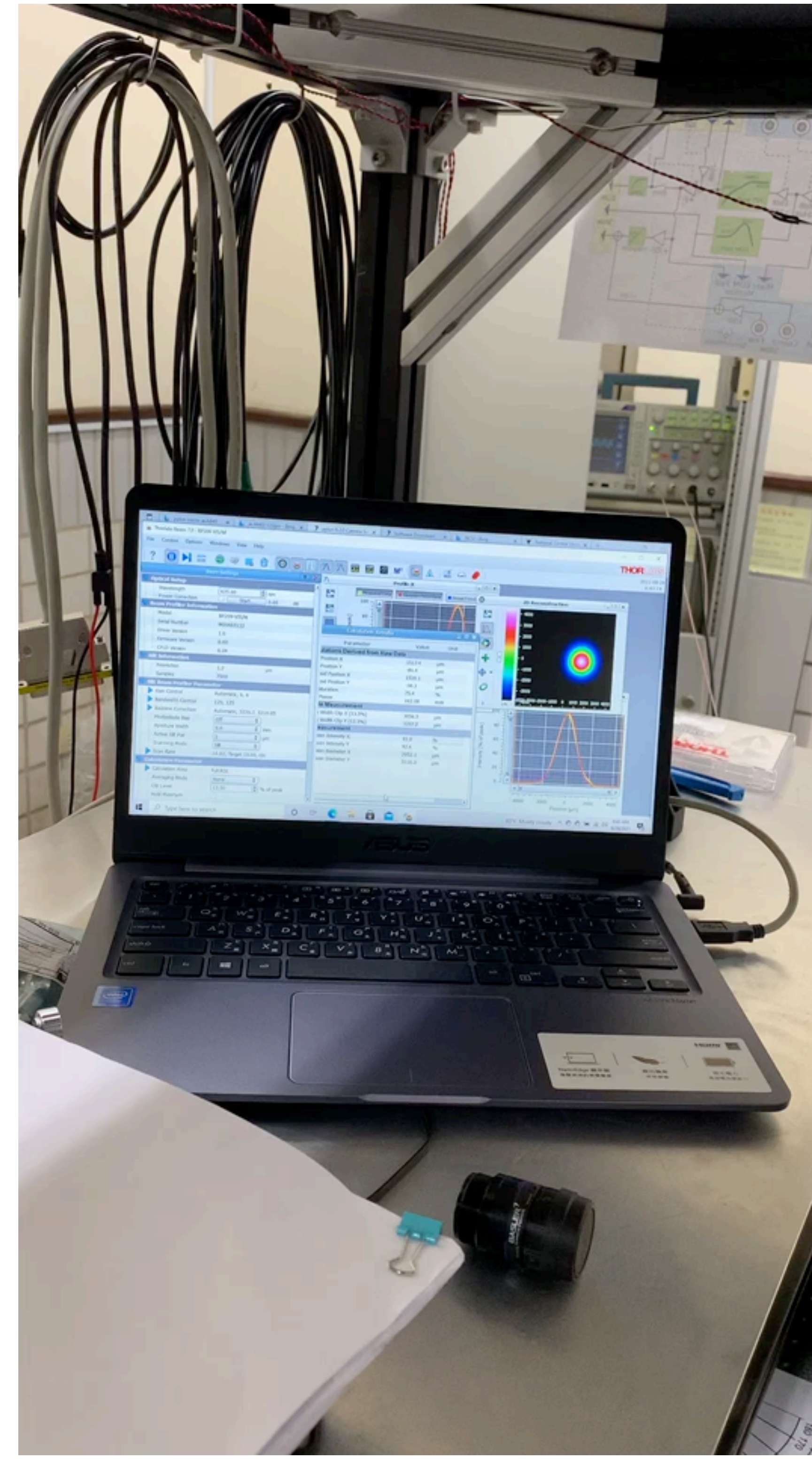


EARLY RUN(2021 MAR)

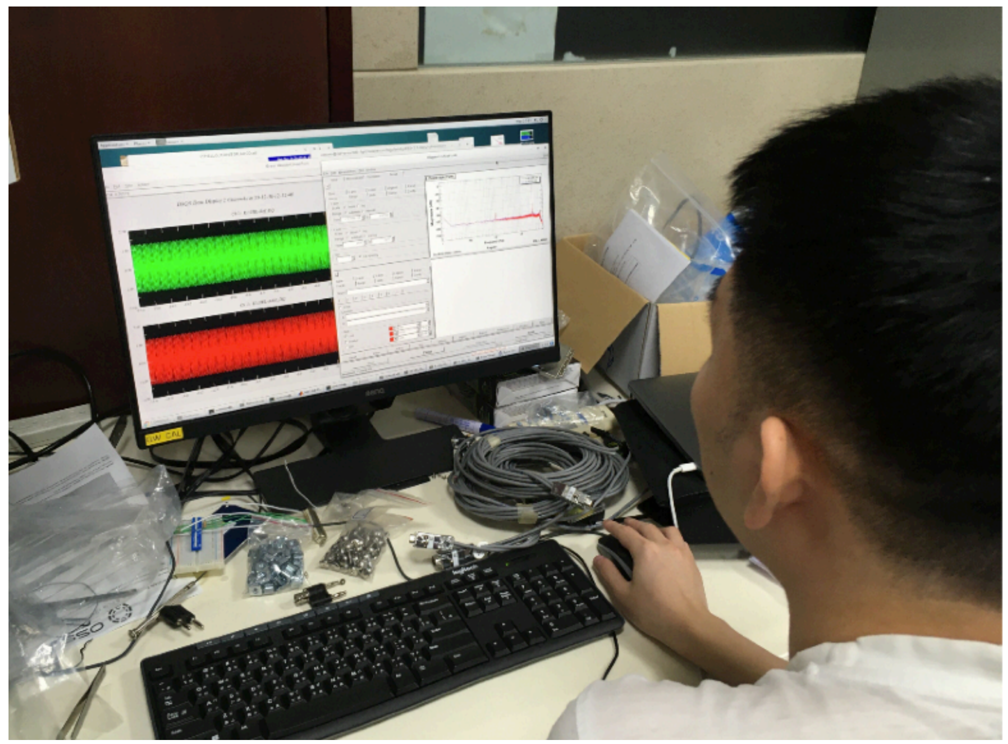


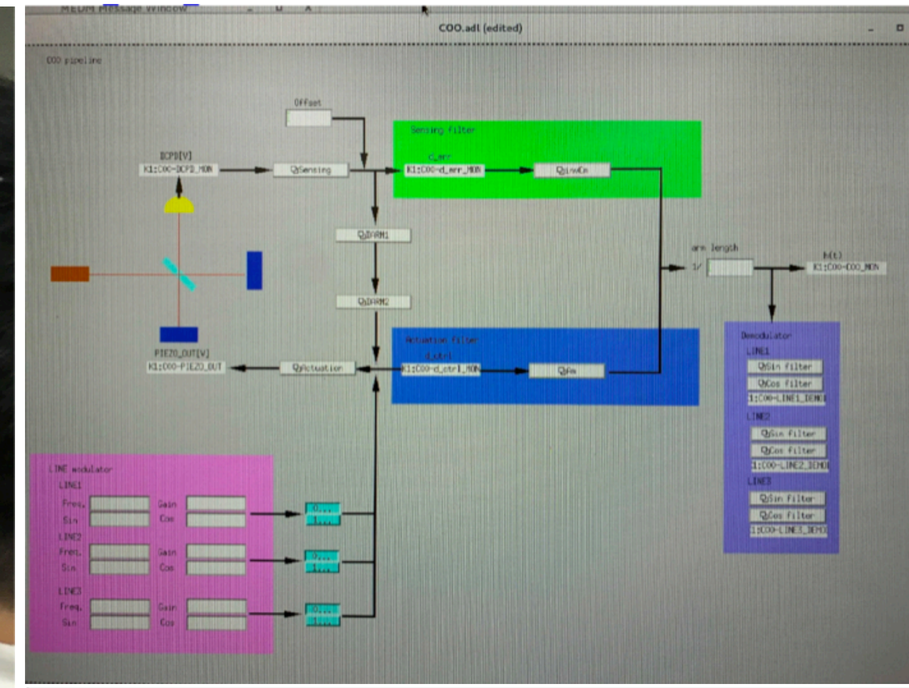
LATE RUN(2021 JULY)

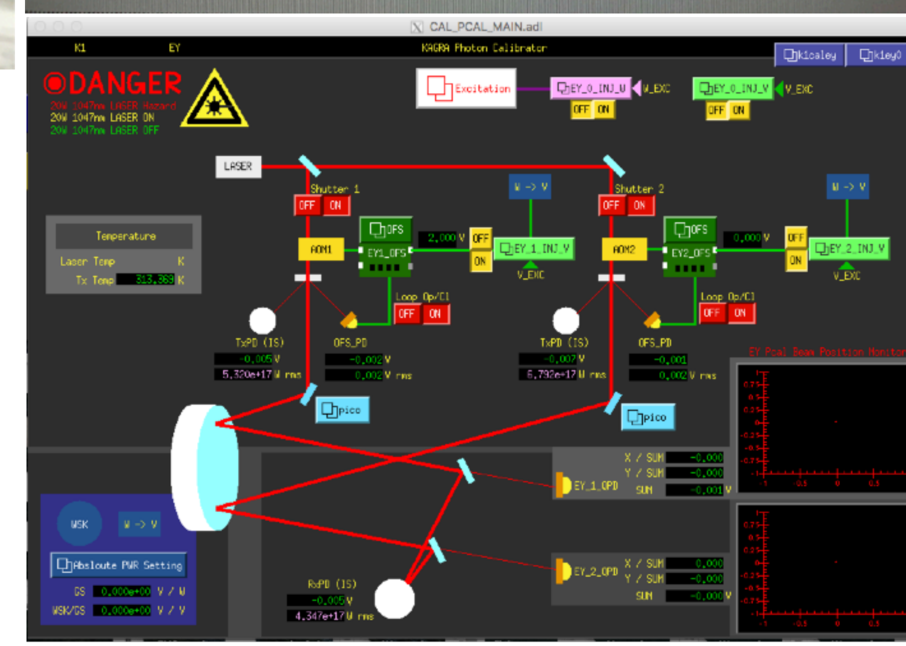




Digital Control System







- Linux base I/O system.
- Employ Epics flame work
- Can apply real time digital feedback filter.
- Can provide Quick monitor, quick analysis, and Controller
- Development is ongoing

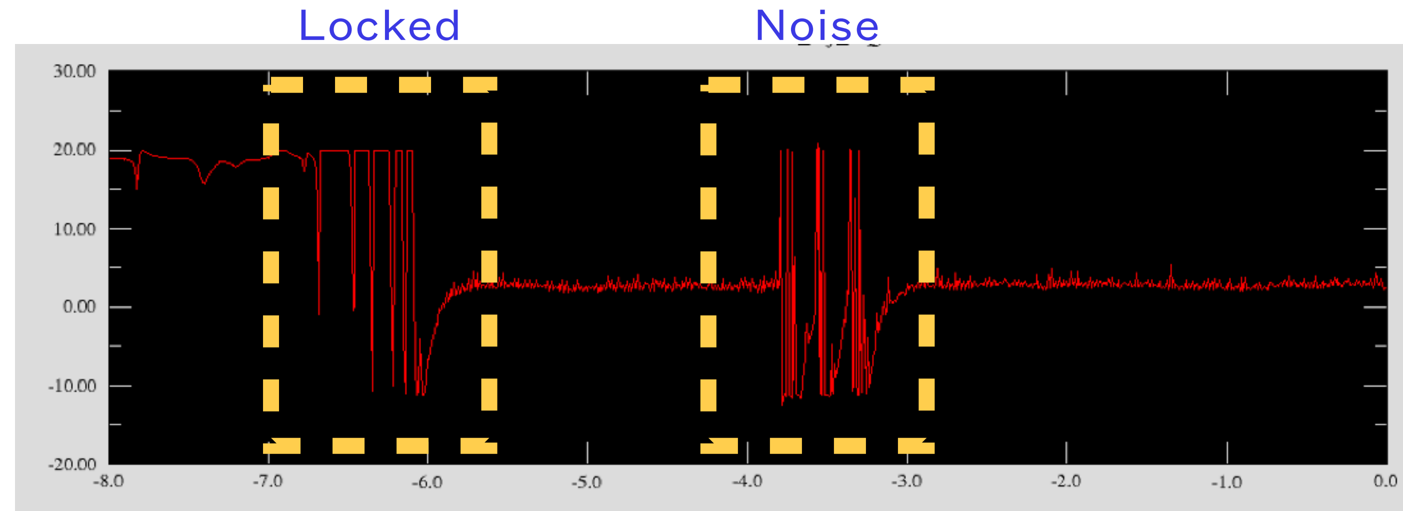
Input Optics

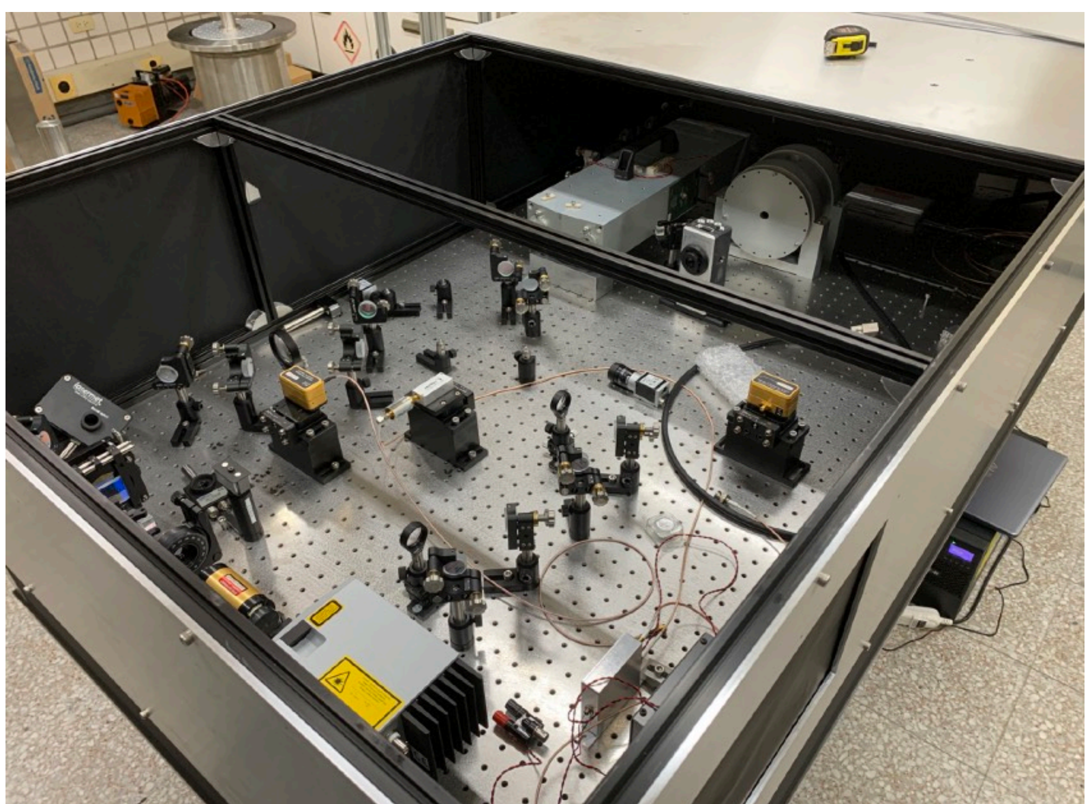
$$E(x,y)=A\exp(i\omega t)$$

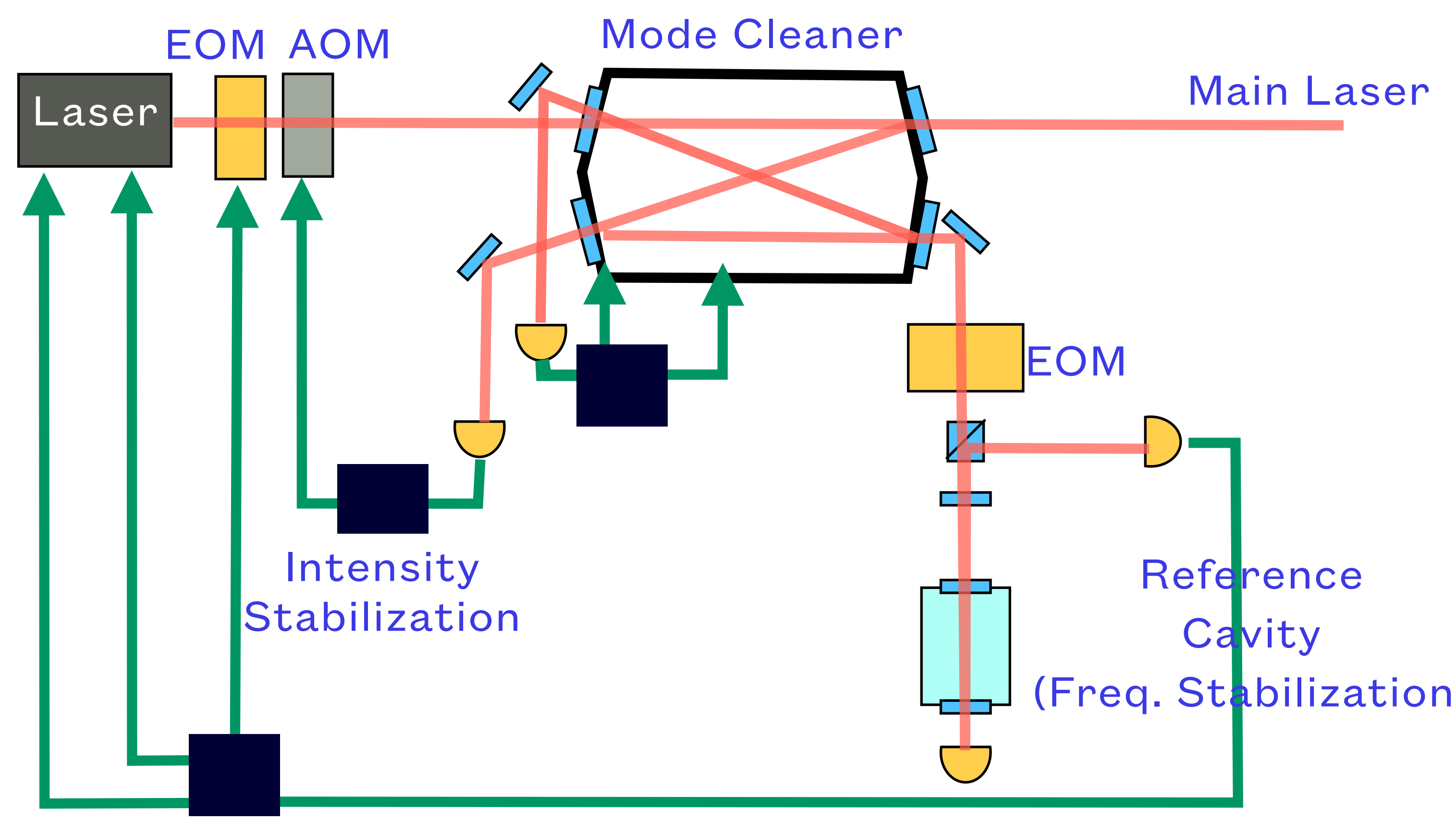
Beam → Mode cleaner

Intensity → Intensity Stabilization

Phase → Frequency Stabilization





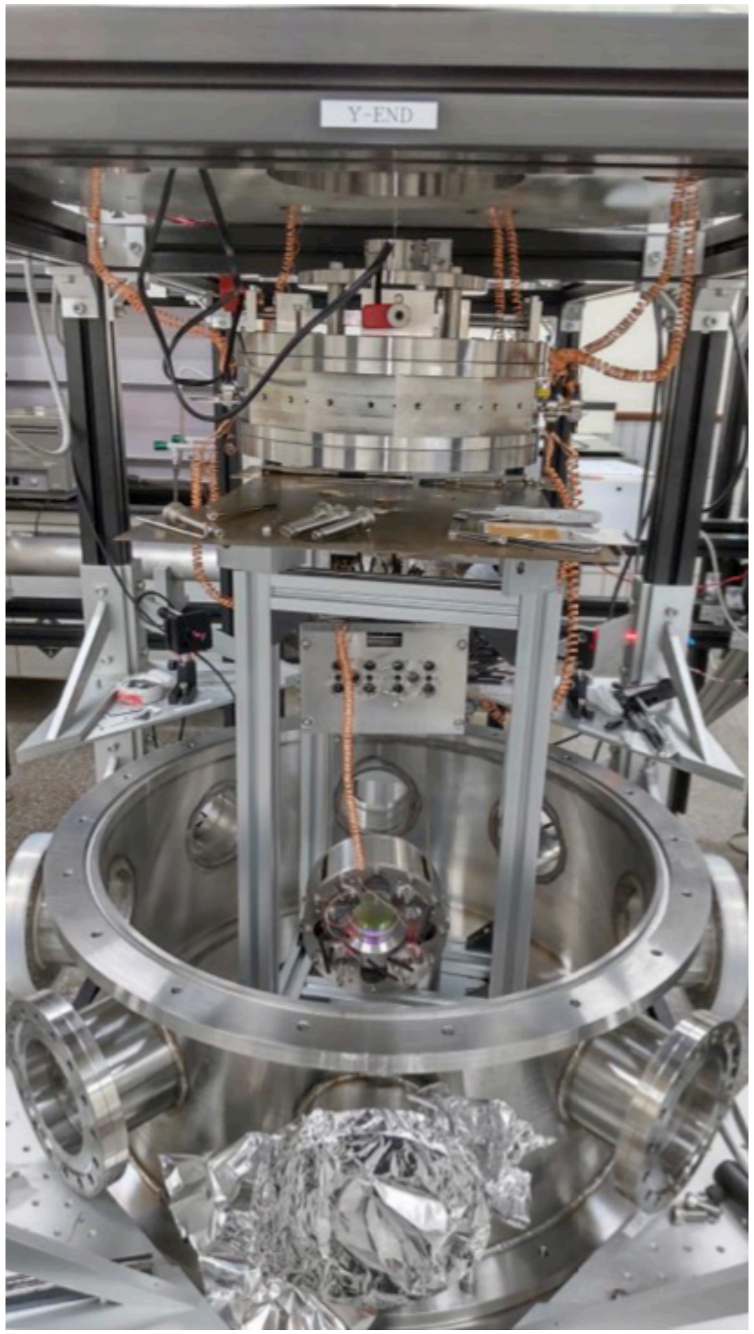


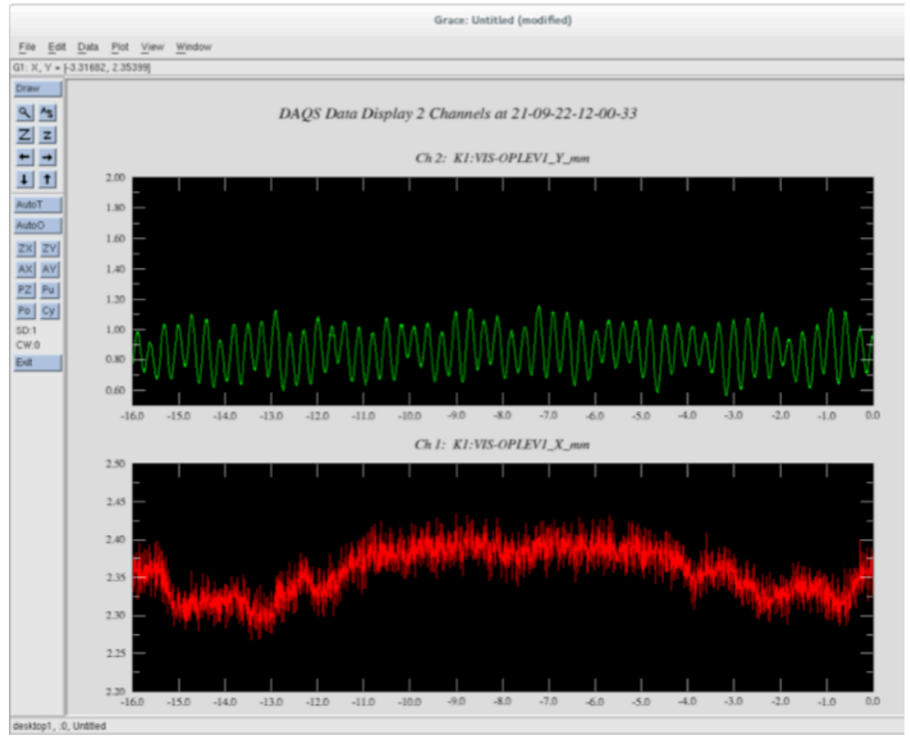
Summary

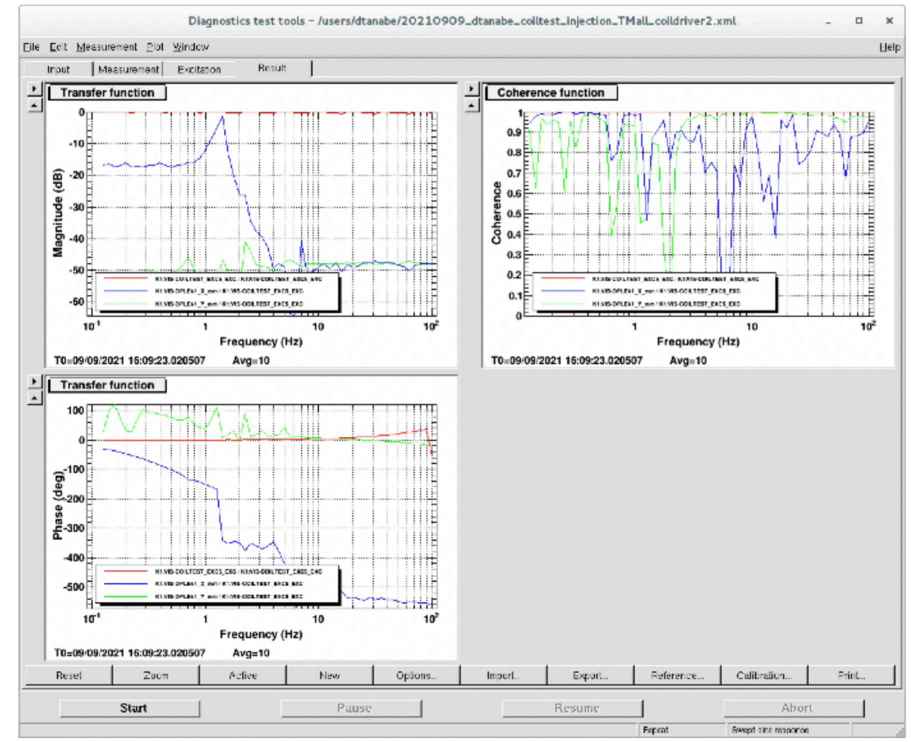
- We are studying the gravitational wave science as LIGO Scientific Collaboration.
- Gravitational wave community will start the observation from June 2022. We expect to observe the gravitational wave signal every 10 days.
- Proposal for Construction of GW test facility was approved in AS. GW test facility will start from next October. We are tying the demonstration R&D in NCU now.
- If you are interested in the collaboration, we are very welcome. We have good synergy for both institute.

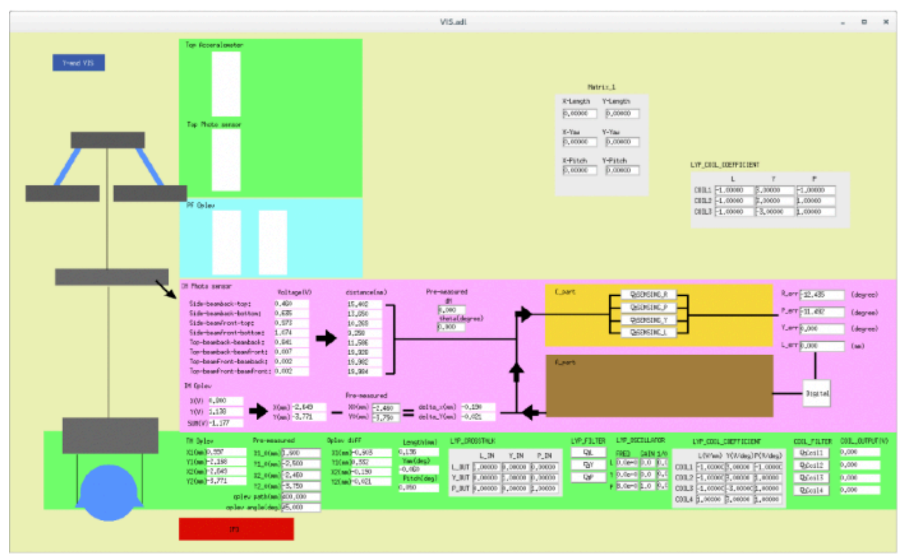
Backup

Vibration Isolation system



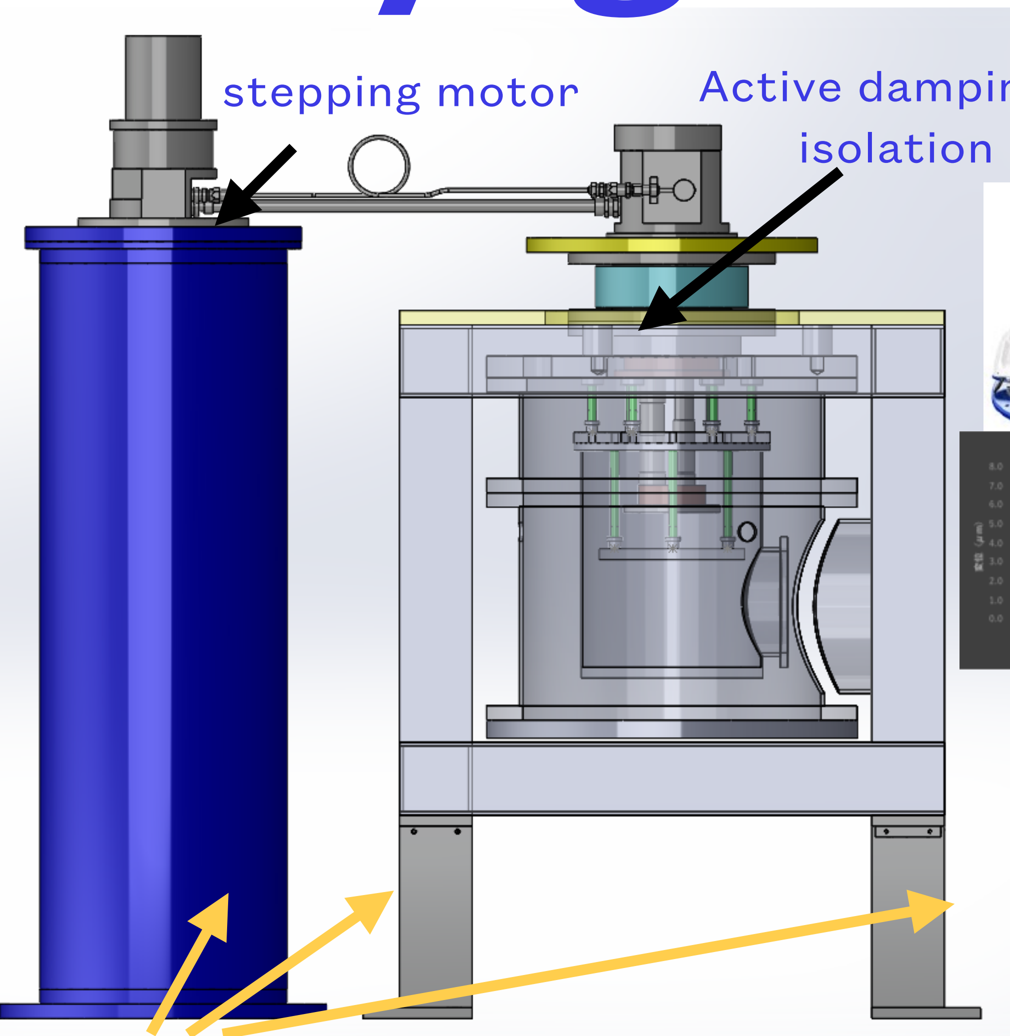


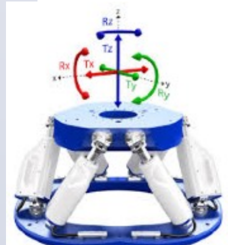


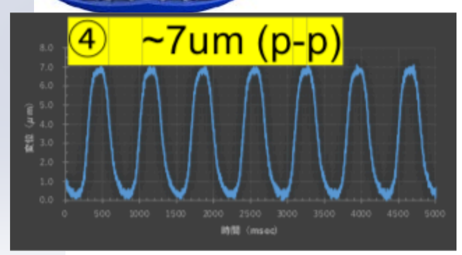


- Isolation from ground motion with feedback control system
- Small suspension test is ongoing.

Cryogenic system



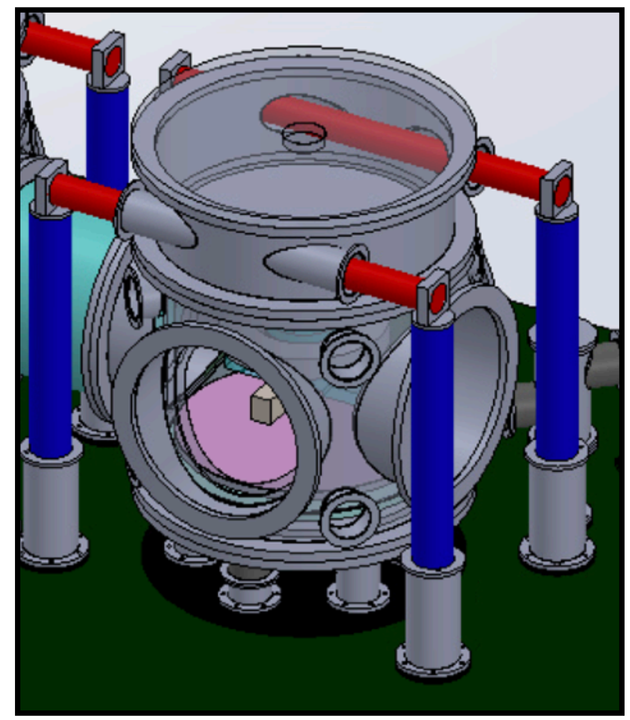


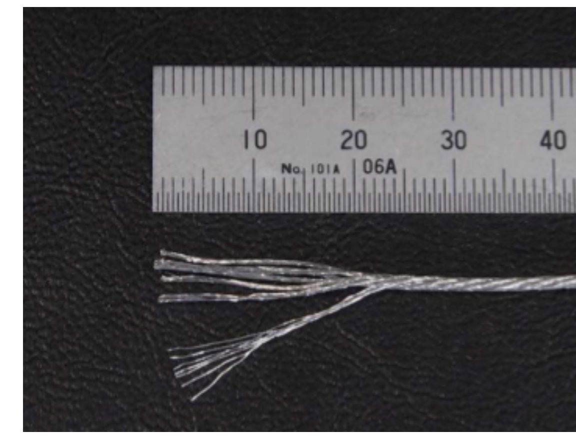


Connect to main chamber

Cryocooler: 2-Stages Puls tube cooler

Stage temperature: 50K, 4K



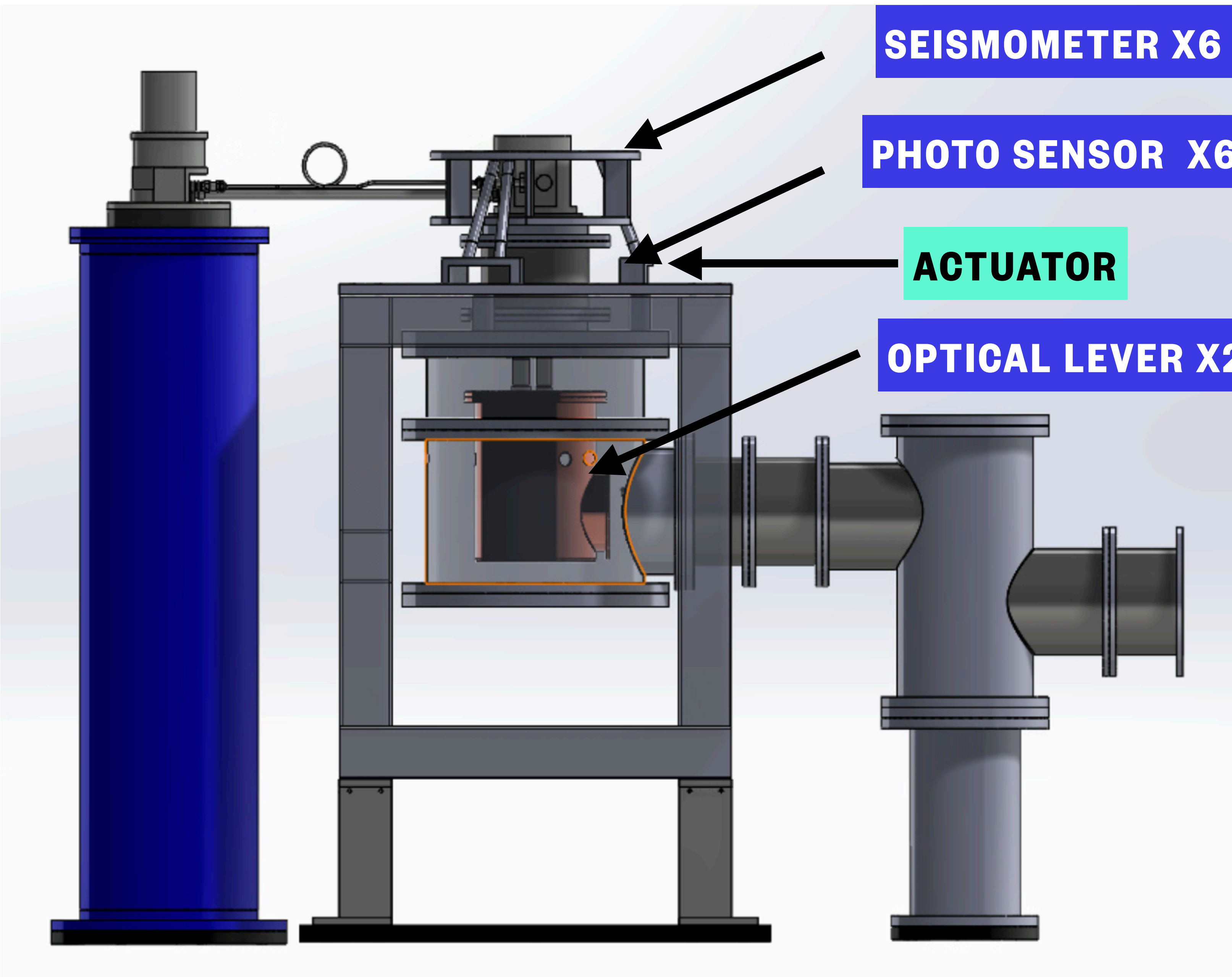


High Performance Heat Conductor with Small Spring Constant for Cryogenic Applications

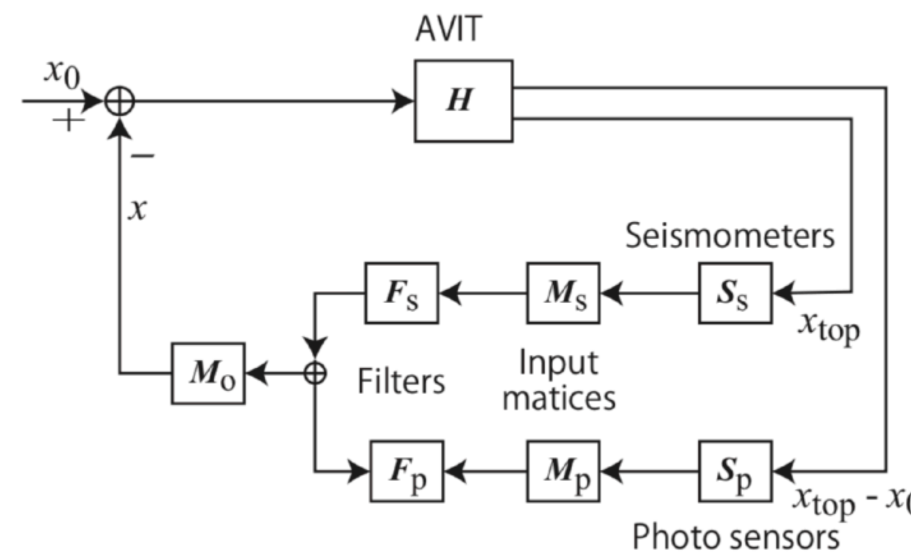
Tomohiro Yamada[a], Takayuki Tomaru[b,c], Toshikazu Suzuki[c], Takafumi Ushiba[d], Nobuhiro Kimura[c,e], Suguru Takada[f], Yuki Inoue[g], Takaaki Kajita[a]

- Plan to improve KAGRA's technique.
- KAGRA requirement:20K
- CHRONOS requirement: 4K

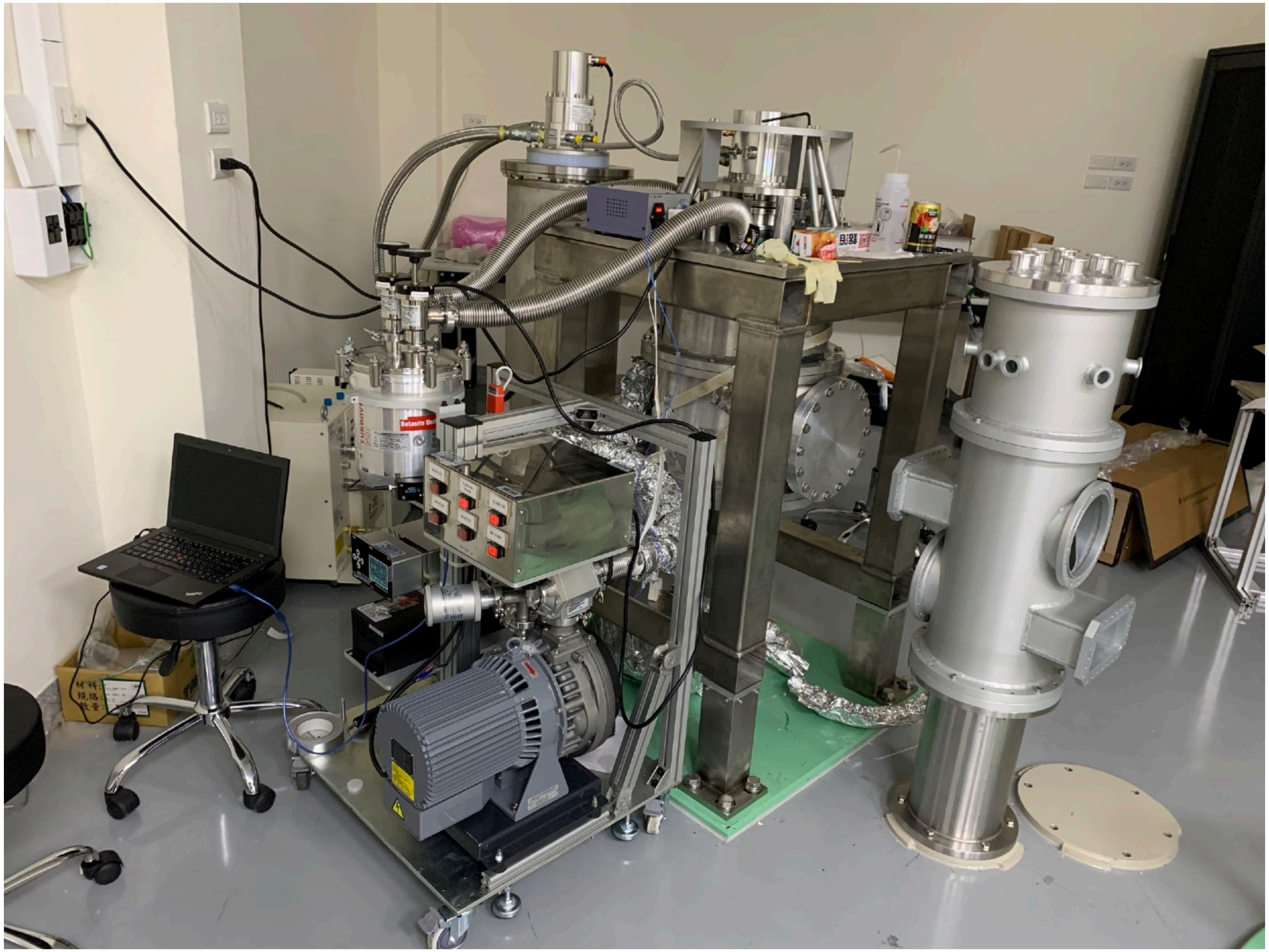
Active vibration isolation test



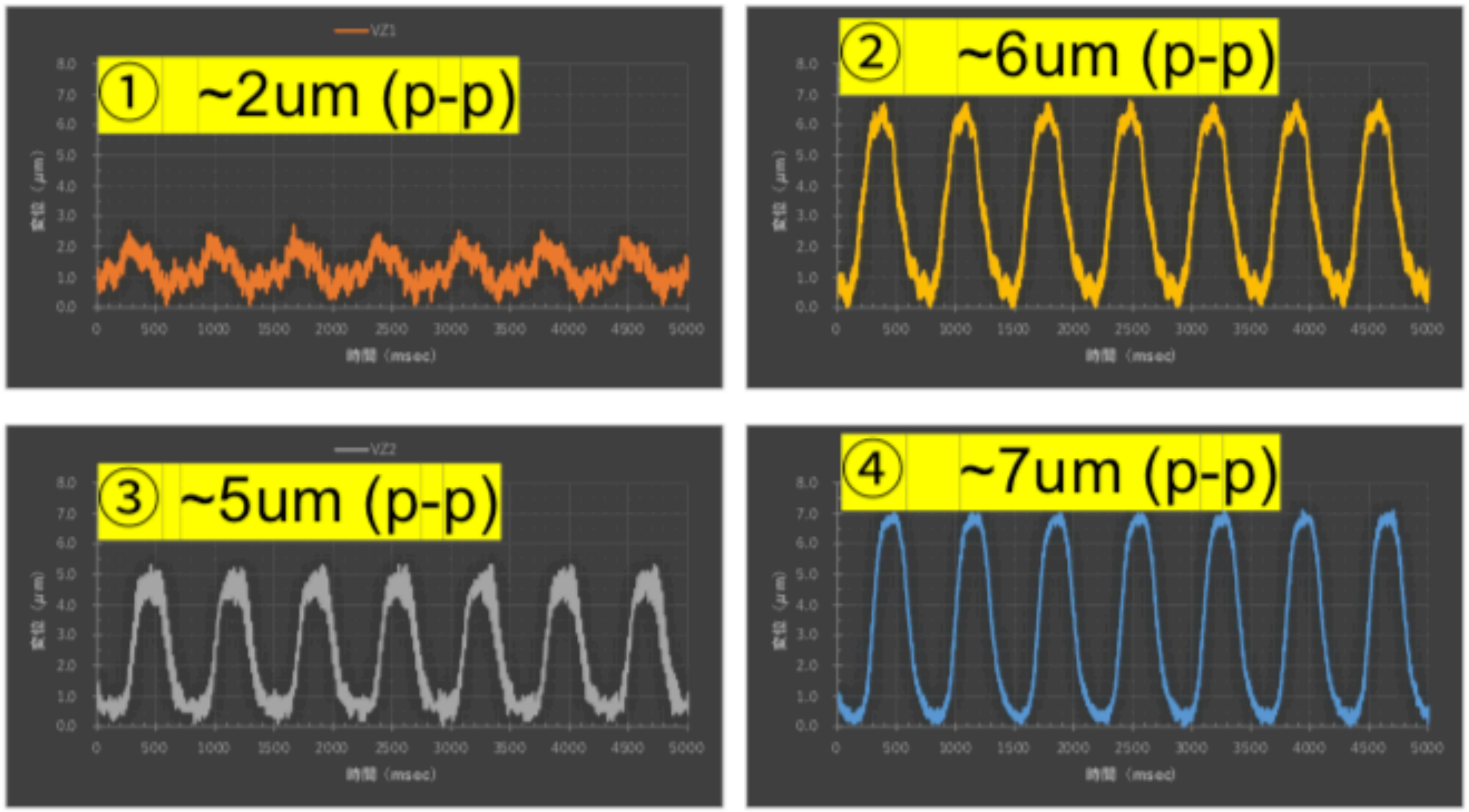
TOBA's feedback loop (A.Shoda)



Experimental Setup in ASIOP

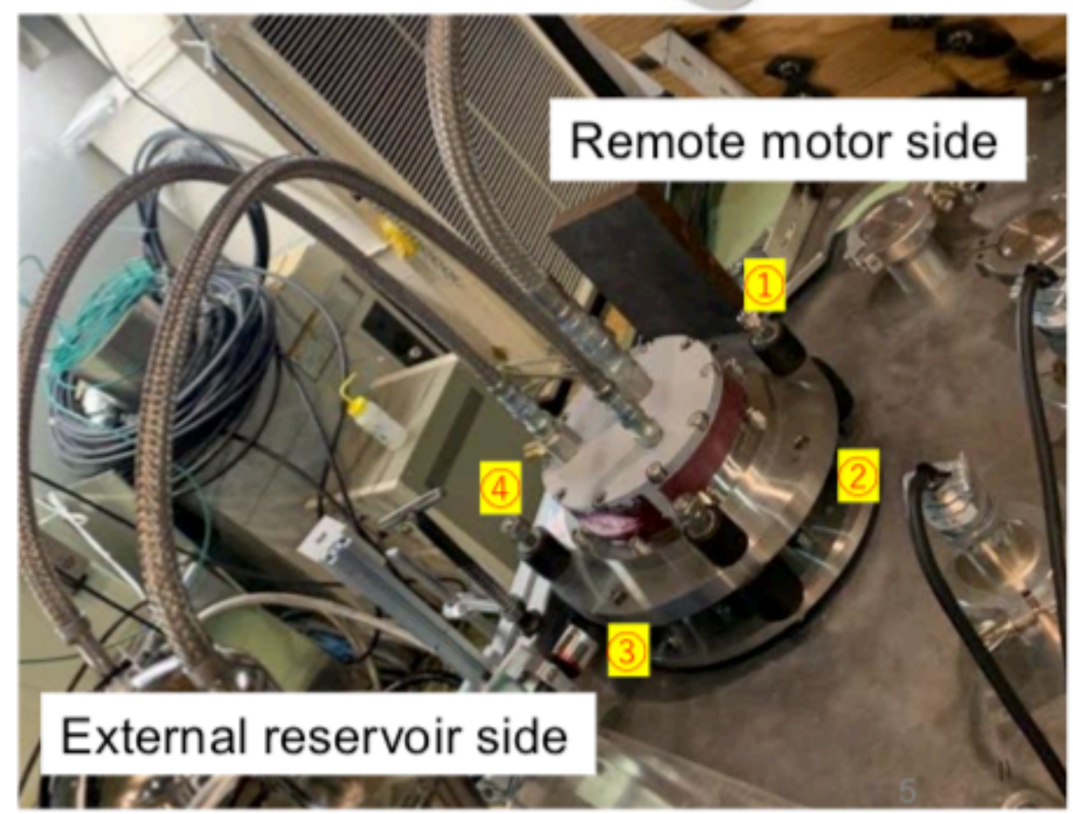


Vibration problem



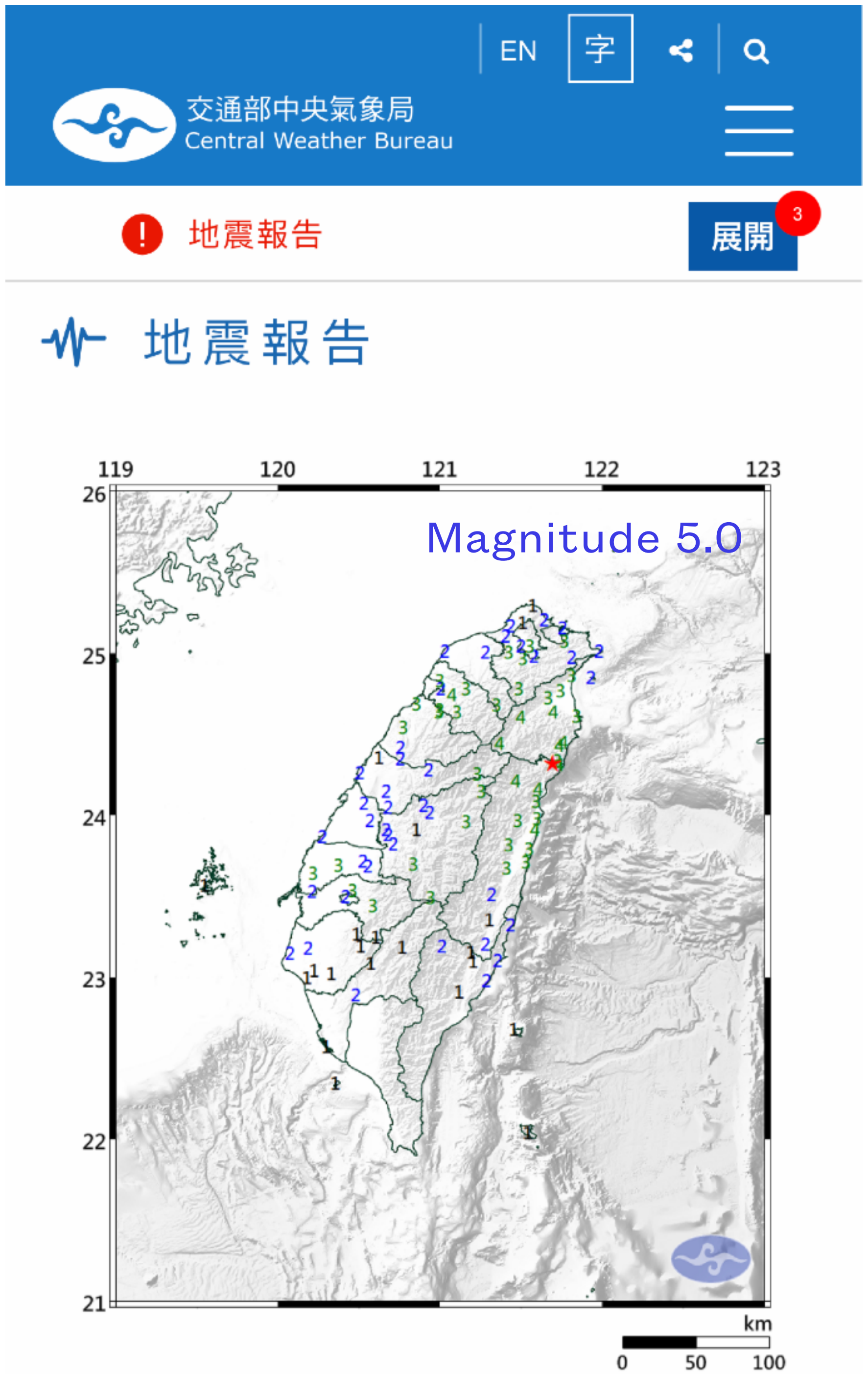
(During operation)

Laser displacement sensor
(CL-P015, Keyence)

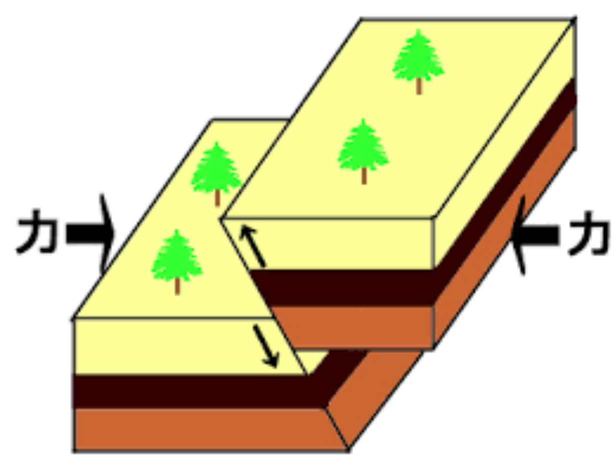


- We checked the displacement at four points vertically and horizontally
  - Vertical: < ~10um, horizontal: < ~5um
- Actuator, PI-844.60 can be used.

Is Earth quake disadvantage?



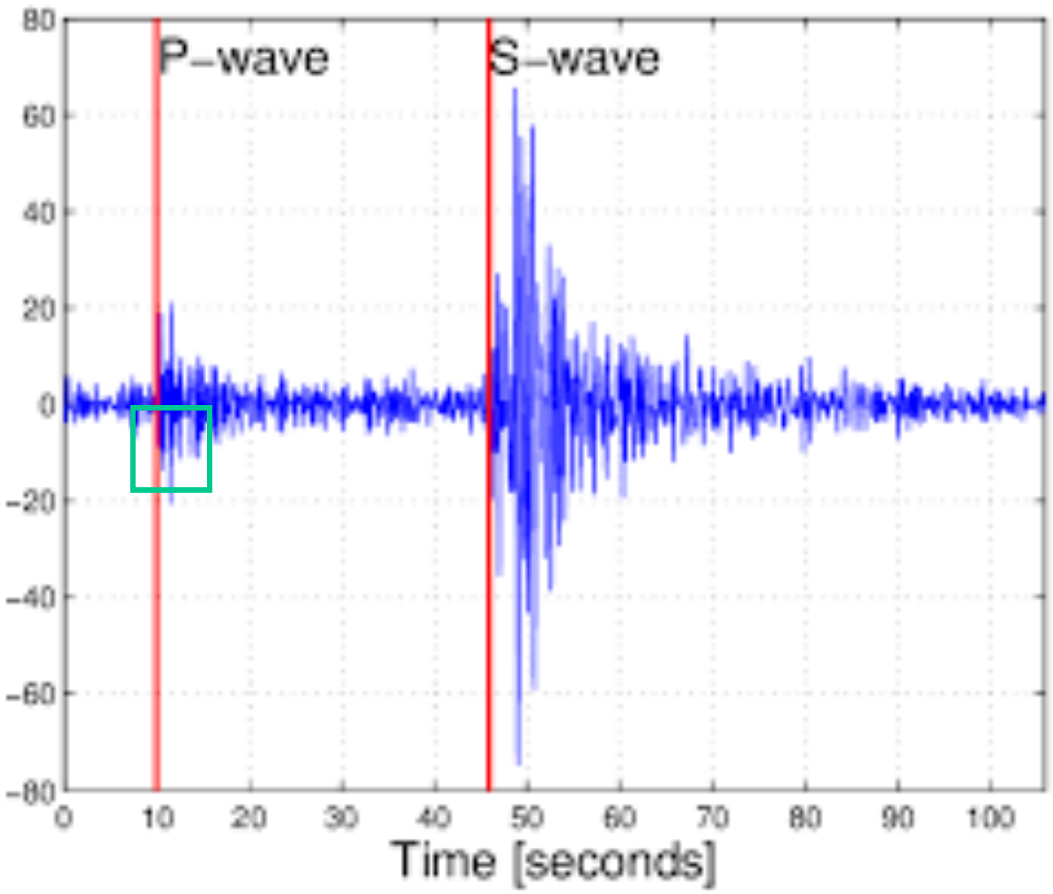
In the case of 4 days ago...

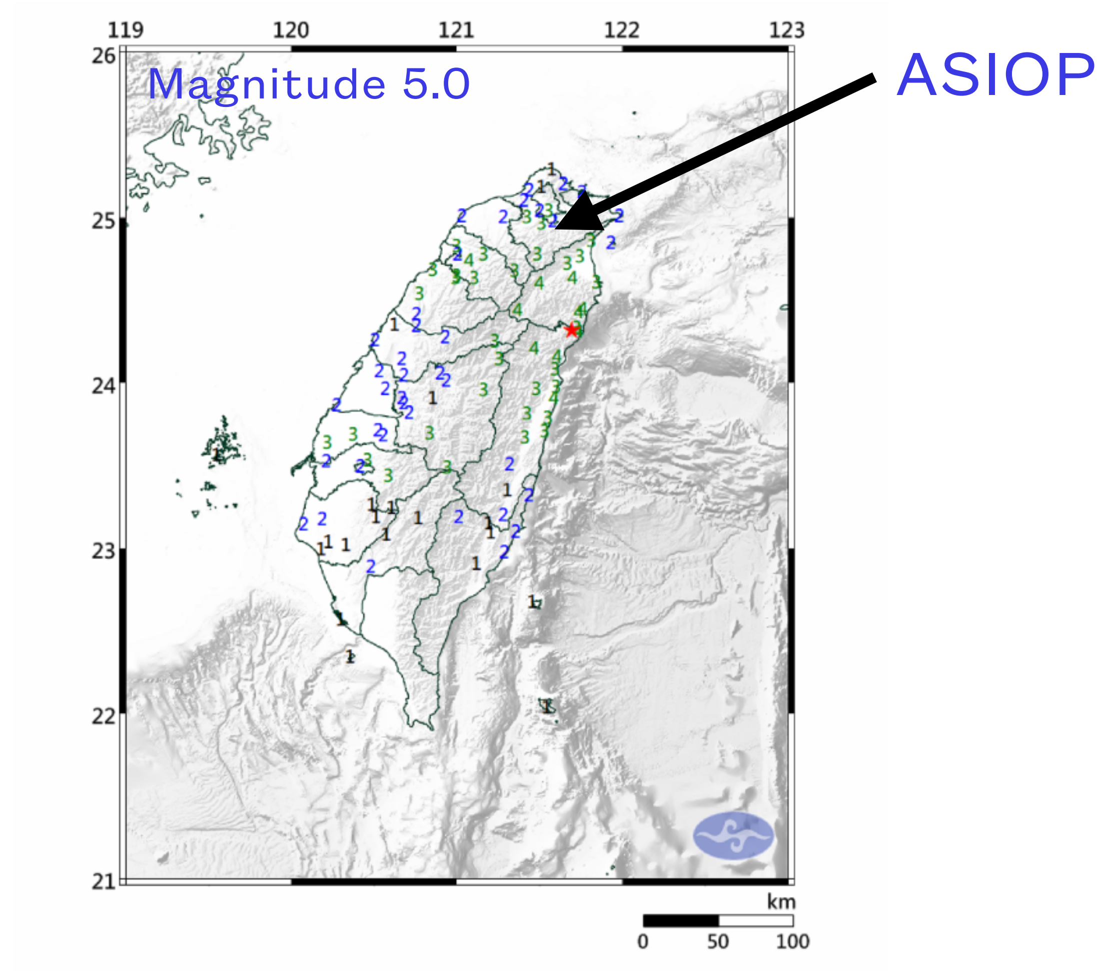


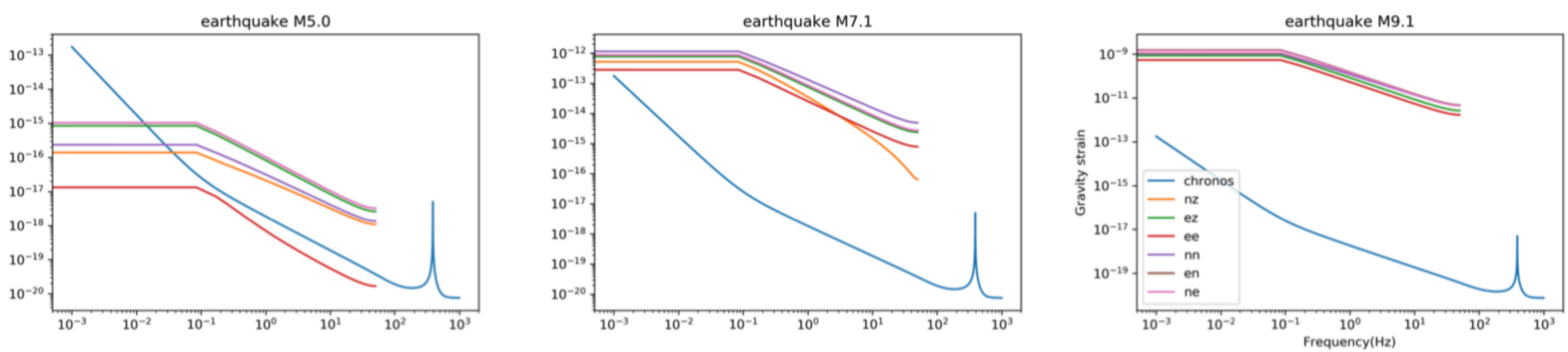
- Dynamical of mass inside the earth surface can generate a perturbation to gravitational potential on the surface of the earth
- It can be observed by strain meter through gravity strain

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

GEO science



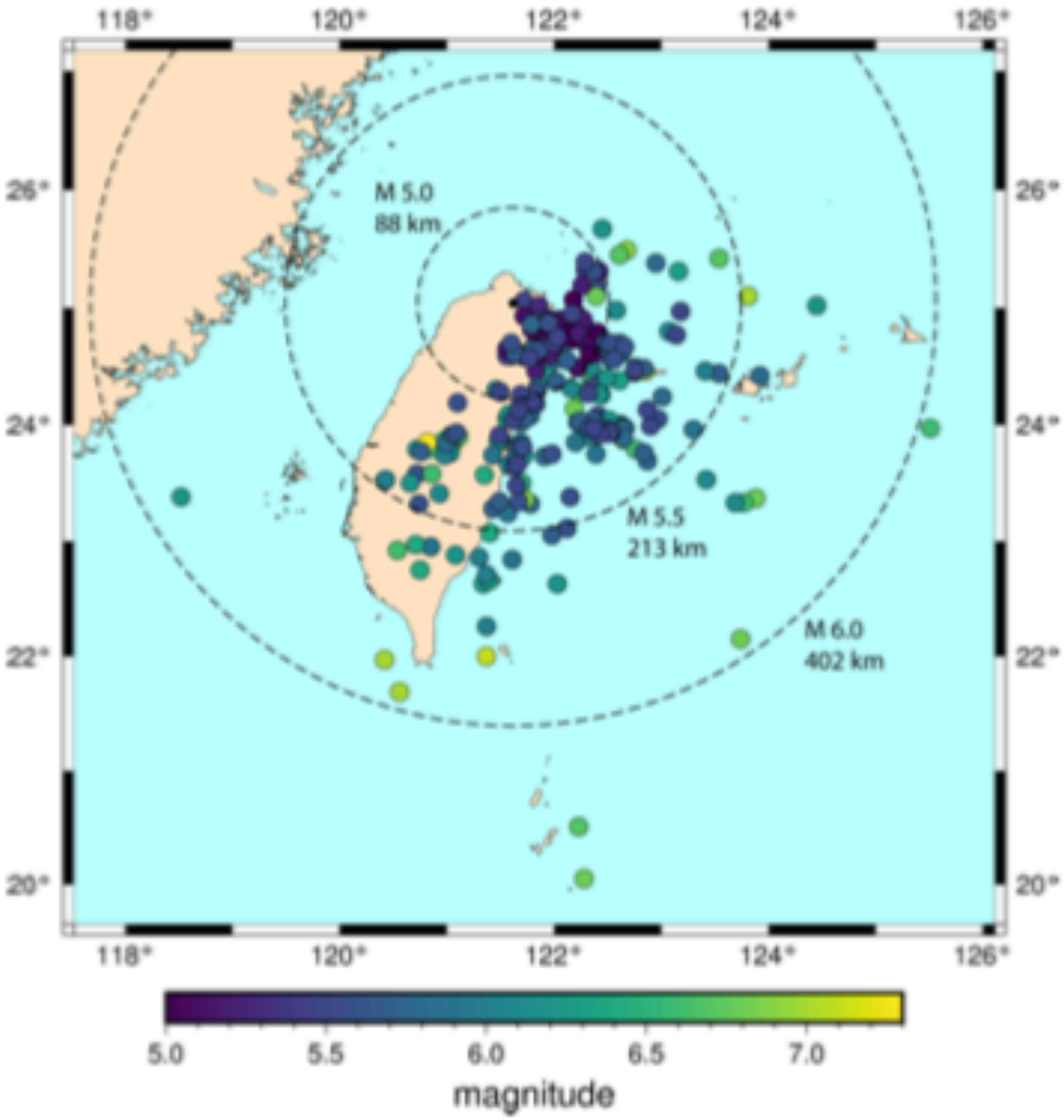




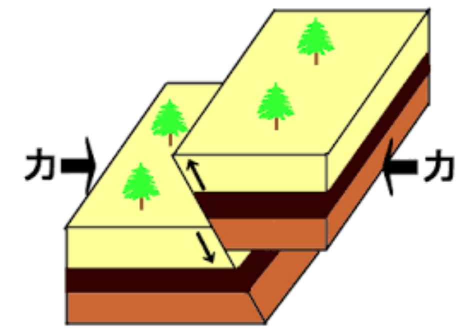
(a) M 5.0 (b) M 7.1 (c) M 9.1

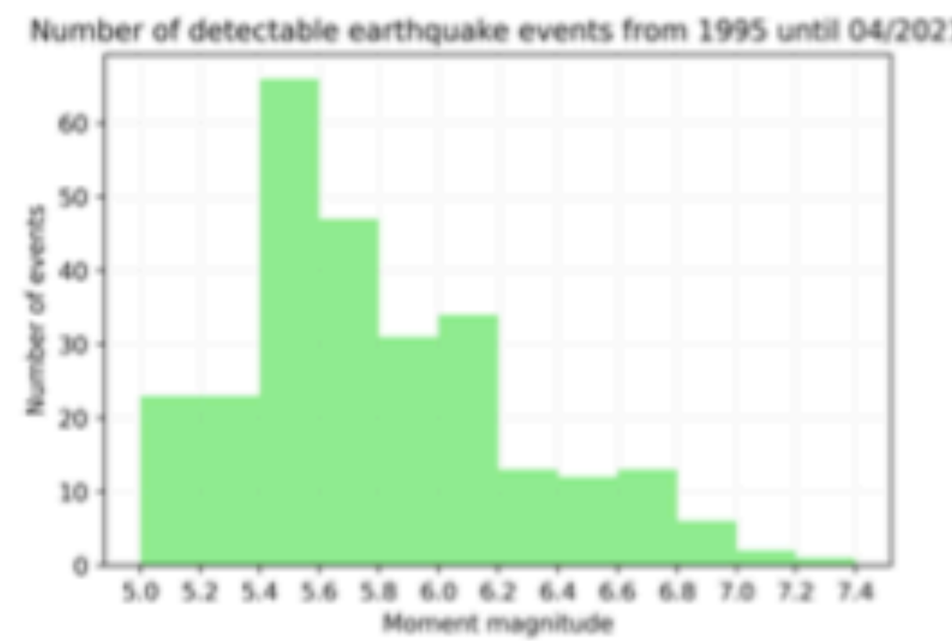
Figure 5: Gravity strain signal in the frequency domain, overplotted with CHRONOS noise

3 sigma detection region



(a)





(b)

Figure 8: (b).Number of detectable earthquake within the last 26 years data