KAGRA - Status and Prospect -

Nishinomiya-Yukawa symposium "General Relativity and Beyond", YITP, Kyoto Univ., Kyoto, Feb. 12, 2024

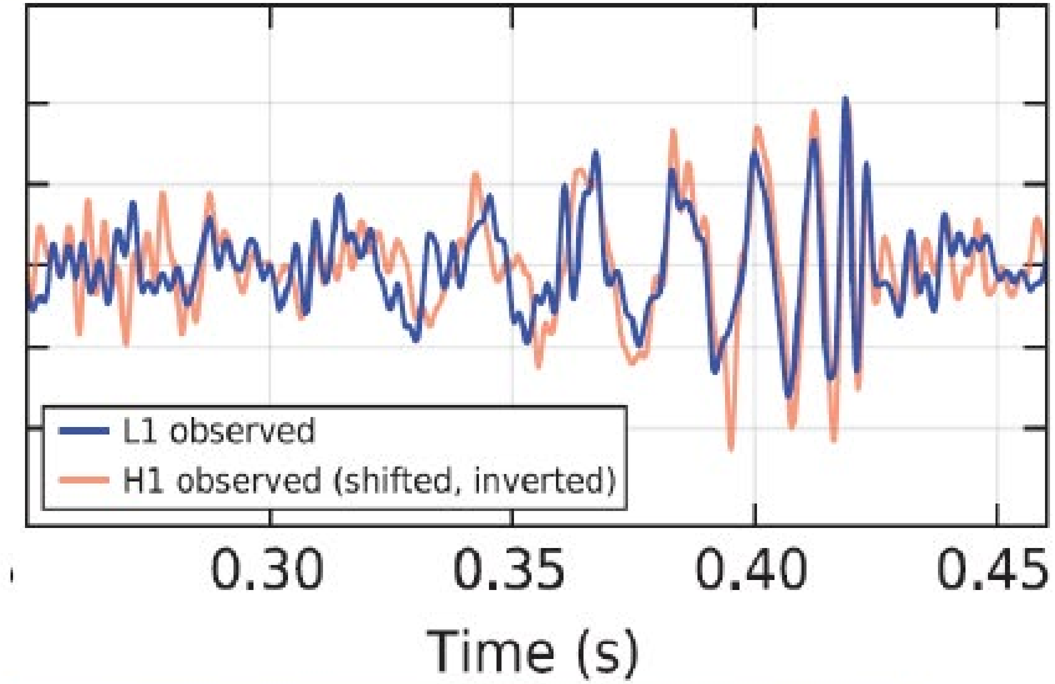
Takaaki Kajita, for the KAGRA collaboration
Institute for Cosmic Ray Research, Univ. of Tokyo

Outline

- *Introduction*
- *The KAGRA project*
- *The earthquake on Jan. 1, 2024 and its effect to KAGRA*
- *KAGRA's contribution to the GW science*
- *Summary*

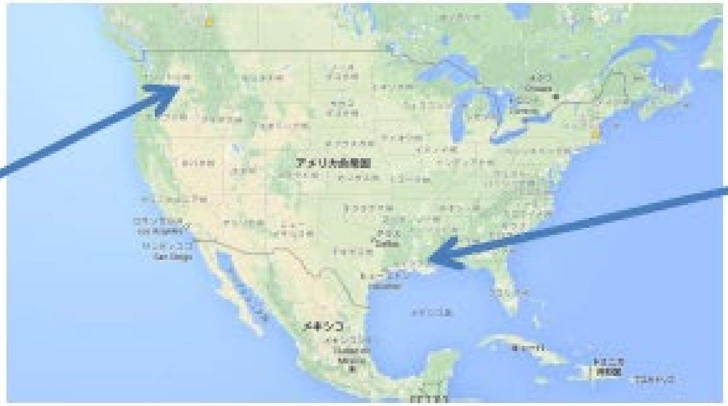
Introduction

Discovery of gravitational waves



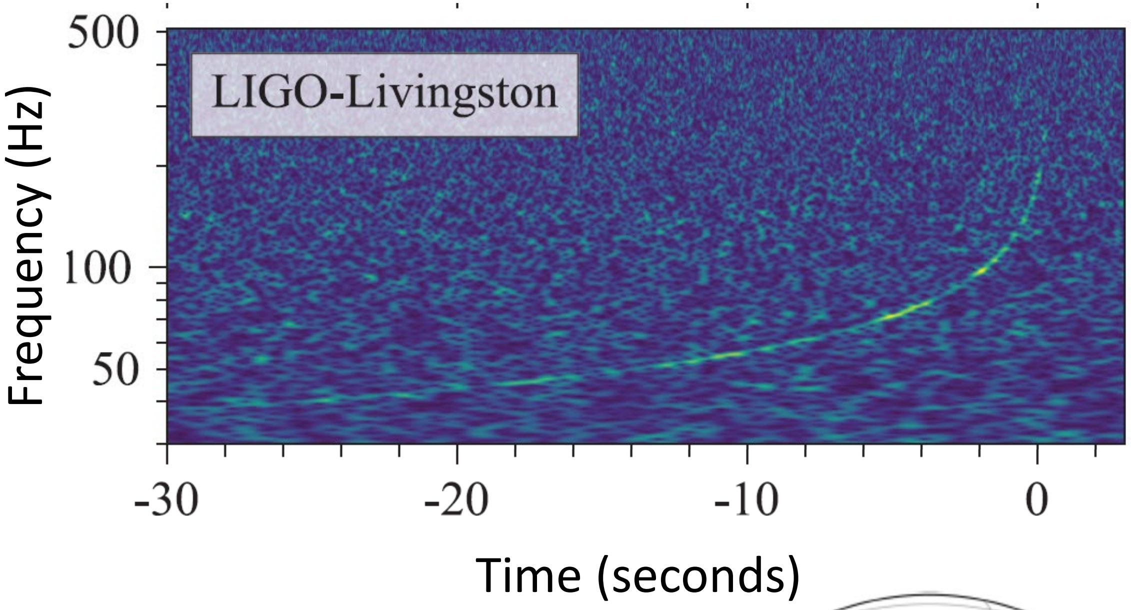
LIGO Scientific Collaboration and Virgo Collaboration, PRL, 116, 061102 (2016)

- ✓ On Sep. 14, 2015, LIGO observed the signals in their 2 laser interferometers. Data told us that 2 blackholes of 36^{+5}_{-4} M_{Sun} and 29^{+4}_{-4} M_{Sun} merged at the distance of 410^{+160}_{-180} Mpc, newly forming a 62^{+4}_{-4} M_{Sun} blackhole.
- ✓ ***This was really a great discovery. The GW astronomy was born!***

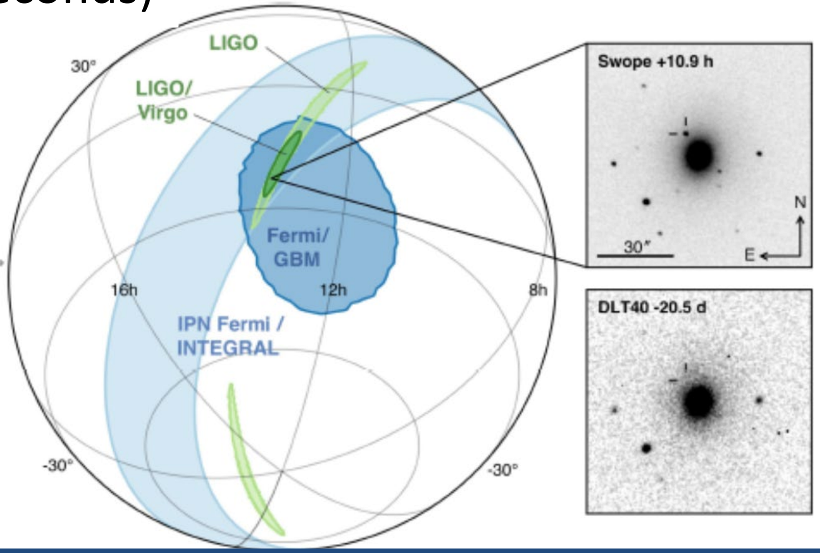


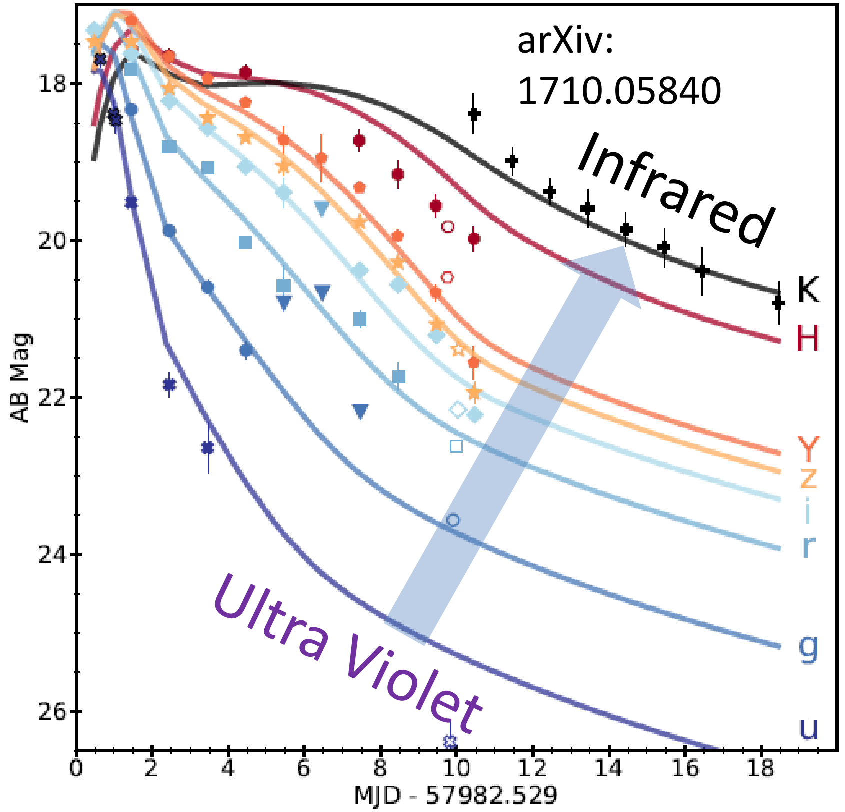
Multi-messenger astronomy with GW

Aug. 17, 2017



Pointing the binary neutron star merger event by LIGO and Virgo and the discovery of the optical counterpart

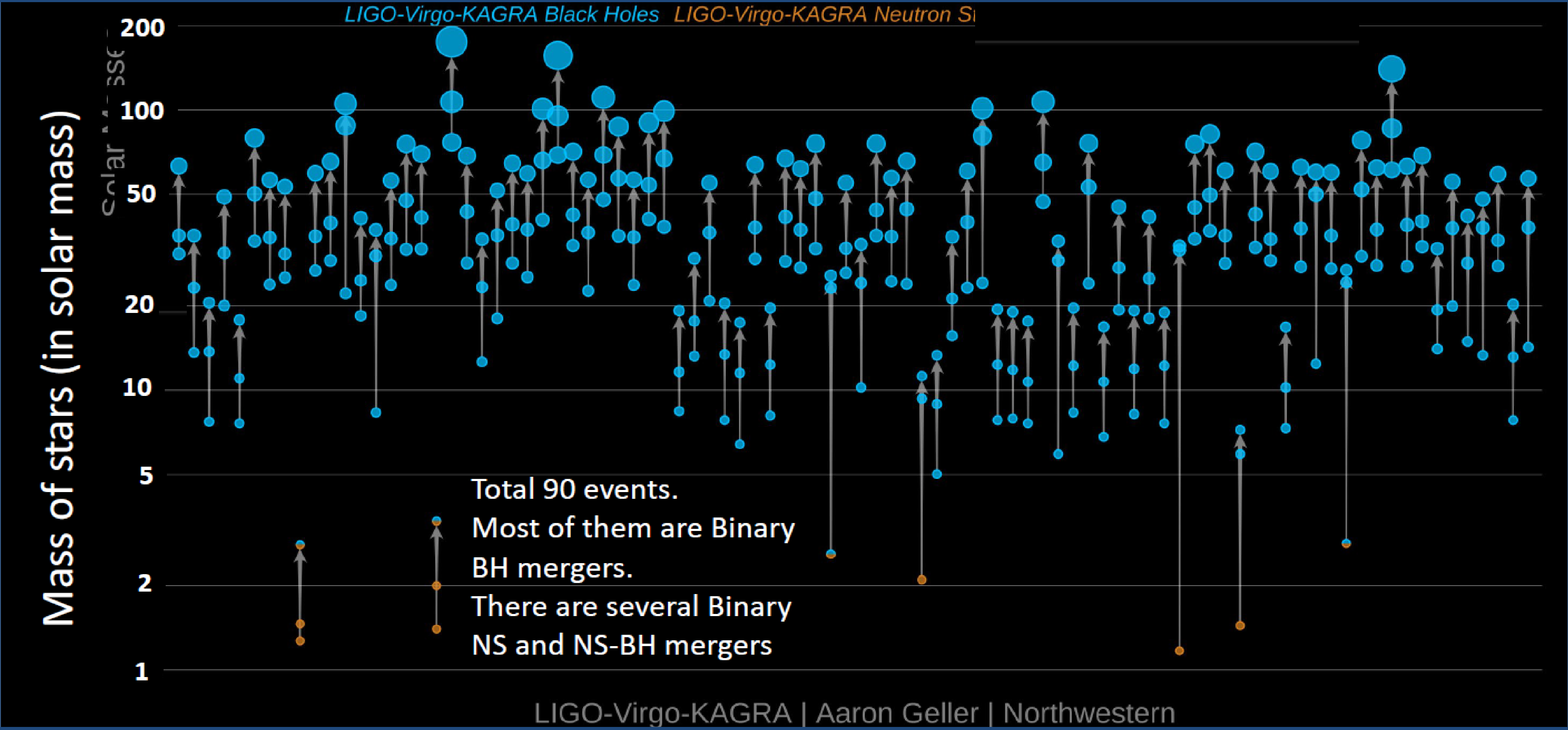




Consistent with heavy metals (such as gold or platinum) generation!
➔ Great start of the multi-messenger astronomy with GW!

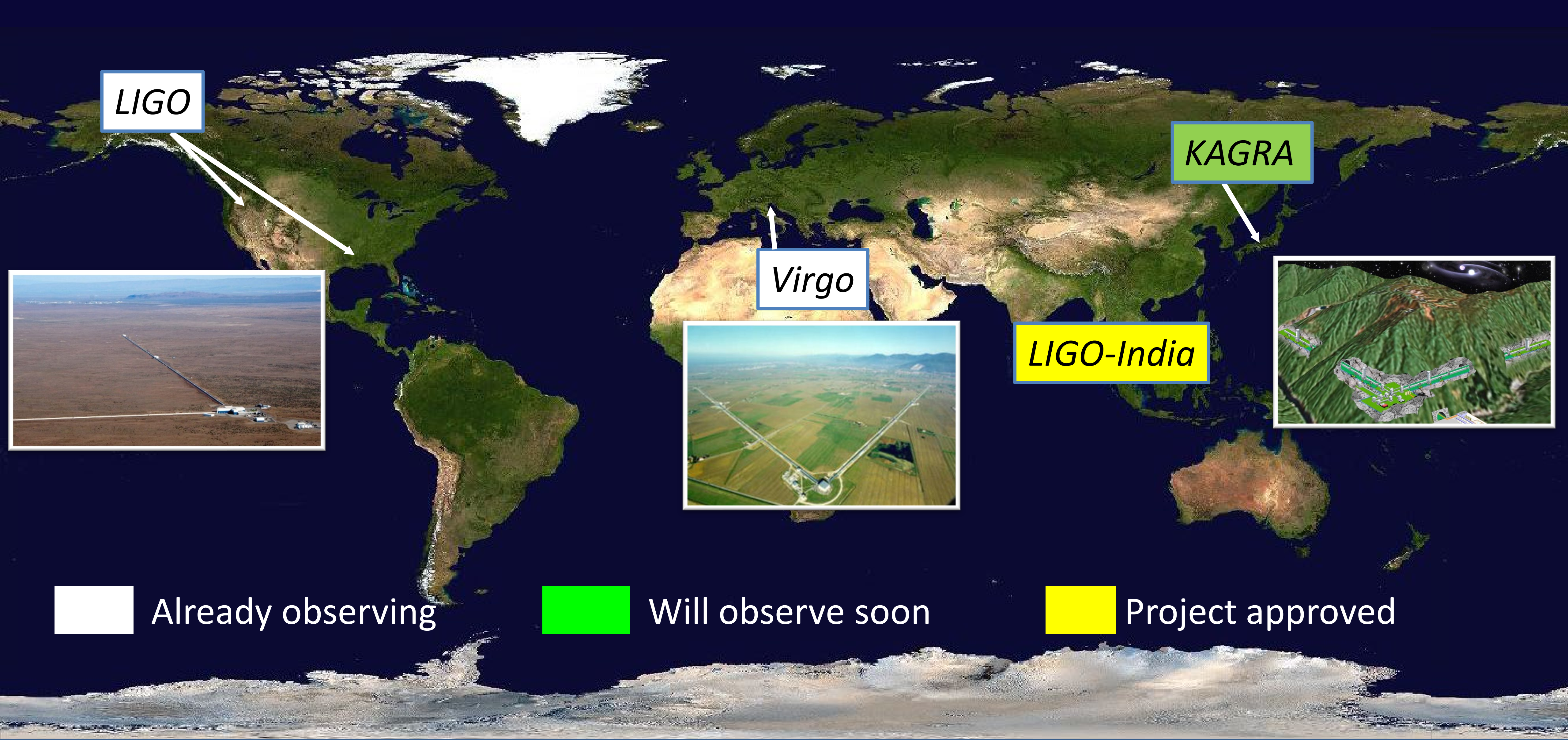
LIGO-Virgo observation summary before 2023

https://www.ligo.org/science/Publication-O3bCatalog/images/12_GWTC-3_Stellar_Graveyard_no_EM.png



Total 90 events.
Most of them are Binary BH mergers.
There are several Binary NS and NS-BH mergers

global map of GW detectors



The KAGRA project

KAGRA collaboration

8 countries/regions, ~150 authors (and ~400 collaborators from 17 countries/regions)

Location of KAGRA

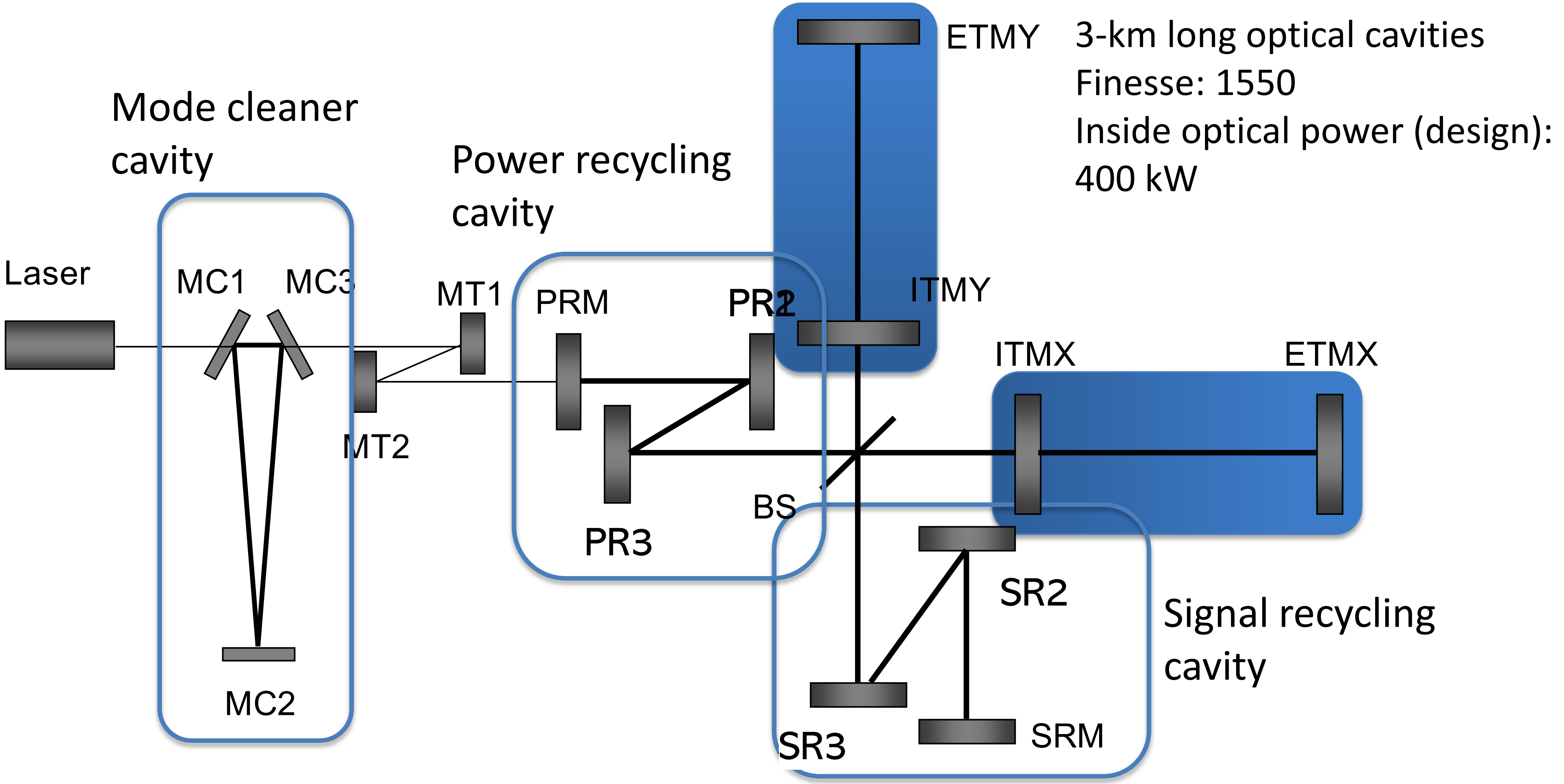
<u>KAGRA key features:</u>

✓ Underground site:
Smaller seismic noise

✓ Cryogenic mirrors:
Smaller thermal noises

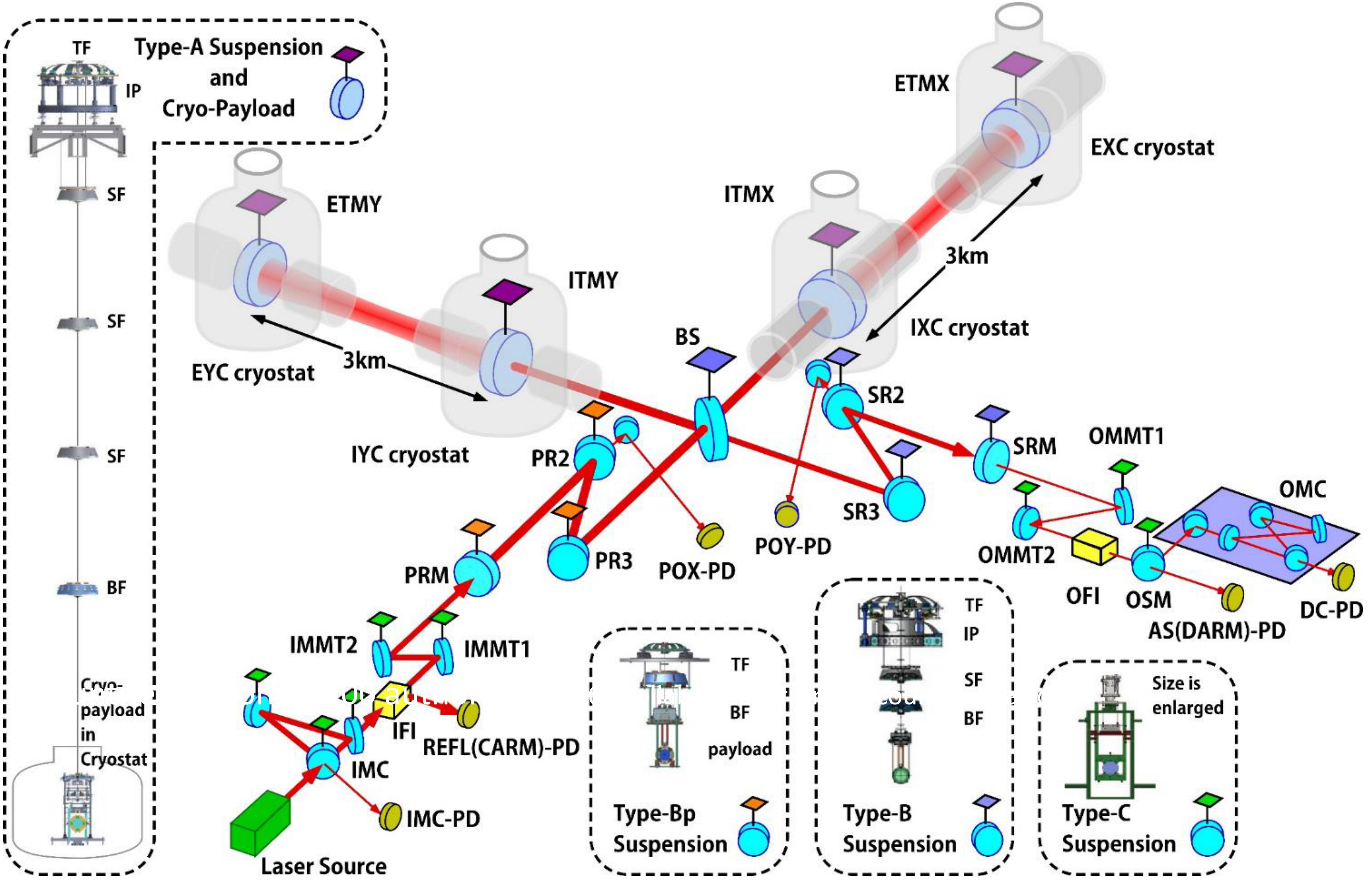
Schematic view of KAGRA optical system

- *KAGRA is a huge Michelson interferometer that has optical cavities in the arms and recycling systems. (Very similar to LIGO and Virgo.)*

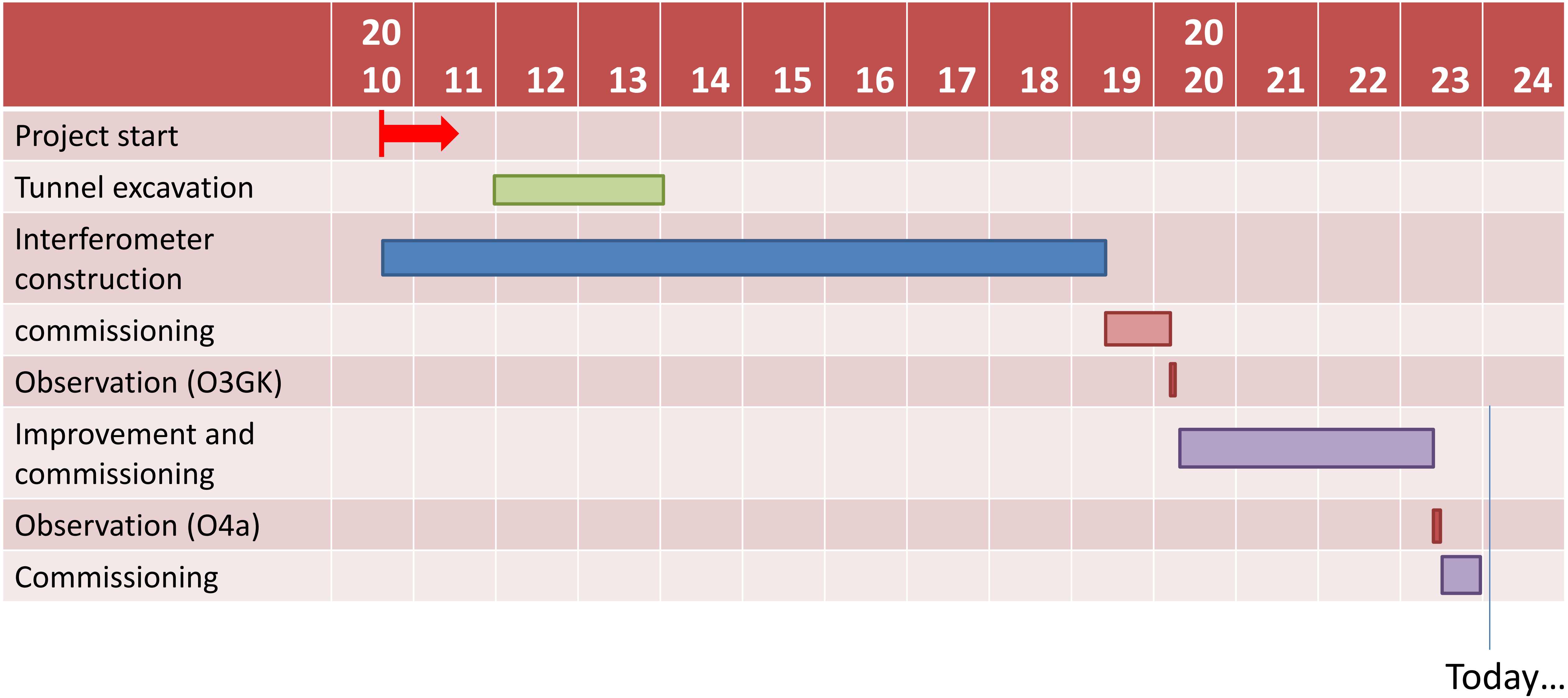


KAGRA Vibration Isolation System

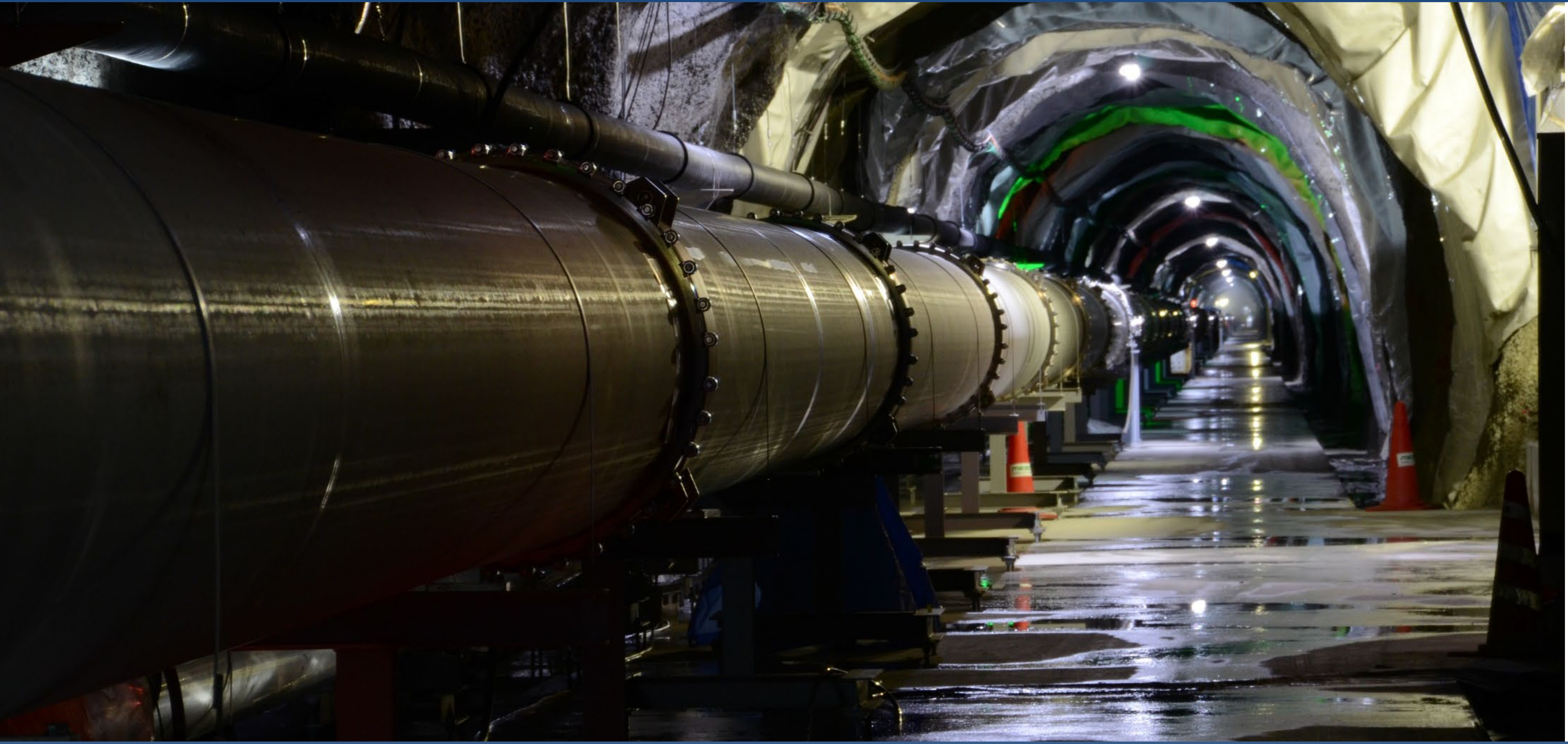
KAGRA has 4 types of Vibration Isolation system (VIS) depending on the requirement.



Project history



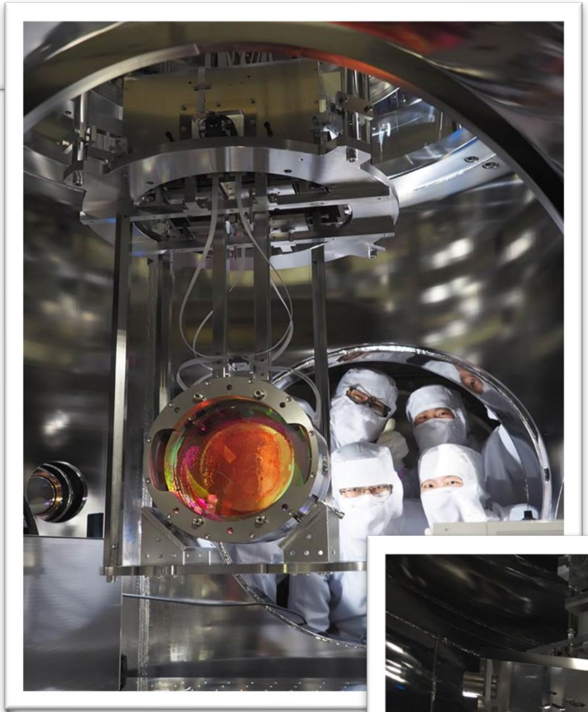
3km long vacuum tube (Feb. 2015）



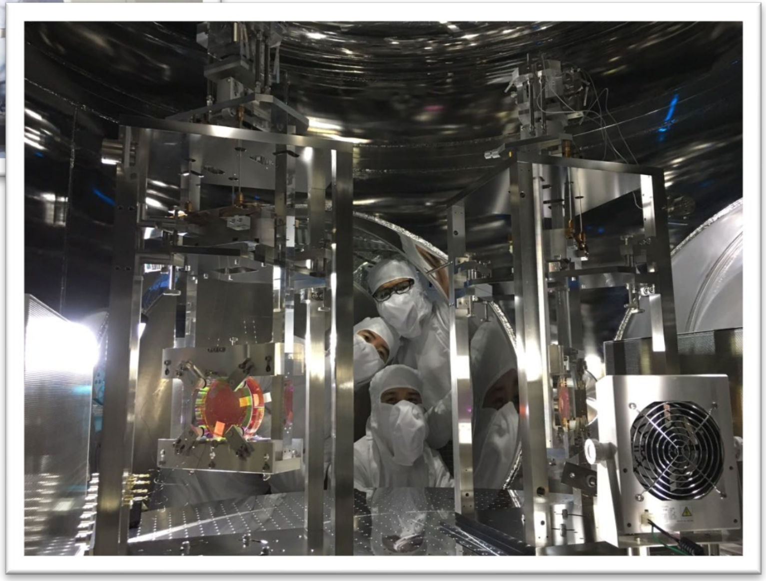
Installation works (until spring 2019)

“Type-A”

“Type-B”

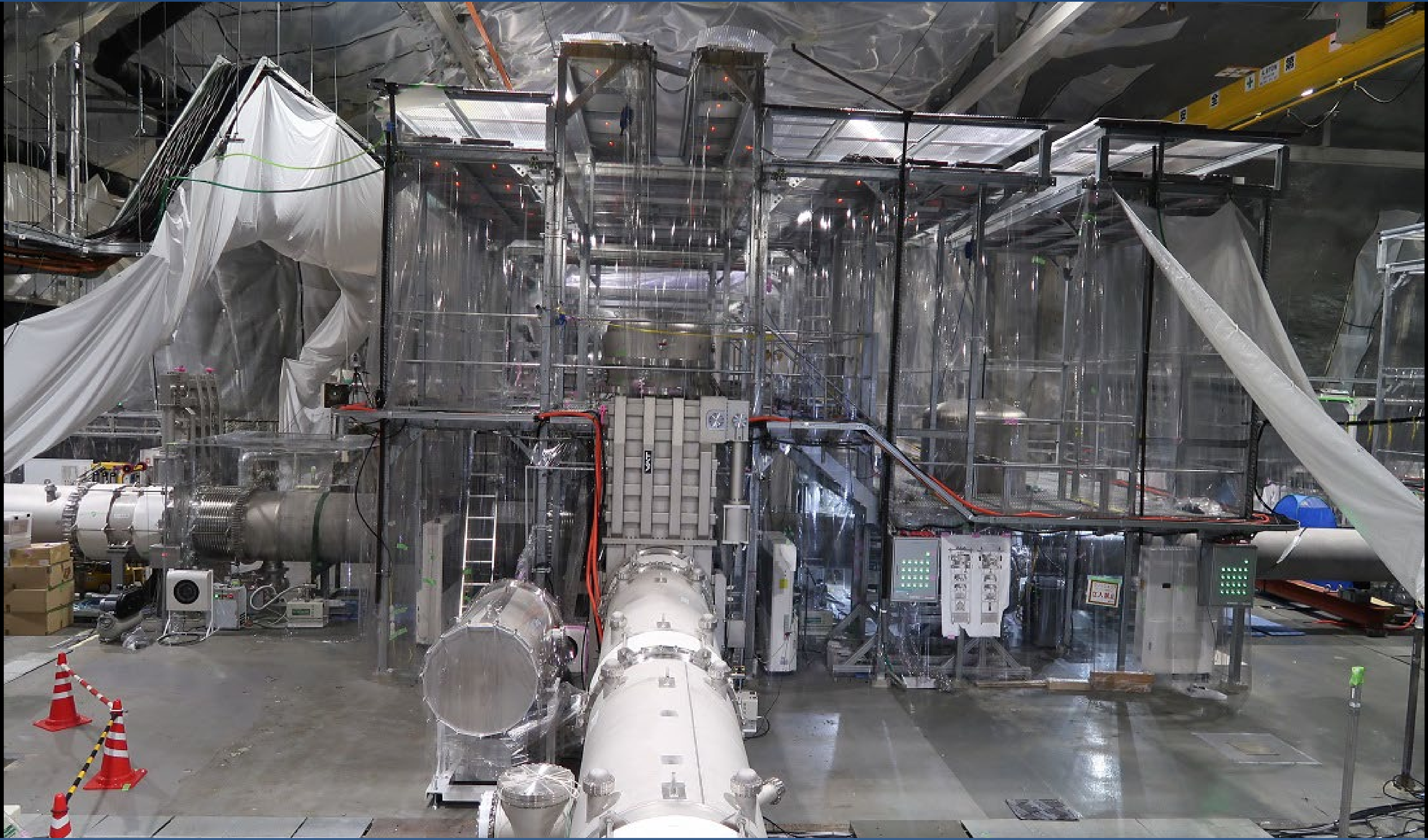


“Type-Bp”

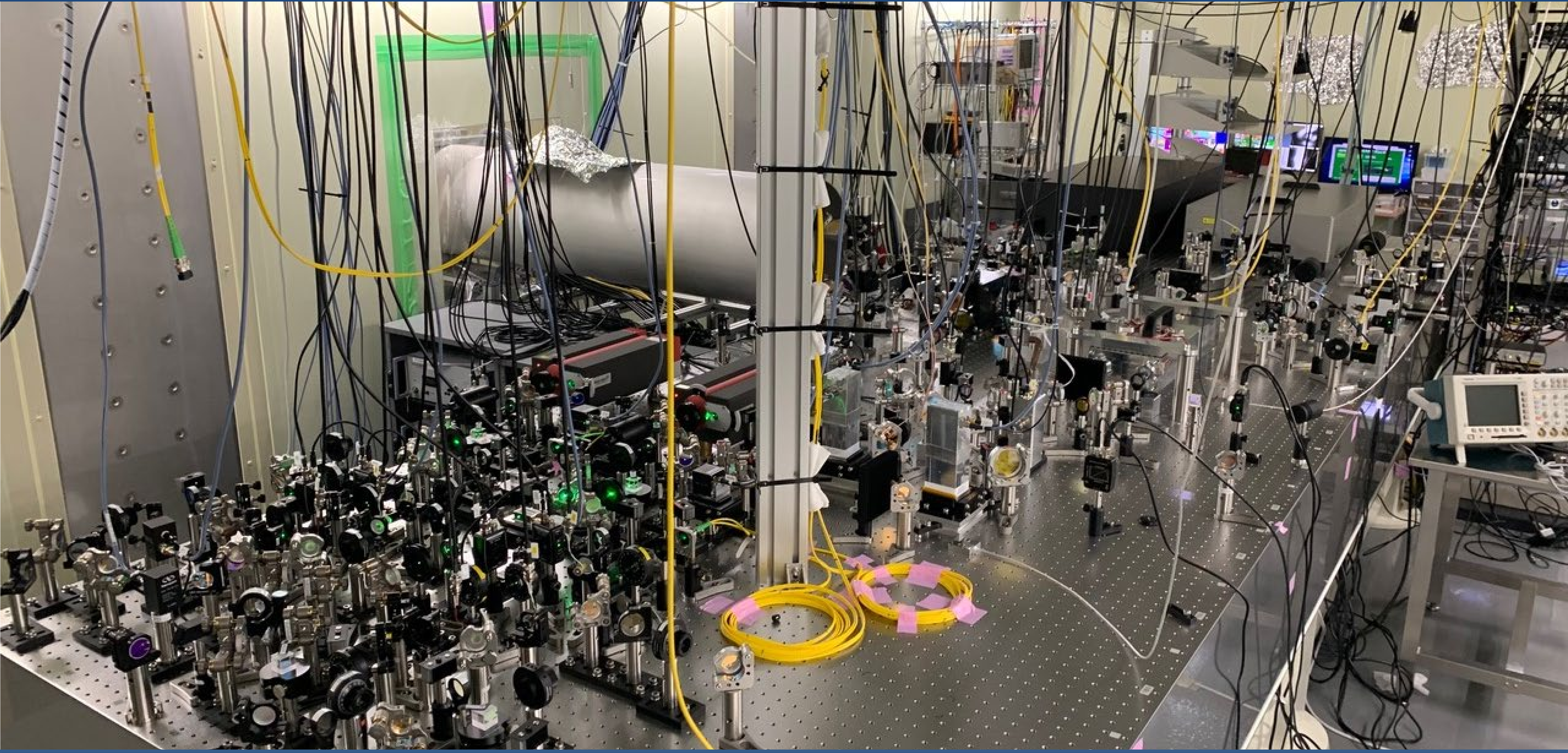


“Type-C”

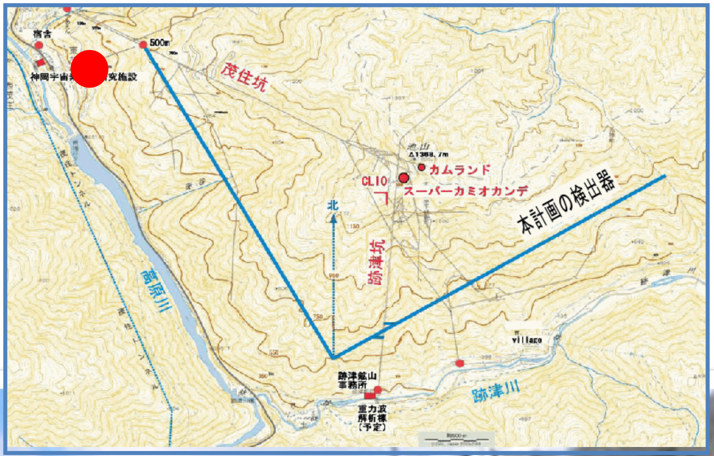
Center area (2020)



Laser room



Office and the KAGRA control room at the surface



The interferometer commissioning is carried out at the surface facility.

Signing Memorandum of Agreement (MoA): LIGO-Virgo-KAGRA

M1900145-v2, VIR-0091A, and JGW-M1910663

Memorandum of Agreement

between

VIRGO,

KAGRA,

and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

October 2019

Purpose of agreement:

The purpose of this Memorandum of Agreement (MOA) is to establish and define a collaborative relationship between VIRGO, KAGRA and the Laser Interferometer Gravitational Wave Observatory (LIGO) to develop and exploit laser interferometry to measure and study gravitational waves.

We enter into this agreement in order to lay the groundwork for decades of world-wide collaboration. We intend to carry out the search for and analysis of gravitational waves in a spirit of teamwork, not competition. Furthermore, we remain open to participation of new partners, whenever additional data can add scientific value to the detection and study of gravitational waves. All partners in the world-wide collaboration should have a fair share in the scientific governance of the collaborative work.

Among the scientific benefits we hope to achieve from this collaboration are: better confidence in detection of signals, better duty cycle and sky coverage for searches, better estimation of the location and physical parameters of the sources, and gravitational wave studies based on the detected signals. Furthermore, we believe that the sharing of ideas will also offer additional benefits.

This MOA supersedes the MOU LIGO-M060038-v5 between VIRGO and LIGO, established in March 2019. This MOA also supersedes the MOU JGW-M1201315-v3 between KAGRA, LSC

M1900145-v2, VIR-0091A, and JGW-M1910663

Approved:

4 OCT 2019
David Reitze Date
LIGO Executive Director and LIGO Principal Investigator

27-Sep-2019
Albert Lazzarini Date
LIGO Laboratory Deputy Director

27 September 2019
Patrick Brady Date
LSC Spokesperson

27 September 2019
James Hough Date
GEO Representative

30-Sep-2019
Stavros Katsanevas Date
Director of EGO

Oct. 4, 2019
Jo van den Brand Date
Virgo Collaboration Spokesperson

Oct. 4, 2019
Takaaki Kajita Date
KAGRA Principal Investigator

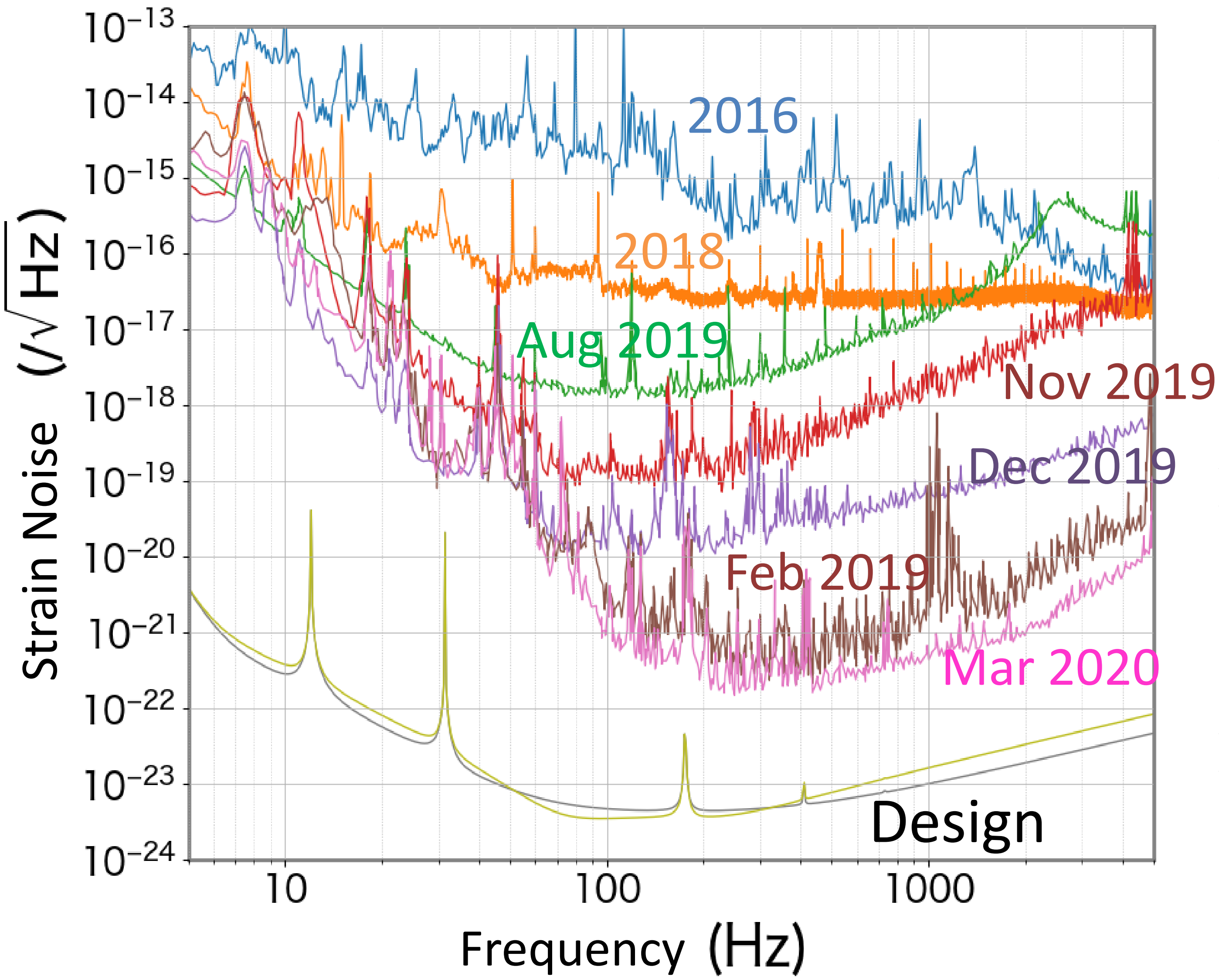
Oct 4, 2019
Hisaaki Shinkai Date
KSC Board Chair

Sign-up ceremony on Oct. 4, 2019

Agreed that KAGRA will join the GW network if it achieves >1Mpc sensitivity for binary neutron star mergers.

KAGRA sensitivity history until spring 2020

KAGRA collabo. PTEP., 2021, 05A101(2021)



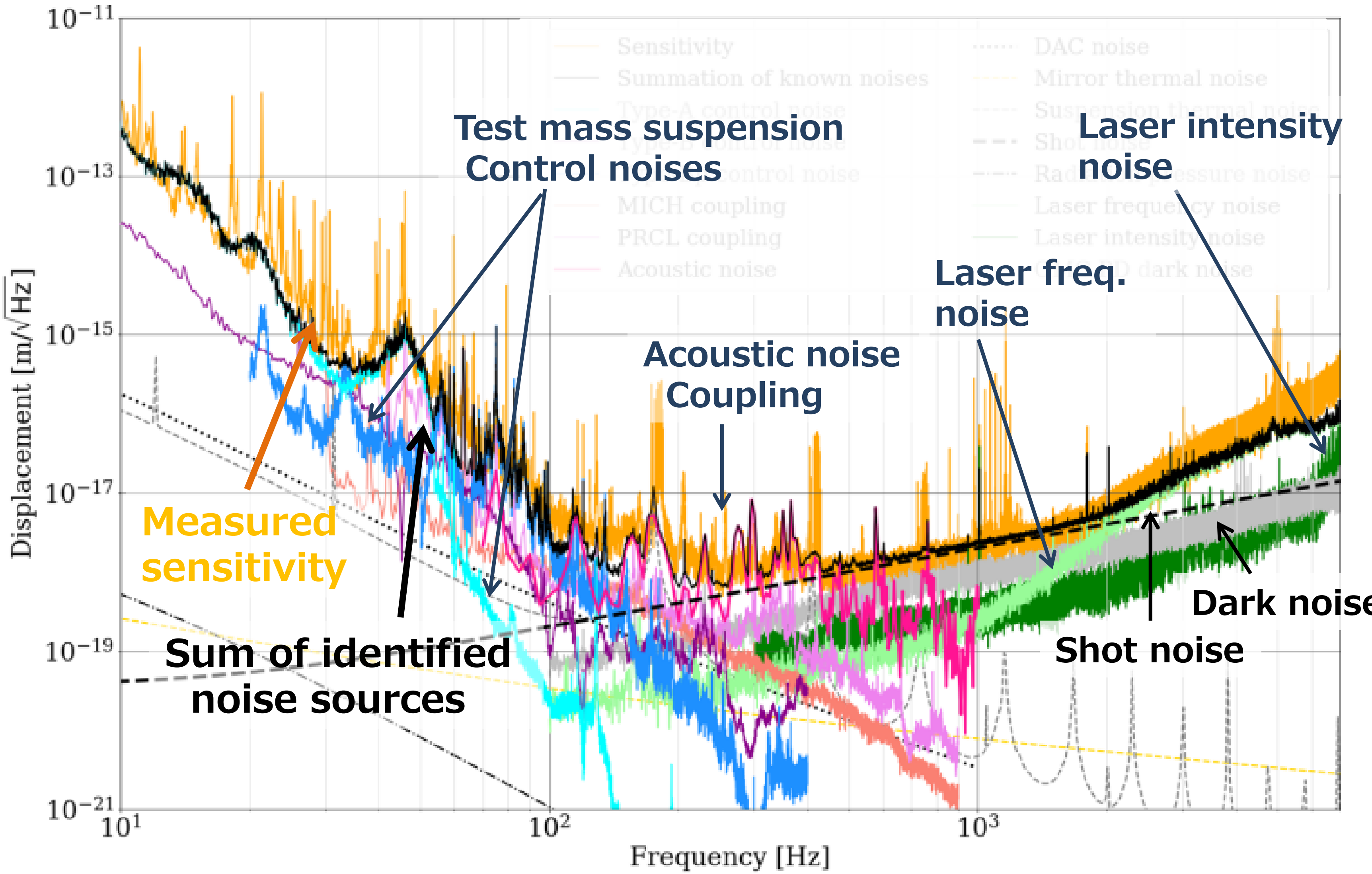
- In March 2020, after about a year of commissioning, KAGRA achieved the sensitivity of 1Mpc, and officially joined the GW network with LIGO and Virgo.
- Due to COVID-19, LIGO and Virgo already stopped the observation. KAGRA had 2 weeks of observation run with GEO in Germany (O3GK).
- Started the improvement work, giving up the observation.

Sensitivity improvement

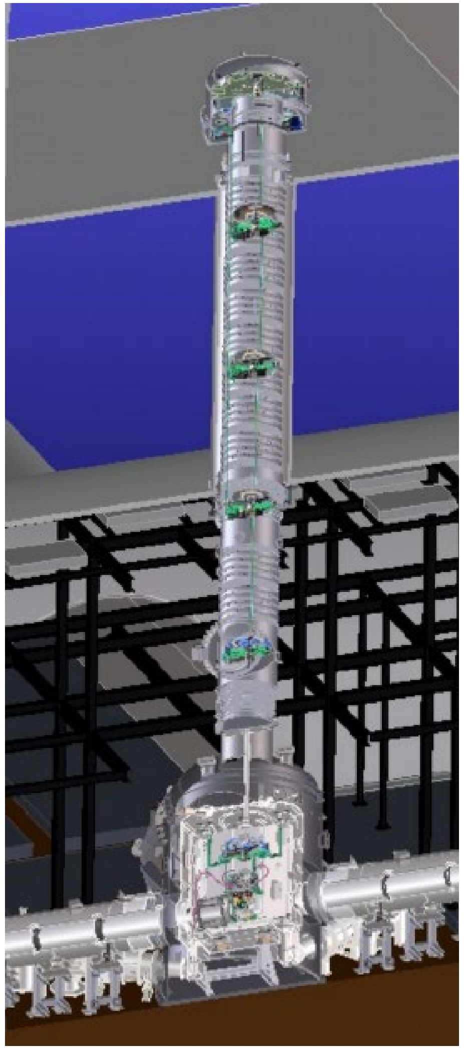
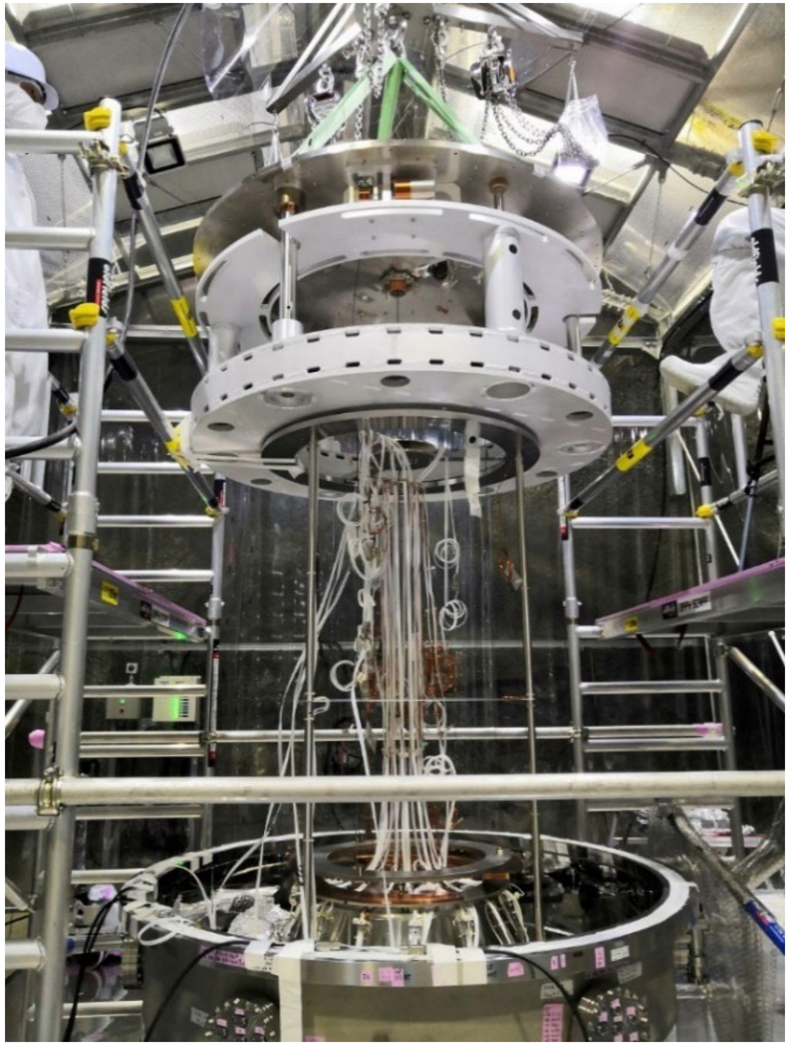
In order to improve the sensitivity, extensive noise analyses were carried out.

- ✓ Re-installation and improvement of the vibration isolation system (for low frequency).
- ✓ Installation of baffles for stray-light reduction (for mid frequency).
- ✓ Shot noise reduction (for high frequency).
- ✓ …

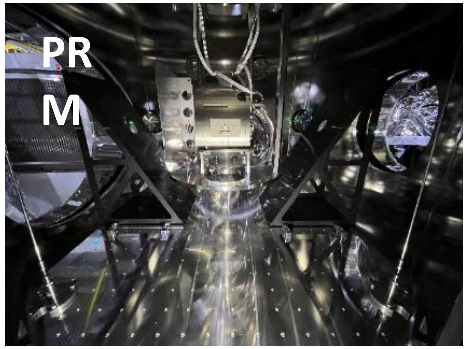
KAGRA collabo. PTEP., 2023, 10A101(2023)

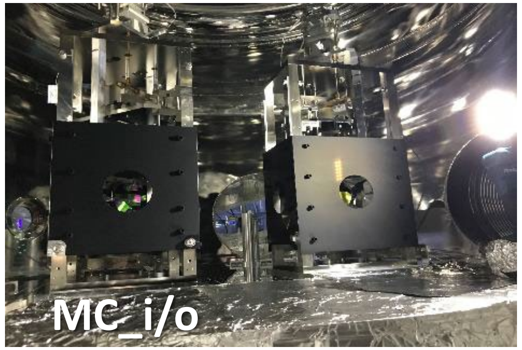


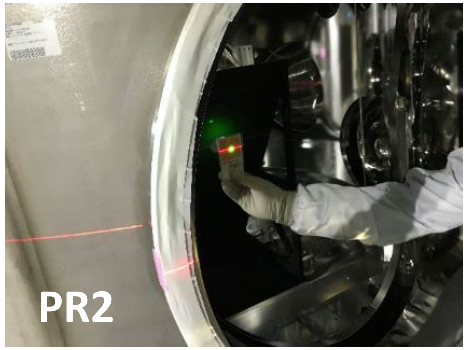
Sensitivity improvement works (2020 to spring 2023)

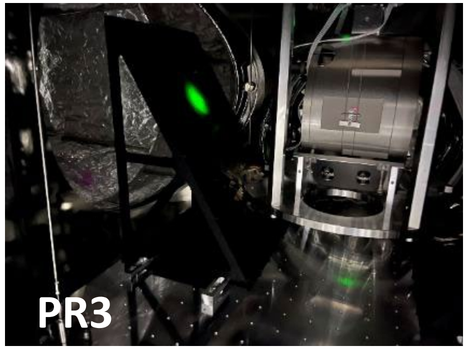



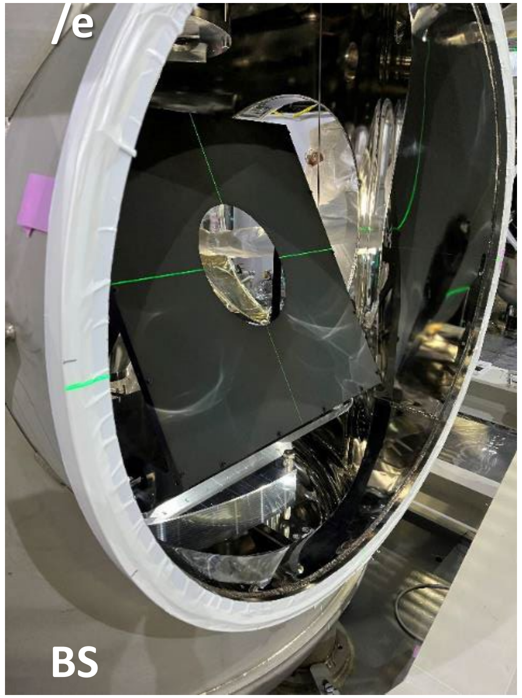
Reinstallation of vibration isolation systems and the tuning of them







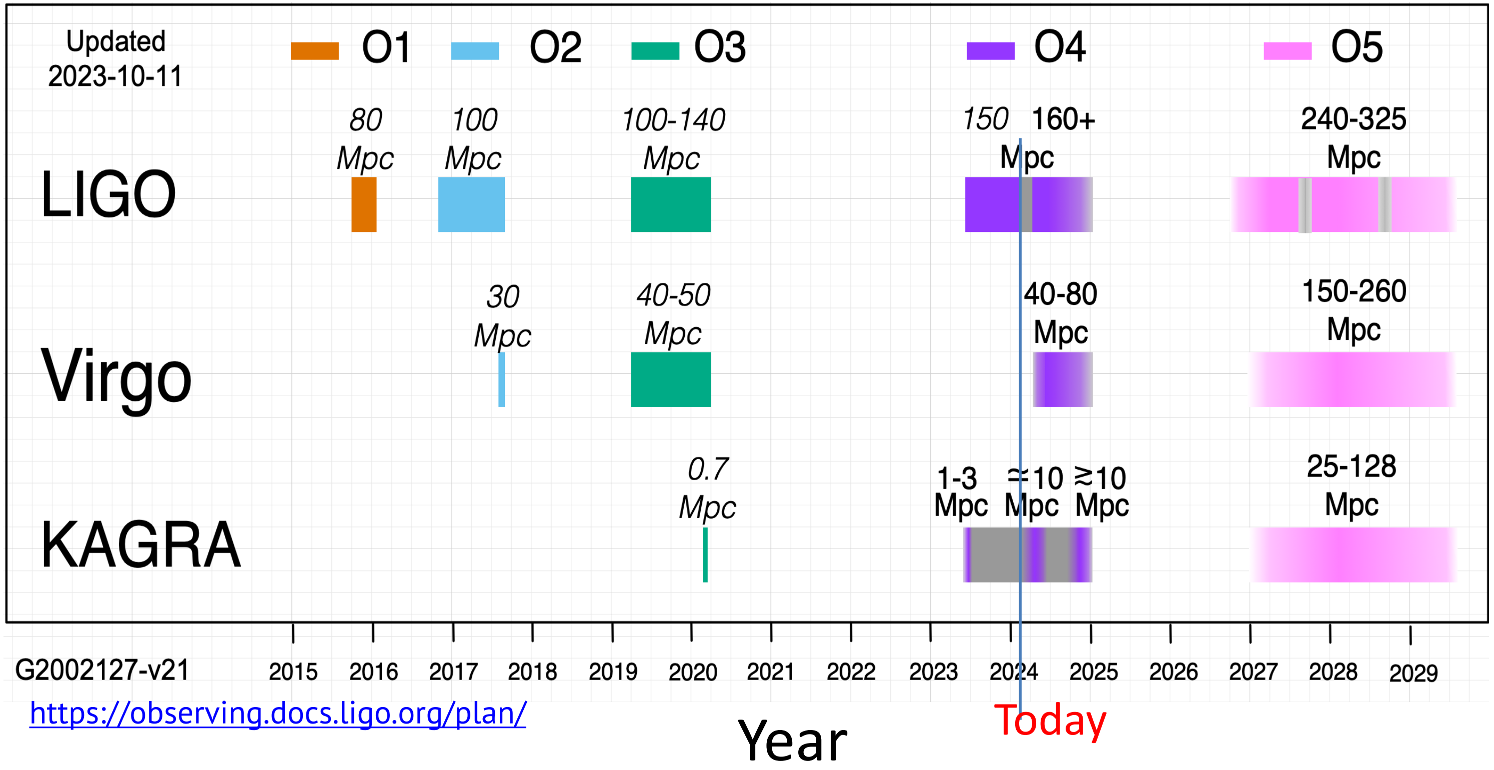


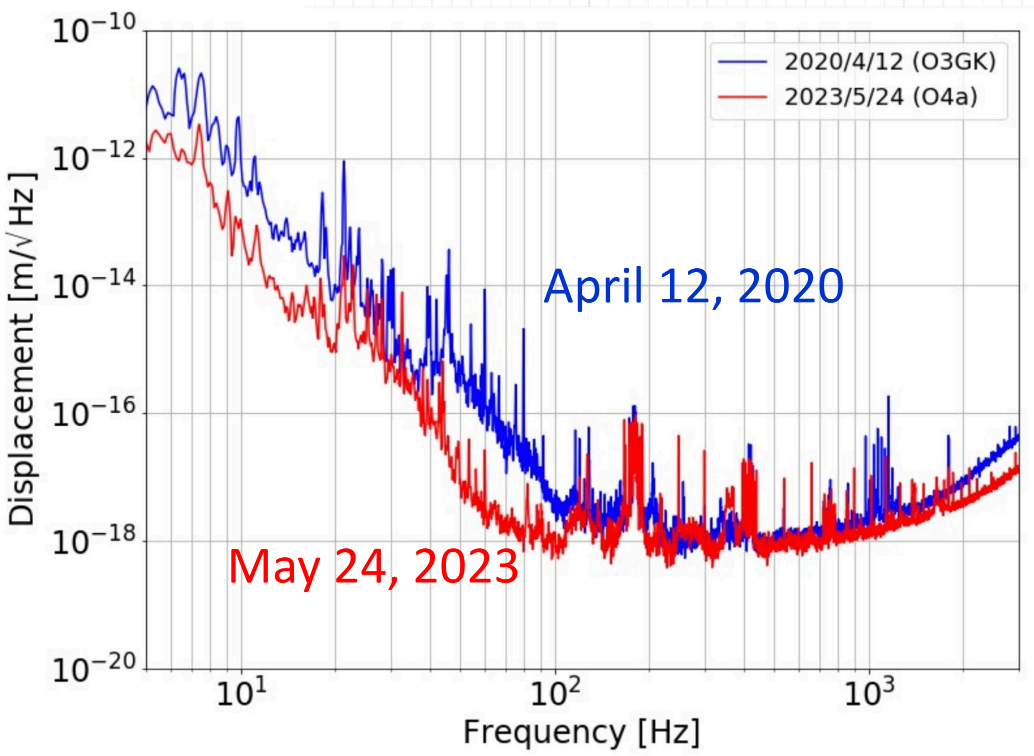


Installation of optical baffles

(and many other small improvements)

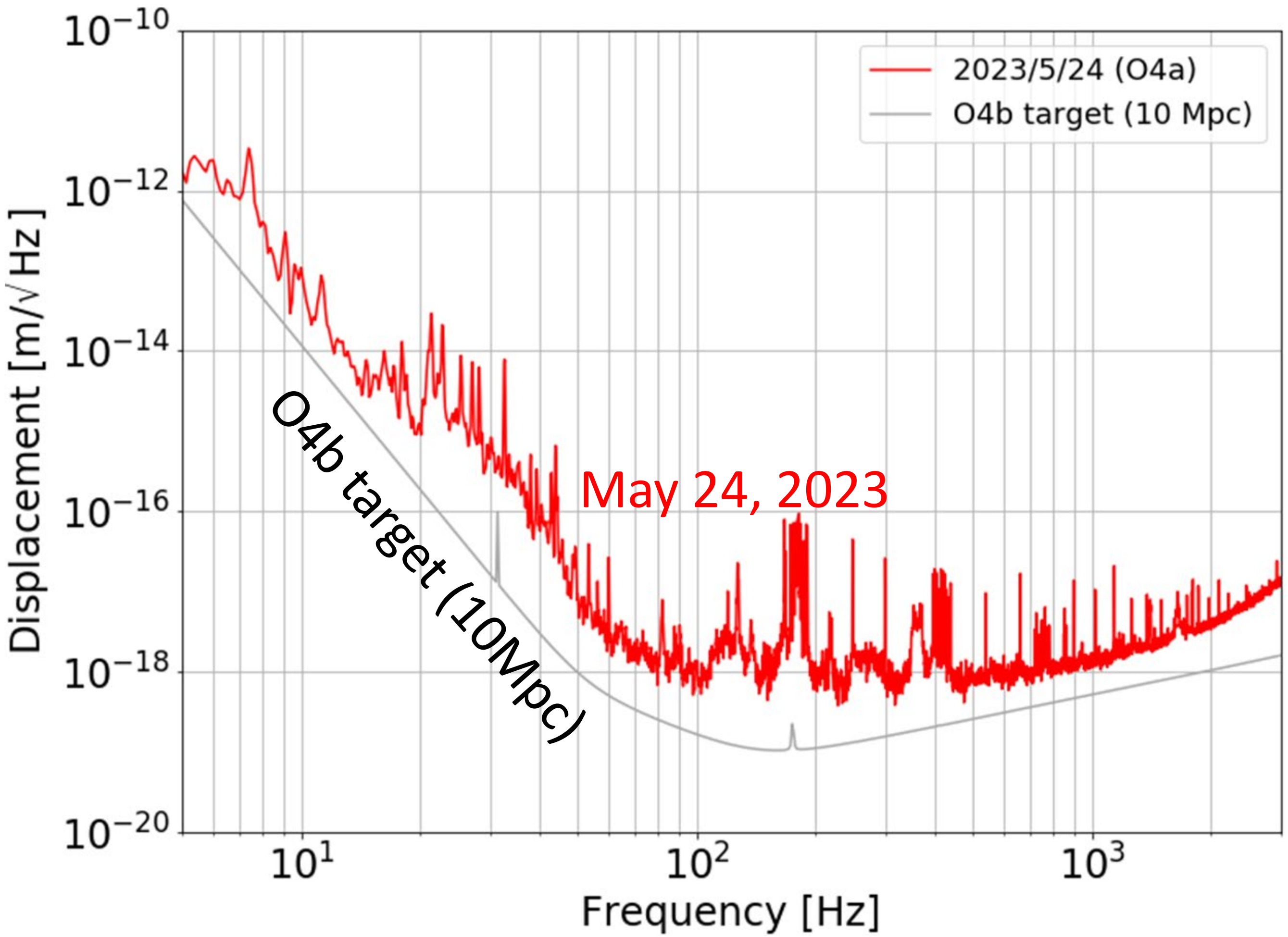
Observation run in 2023 (O4a)





- ✓ KAGRA joined the O4 observation on May 24, 2023.
  Compared with KAGRA in 2020, the sensitivity was improved (0.7Mpc → 1.3 Mpc). The duty cycle was also improved significantly (53% → 80%).)
- ✓ After 1 month of observation, KAGRA stopped the observation and resumed the commissioning.
- ✓ KAGRA will rejoin O4 (O4b) in the spring of 2024.

Toward the next run in 2024 (O4b)



We need to;

- ✓ Further reduce the suspension control noises (low frequency).
- ✓ Cool down the sapphire mirrors below 100K (low-mid frequency).
- ✓ Reduce the acoustic nises (around the Output Mode Cleaner) (mid frequency).
- ✓ Input higher power laser (high frequency).

By the spring of 2024, we hope we will reach the targeted sensitivity for O4b, which is approximately 10Mpc. We will run at least for 3months. We hope that we can see the GW signal during O4.

Our plan reported to the community in 2023

The earthquake on Jan. 1, 2024 and its effect to KAGRA

Earthquake on Jan. 1, 2024

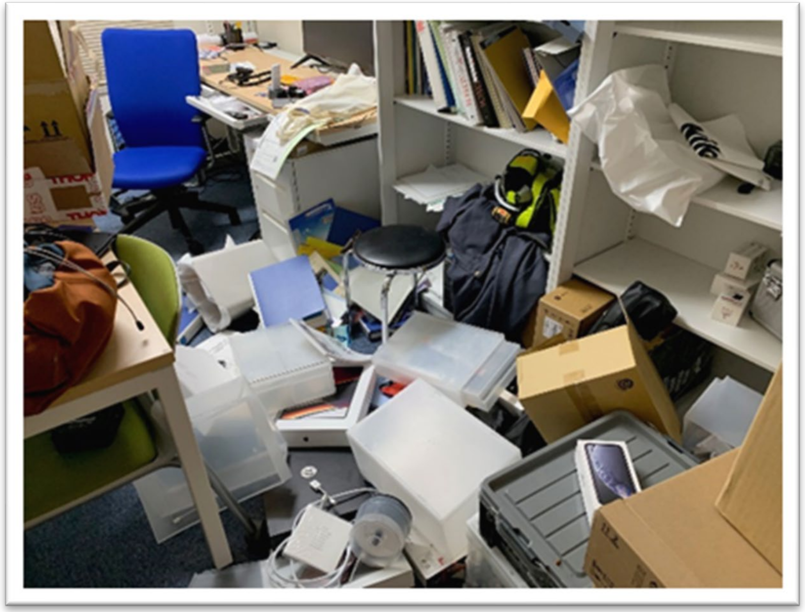
A magnitude 7.6 earthquake occurred at 16:10 (JST) on Jan. 1, 2024.

Seismic intensity based on Japanese seismic intensity scale (of 0 to 7)

https://www.tokyo-np.co.jp/article/307296

The ground rose 4 meters in some area of the Noto peninsula. (In Hida city (where KAGRA locates), the land displacement was 2-4 centimeters.)

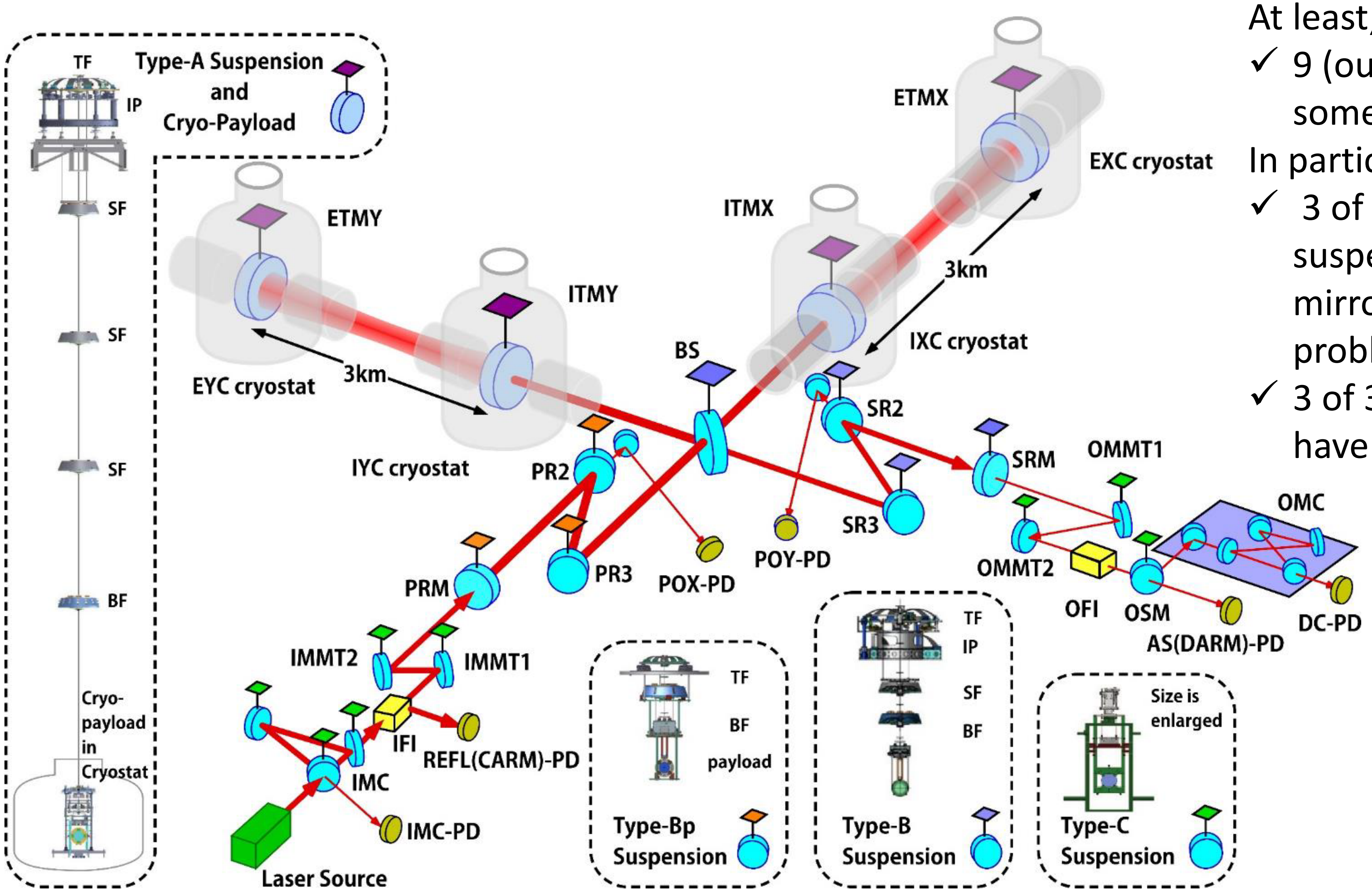
The data indicate that this earthquake was the strongest one in Hida city in the last 100 years.



Inside the KAGRA surface building on Jan. 1

Damage to KAGRA (as of end of Jan.)

Mirror	
MCi	x
MCo	x
MCe	x
IMMT1	o
IMMT2	o
PRM	x
PR2	x
PR3	x
BS	o
SR3	o?
SR2	o?
SRM	o?
OMMT1	o
OMMT2	o
OSM	o
OMC	?
ITMX	x
ITMY	o?
ETMX	x
ETMY	x



At least;

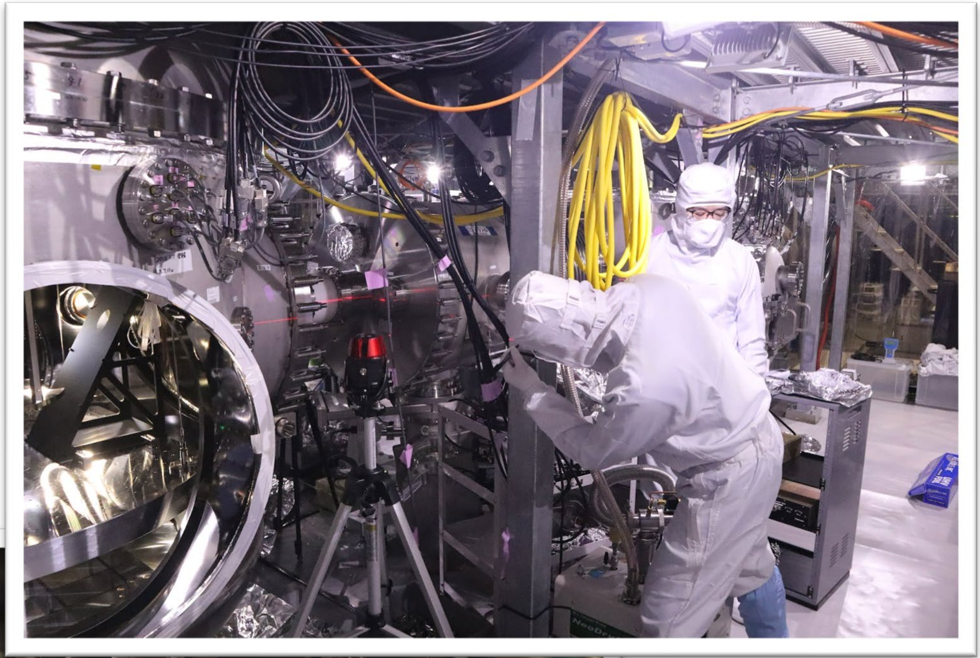
- ✓ 9 (out of 20) VIS have some problems.

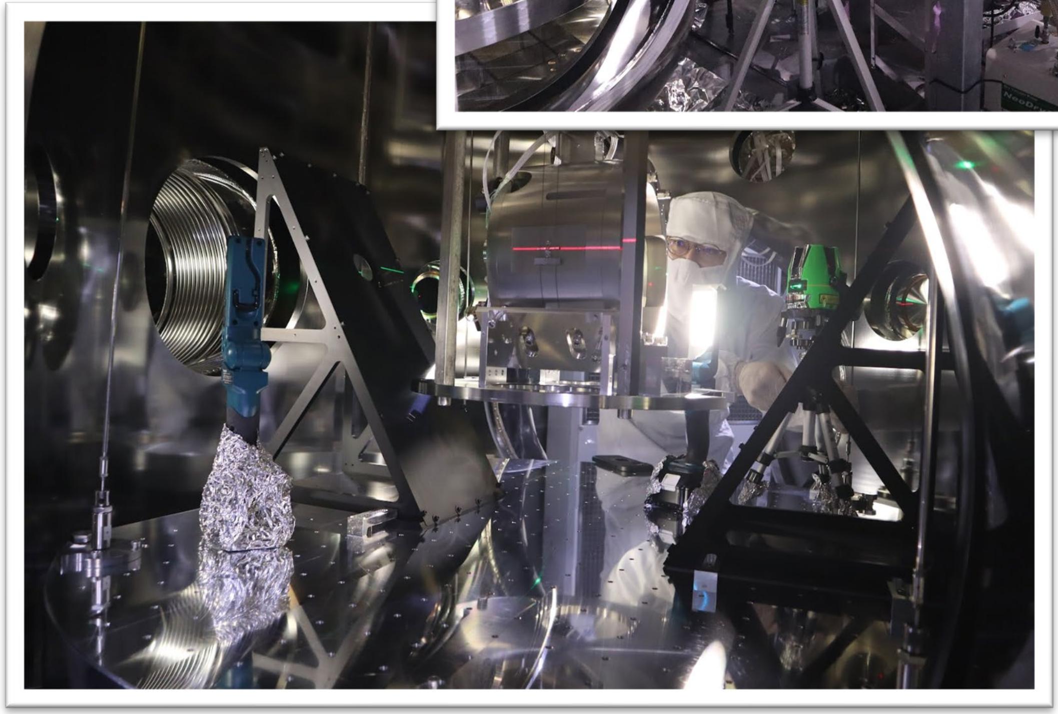
In particular;

- ✓ 3 of 4 Type-A VIS (that suspend cryogenic mirrors) have problems.
- ✓ 3 of 3 Type-Bp VIS have problems.

Recovery plan (as of end of Jan.)

- Started the recovery work (➔ photos)
- At the same time, the cryogenic mirrors are being brought back to room temperature.
- From now on:
  - Recovery of the hardware (will take at least several months)
  - Health-check and alignment
  - Cooling down the mirrors
  - Recovery to the interferometer in O4a
  - Sensitivity improvement to about 10Mpc
- We hope that KAGRA can join O4b before finishing the observation run. (O4b is expected to finish in Jan. 2025).





Work at PRM (Feb.1, 2024)

KAGRA’s contribution to the GW science

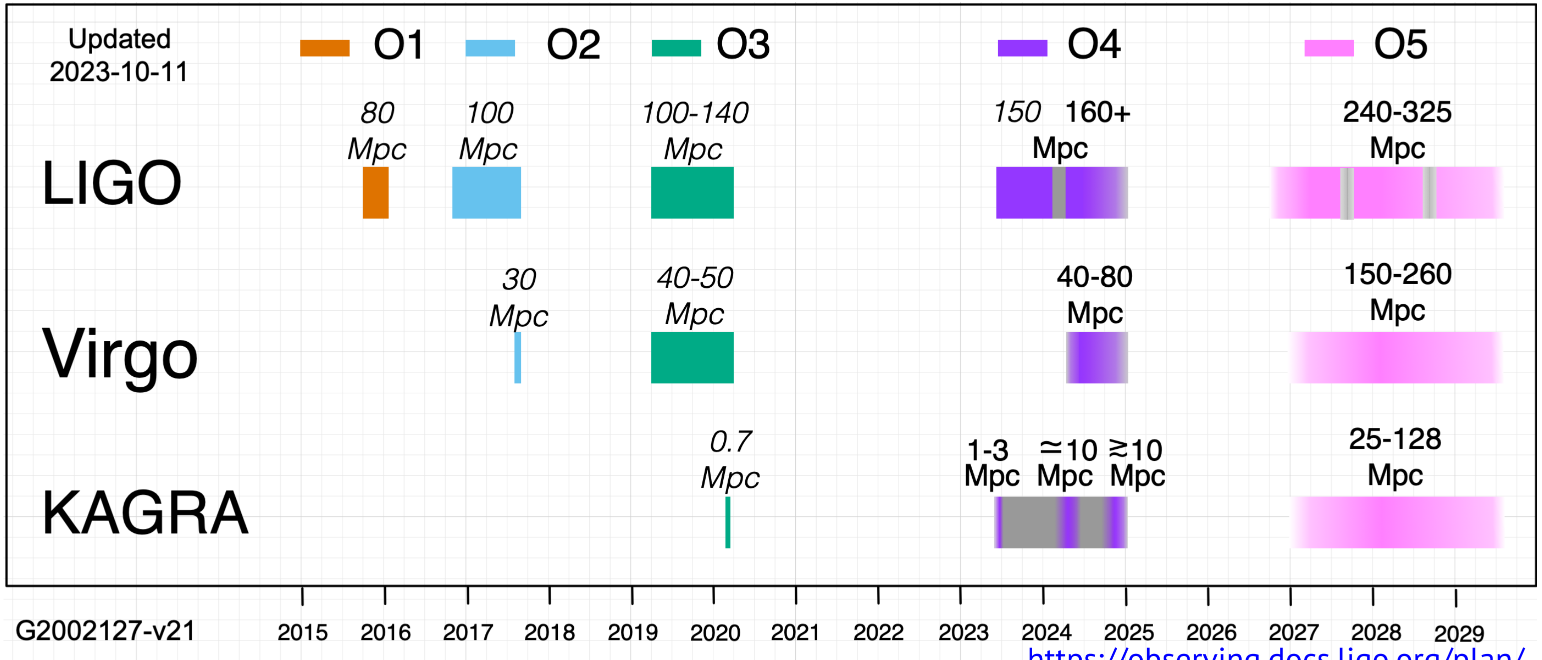
KAGRA's plan after O4

✓ After O4, KAGRA will further improve the sensitivity to really contribute to the GW astronomy.

✓ The target sensitivity (tentative) is 25-128 Mpc in O5, which will start around 2027.

✓ Possible improvements for O5 (*):

- Better sapphire mirrors
- Higher laser power
- Better tuning of the vibration isolation system
- Operating the signal recycling system
- Squeezing technology, and so on



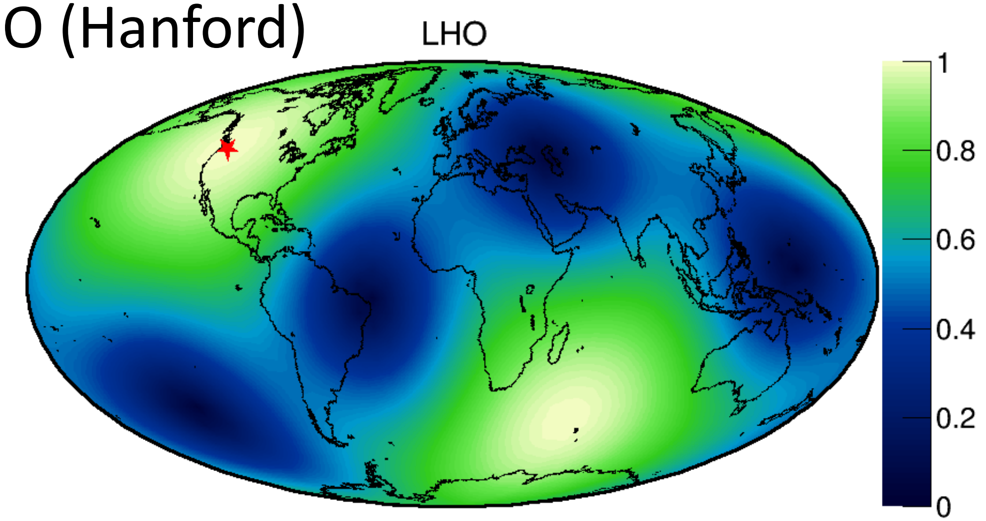
https://observing.docs.ligo.org/plan/

(*) KAGRA has set up a task force in Dec 2023 to discuss the actual work plan for O5

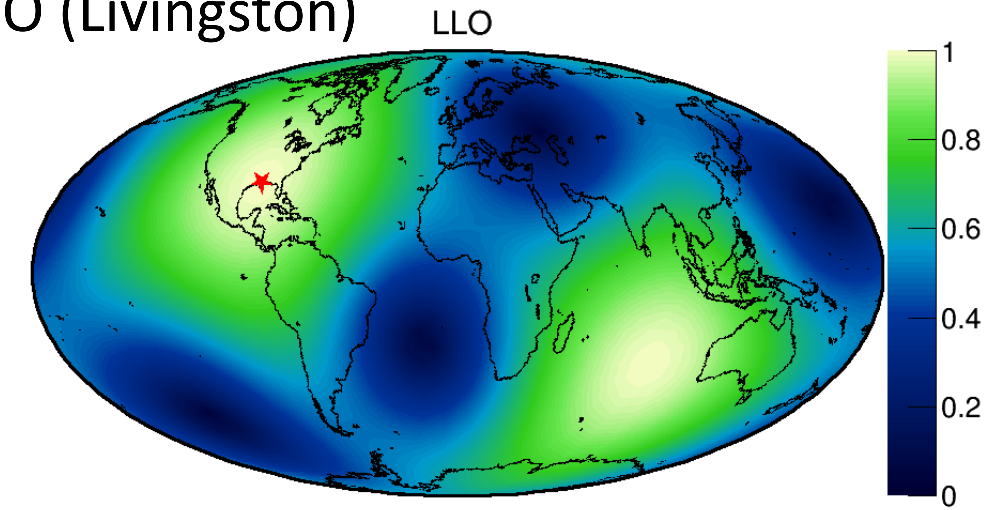
✓ After O5, KAGRA would like to improve the sensitivity further, and contribute to the GW astronomy significantly. KAGRA has set up another task force (which was agreed in Dec. 2023 and started in Feb. 2024) to discuss the KAGRA 10-year plan.

Importance of Global GW Network: Detector antenna patterns

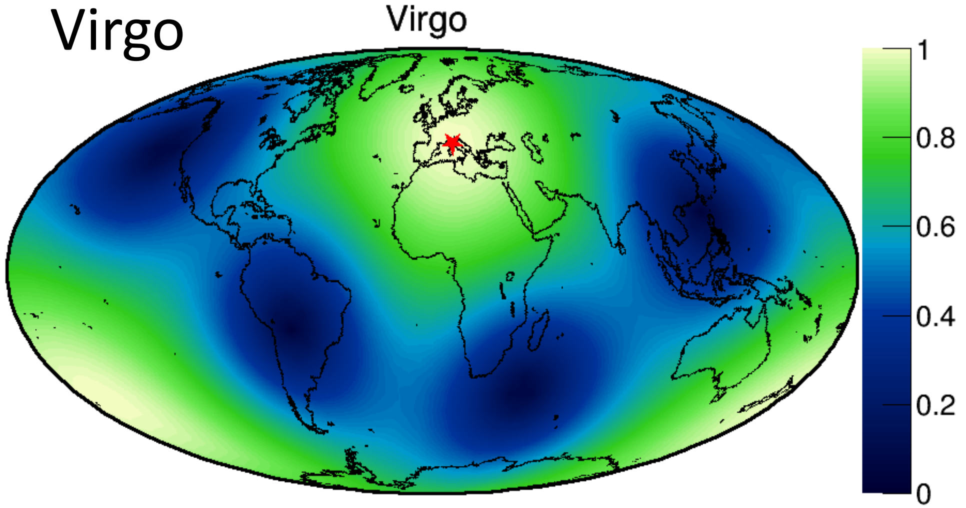
LIGO (Hanford)



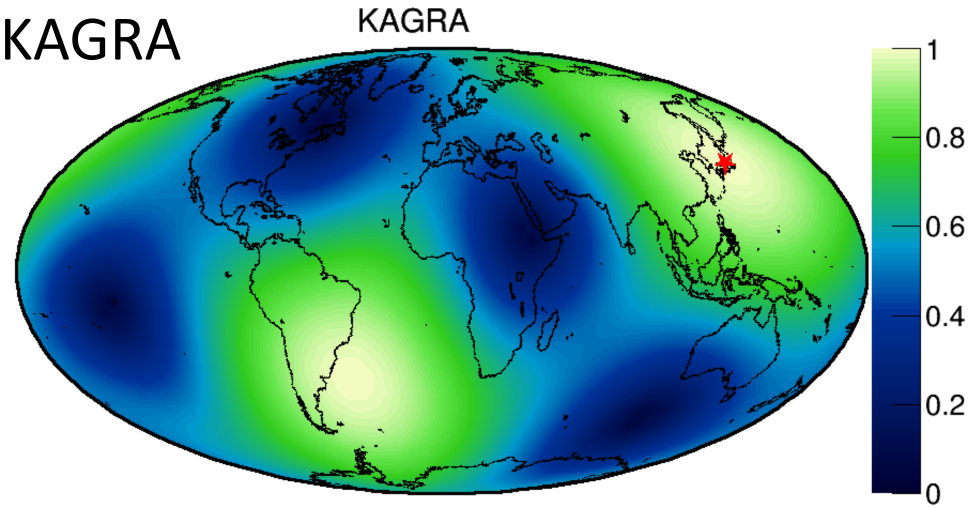
LIGO (Livingston)



Virgo



KAGRA



KAGRA is complementary in the sensitive direction to other detectors.

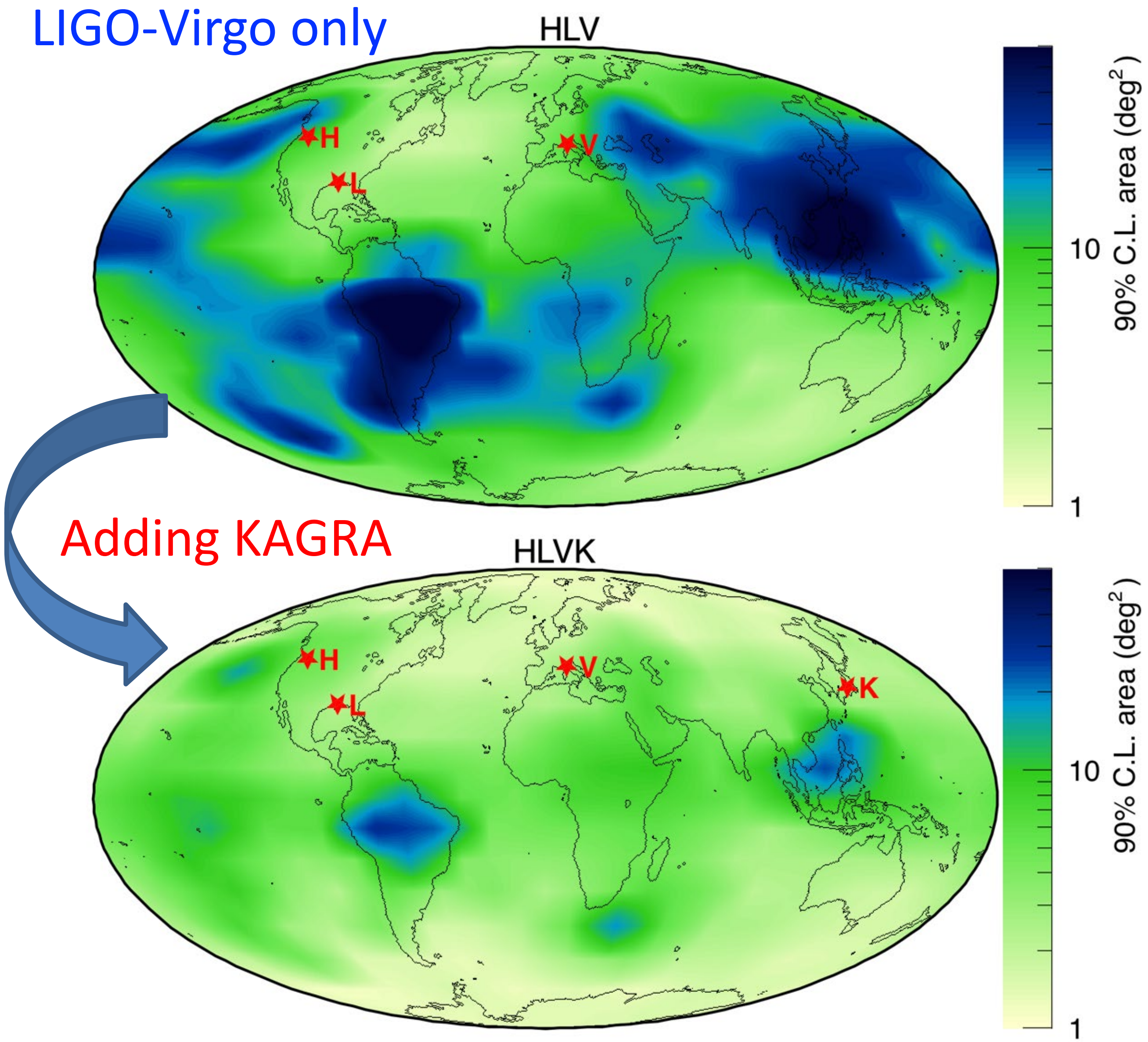
Importance of Global GW Network: Sky localization

- Assuming the sensitivity of;

LIGO	Virgo	KAGRA
205 Mpc	126 Mpc	152 Mpc

LV: *LIGO-P1200087*, K: *JGW-T1707038*

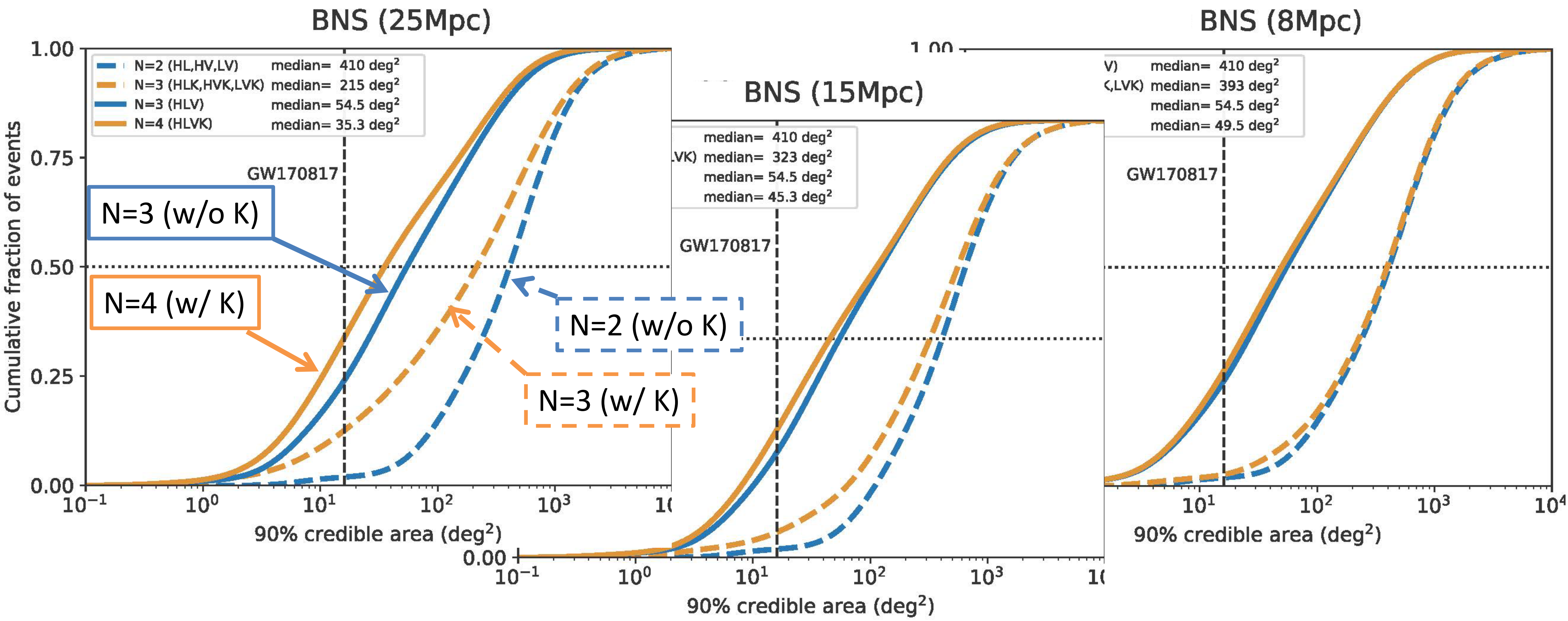
- Also, assuming NS-NS merger ($1.4\ M_{Sun}$ -$1.4\ M_{Sun}$) at 150 Mpc



However, the expected sensitivity of KAGRA during O4 is much lower than the design sensitivity…

Source localization in the near future

- Assumed sensitivity (Binary NS range): LIGO 120Mpc, Virgo 60Mpc, KAGRA 8, 15 and 25Mpc



KAGRA should try to maximize the sensitivity as much as we can (>25Mpc in O5).

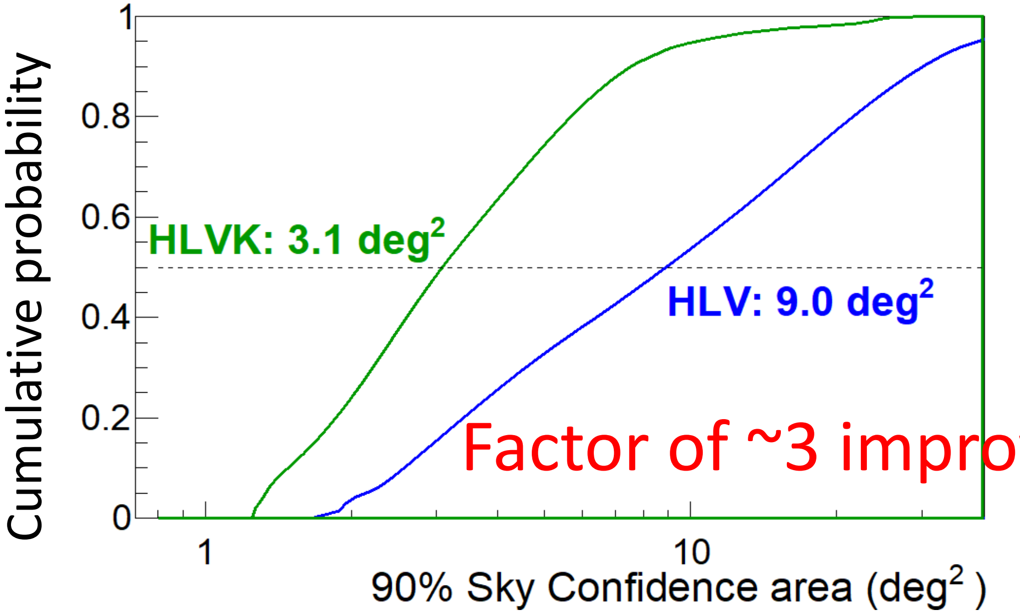
Importance of Global GW Network: Sky localization

- Assuming the sensitivity of;

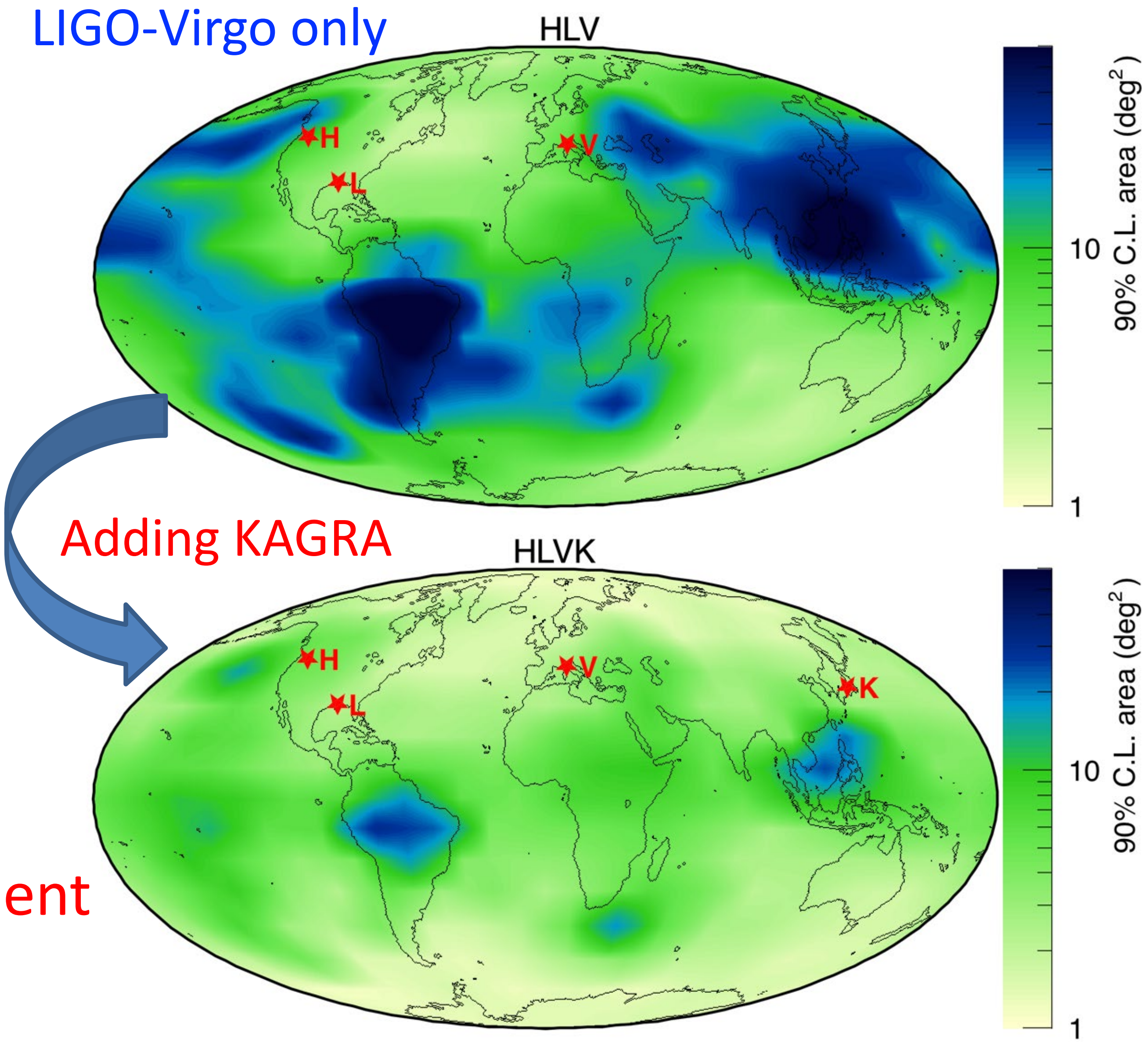
LIGO	Virgo	KAGRA
205 Mpc	126 Mpc	152 Mpc

LV: *LIGO-P1200087*, K: *JGW-T1707038*

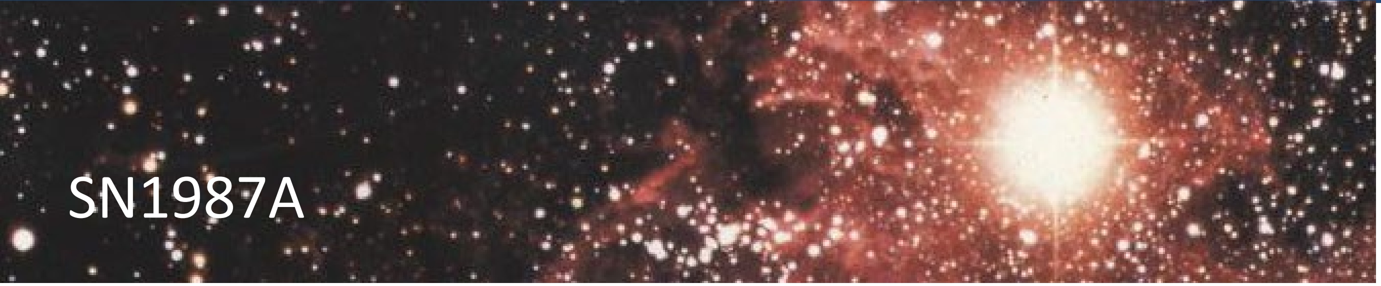
- Also, assuming NS-NS merger ($1.4\ M_{Sun}$ -$1.4\ M_{Sun}$) at 150 Mpc



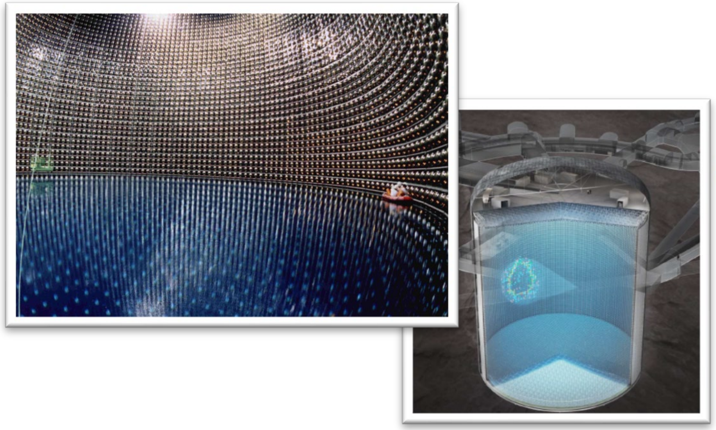
Factor of ~3 improvement

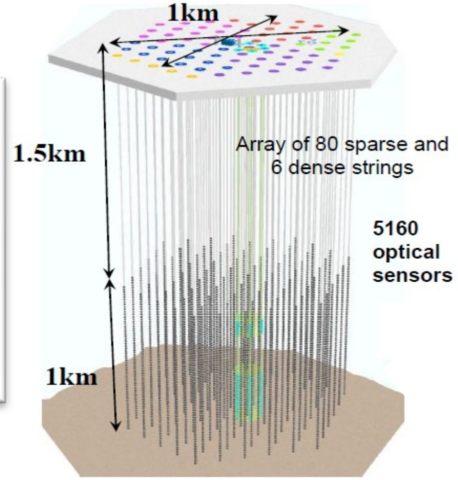


Multi-messenger astronomy with GW



If a supernova explodes at the center of the Milky Way…





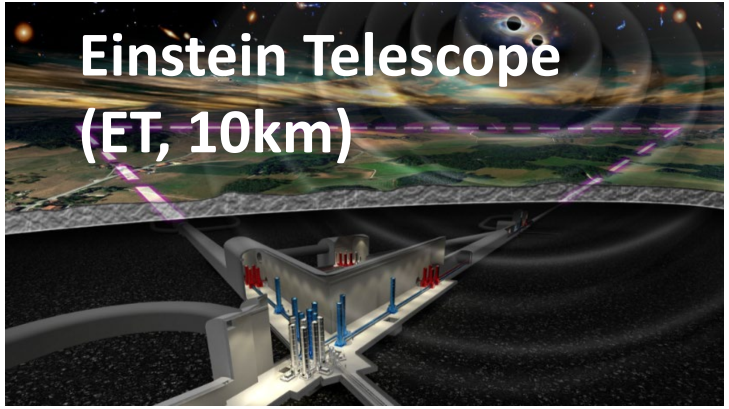
Gravitational waves

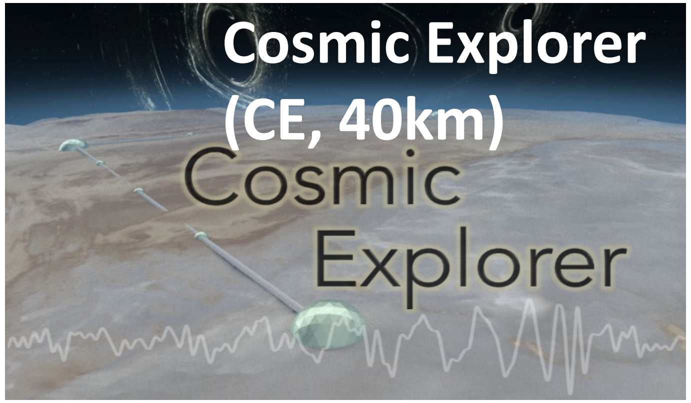
Neutrinos

Truly understanding the mechanism of the Supernova explosion !

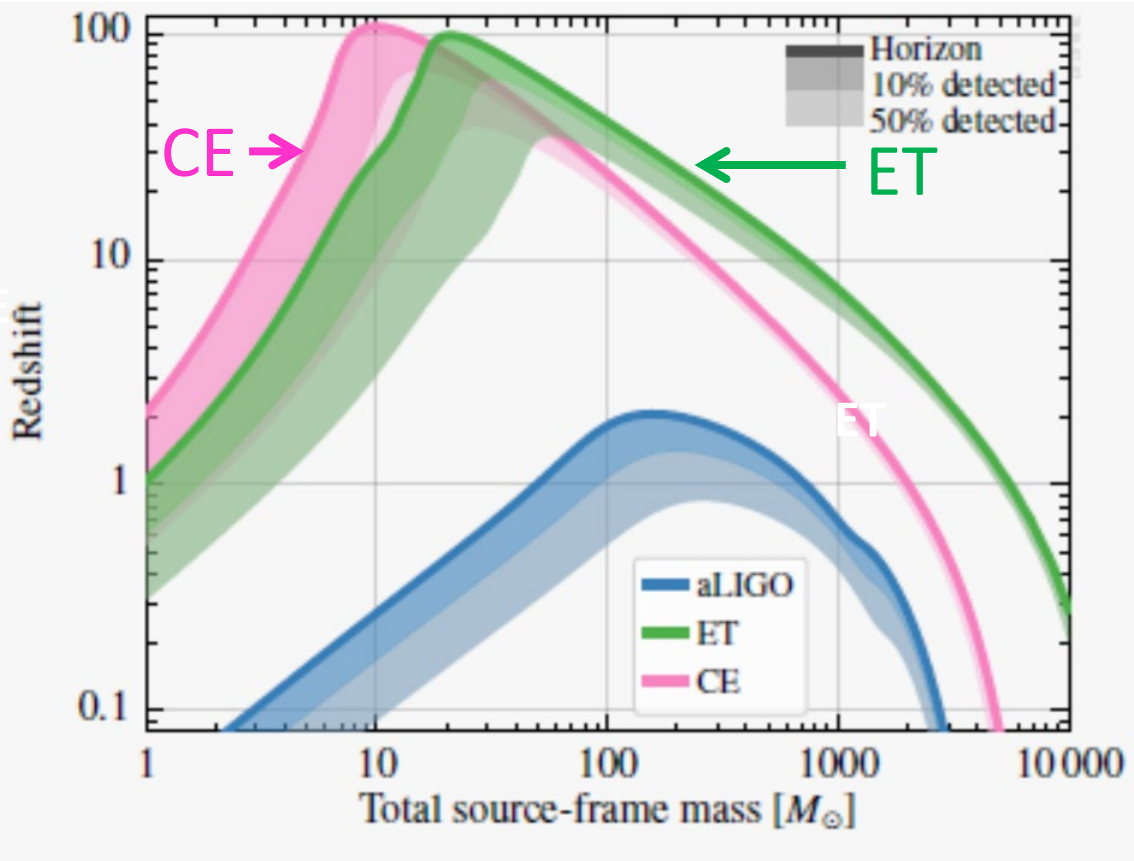
+Electromagnetic observations,
+ Simulations

Future ground-based GW detectors and KAGRA



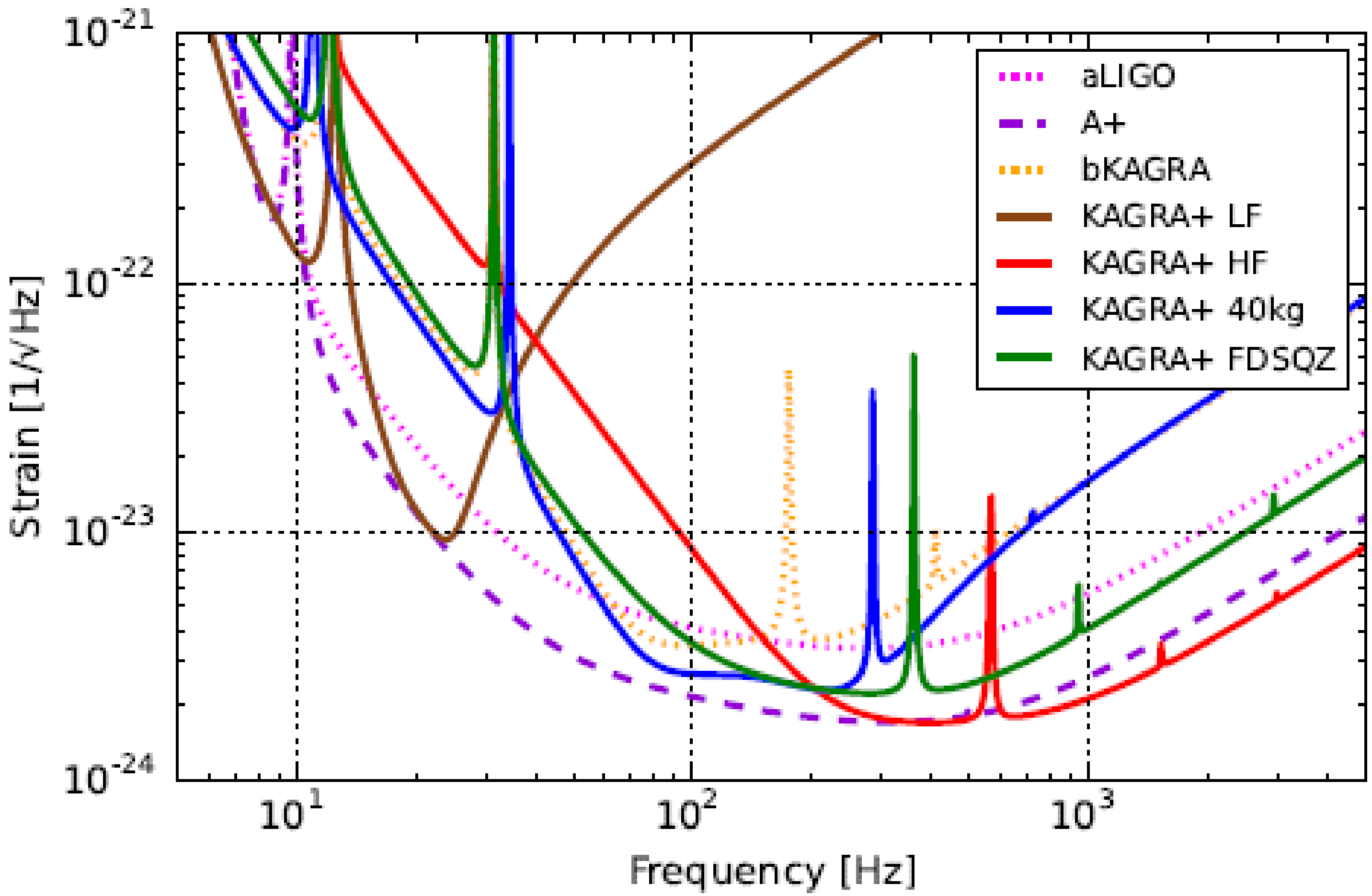


- Since the present generation of ground-based GW detectors have been so successful, there have been intense activities to design and propose the next generation detectors (ET and CE).
- These detectors will produce very important scientific results.
- These future detectors will use cryogenic mirrors to improve the sensitivity. One of them (ET) will be constructed in underground for the better sensitivity. KAGRA would like to contribute to these projects by the experience and technology in the cryogenic mirrors and the underground site.



The next generation global gravitational wave observatory, The Science Book, Vicky Kalogera et al., GWIC 2021

Possible future sensitivities of KAGRA



	Mirror mass	Input power @BS	SRM reflectivity(%)	Detuning angle	Squeezing (DB)
bKAGRA	22.8	673	84.6	3.5	0
LF	22.8	4.5	95.5	28.5	0
HF	22.8	3440	90.7	0.1	6.1
40kg	40	1500	92.2	3.5	0
FDsq	22.8	1500	83.2	0.2	5.2 (FC)

- ✓ Several possible upgrade of KAGRA have been considered already.
- ✓ It is time to discuss what will be the actual upgrade of KAGRA in the next 10 years (which will be discussed in the task force) and the subsequent 10 years.

Summary

- KAGRA is a unique gravitational wave detector with cryogenic mirrors and the underground site.
- KAGRA has hoped to achieve a reasonably good sensitivity and observe GW signals during O4. Due to the effect of the earthquake, it is clear that achieving this goal is not easy. We will do our best.
- In the near future, KAGRA would like to really contribute to the global network of gravitational wave detectors and to the science of gravitational wave astronomy.