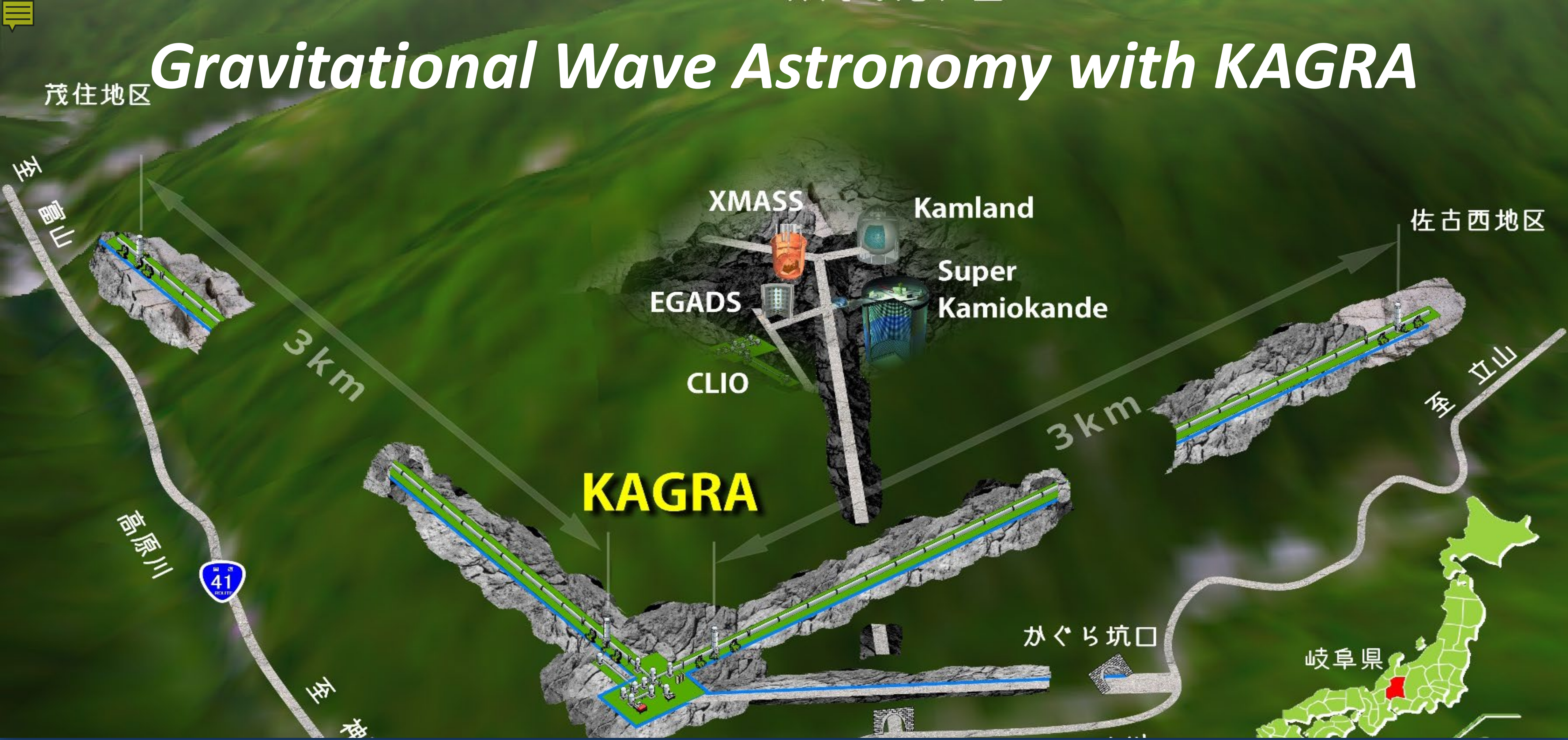
Gravitational Wave Astronomy with KAGRA



Tamkang University Taiwan, May 31, 2023

Takaaki Kajita,
Institute for Cosmic Ray Research, The Univ. of Tokyo

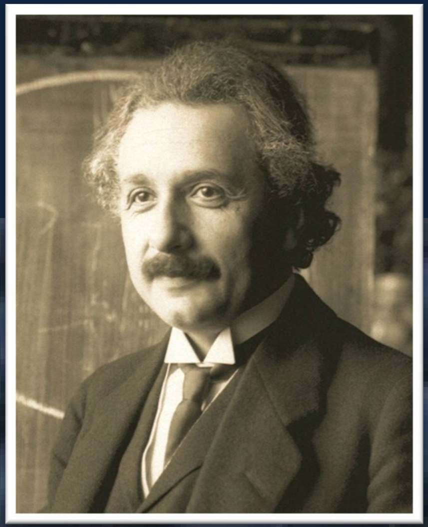
Outline

- *Introduction*
- *The KAGRA project*
- *KAGRA's contribution to the GW science*
- *Future ground-based GW detectors*
- *Summary*

Introduction

Gravitational waves

In 1916, A. Einstein predicted gravitational waves based on his theory of general relativity.



A. Einstein
（by F. Schmutzer, Wikipedia）

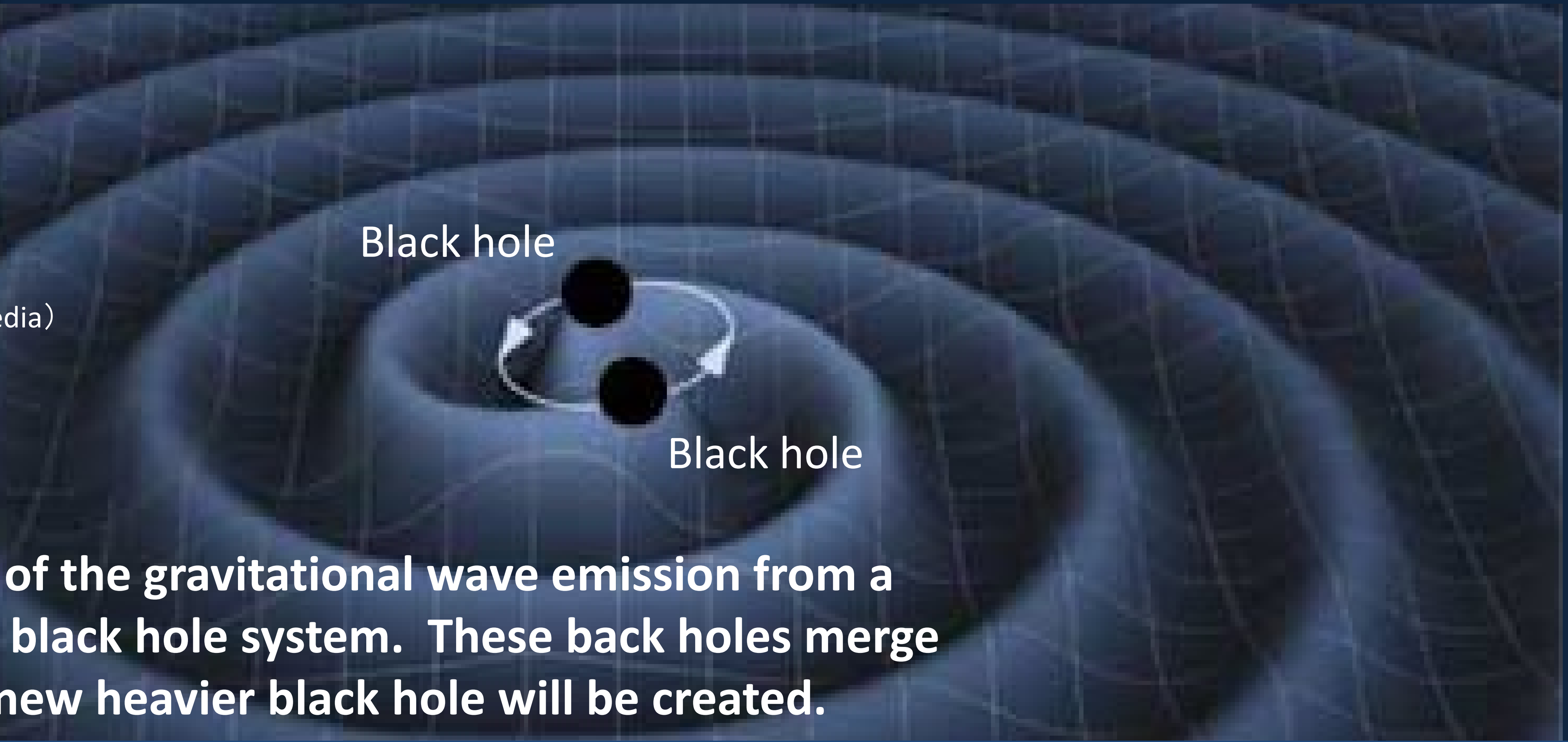
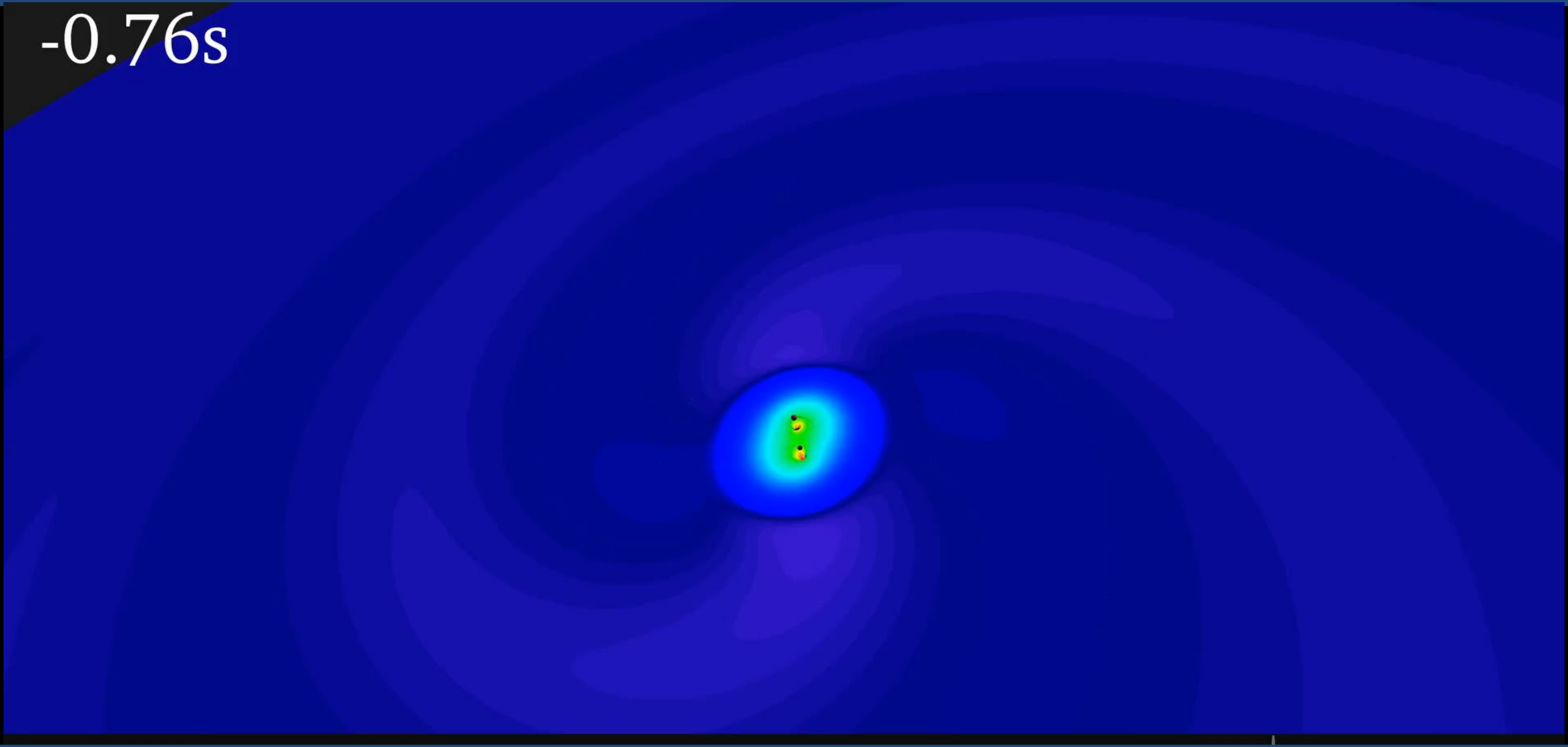


Image of the gravitational wave emission from a binary black hole system. These back holes merge and a new heavier black hole will be created.

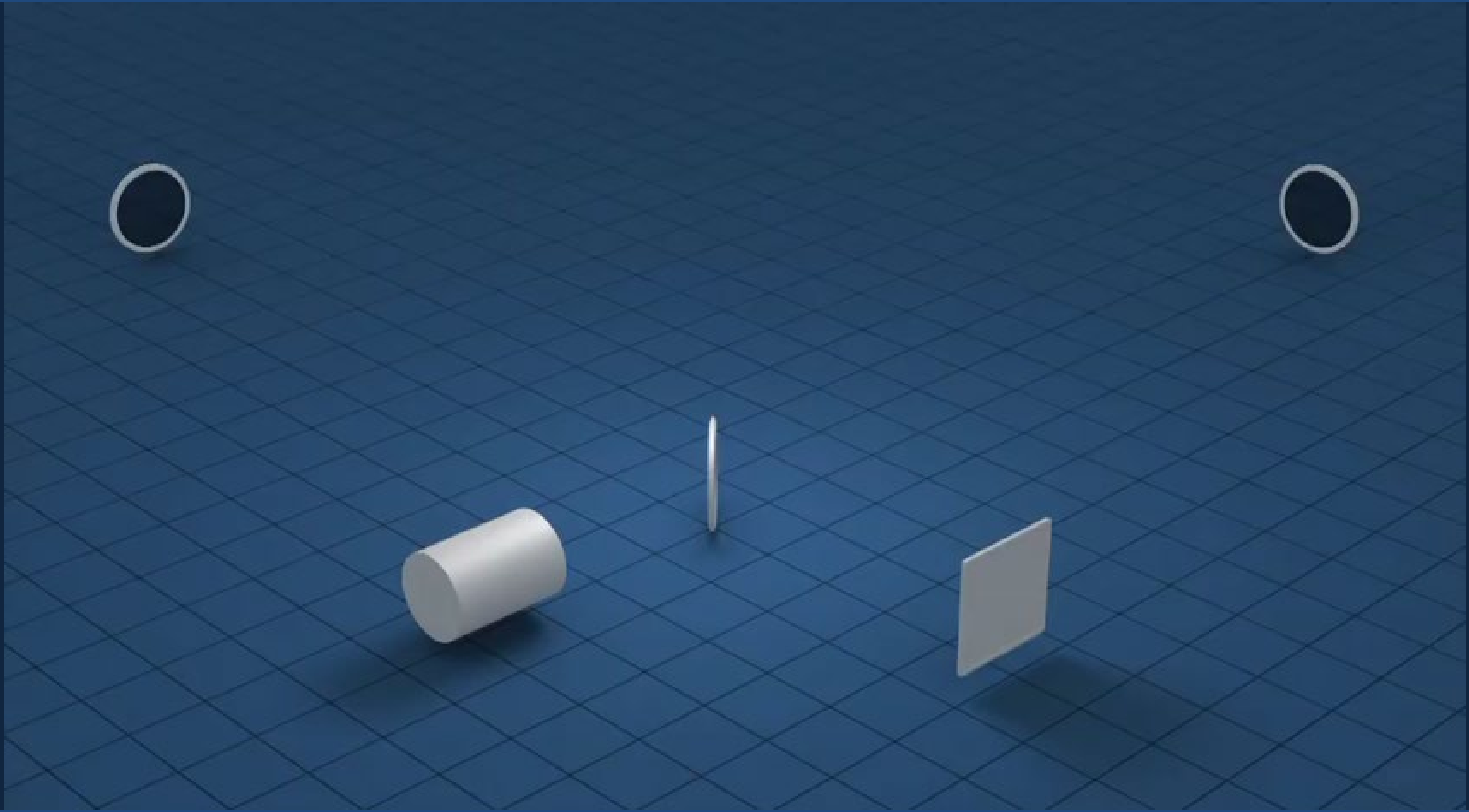
Gravitational waves: Example (merger of two black holes)

https://www.ligo.caltech.edu/news/ligo20160211

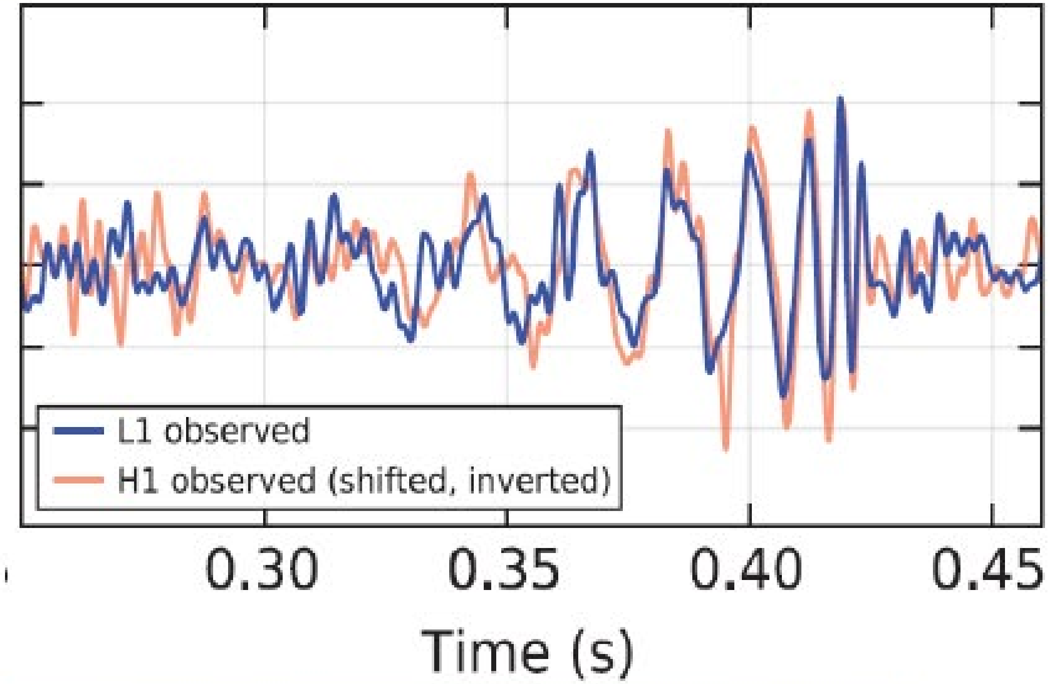


How to detect gravitational waves

https://www.ligo.caltech.edu/video/ligo20160211v6

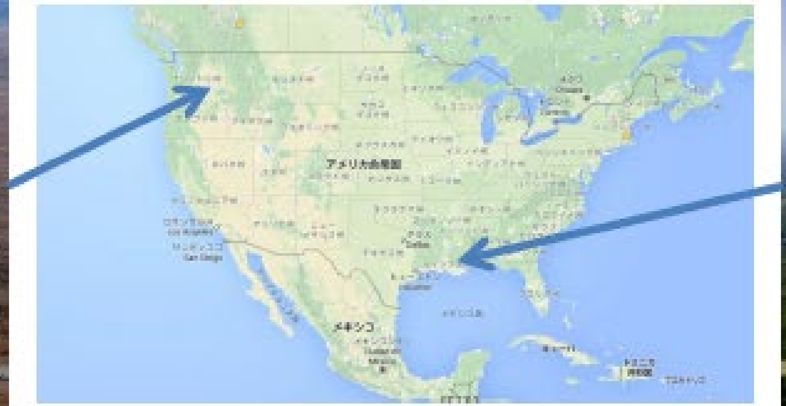


Discovery of gravitational waves

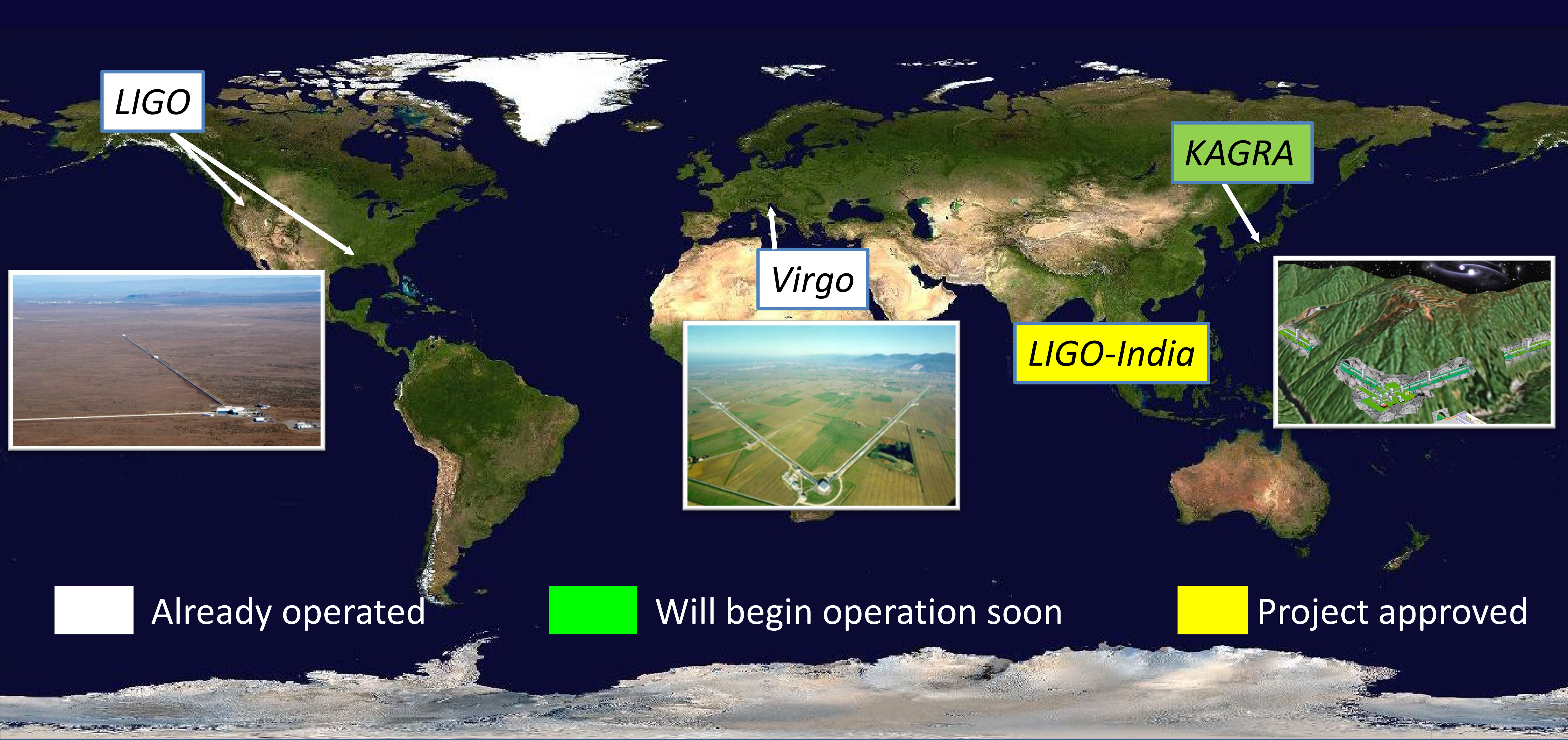


LIGO Scientific Collaboration and Virgo Collaboration, PRL, 116, 061102 (2016)

- ✓ 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!***



global map of GW detectors

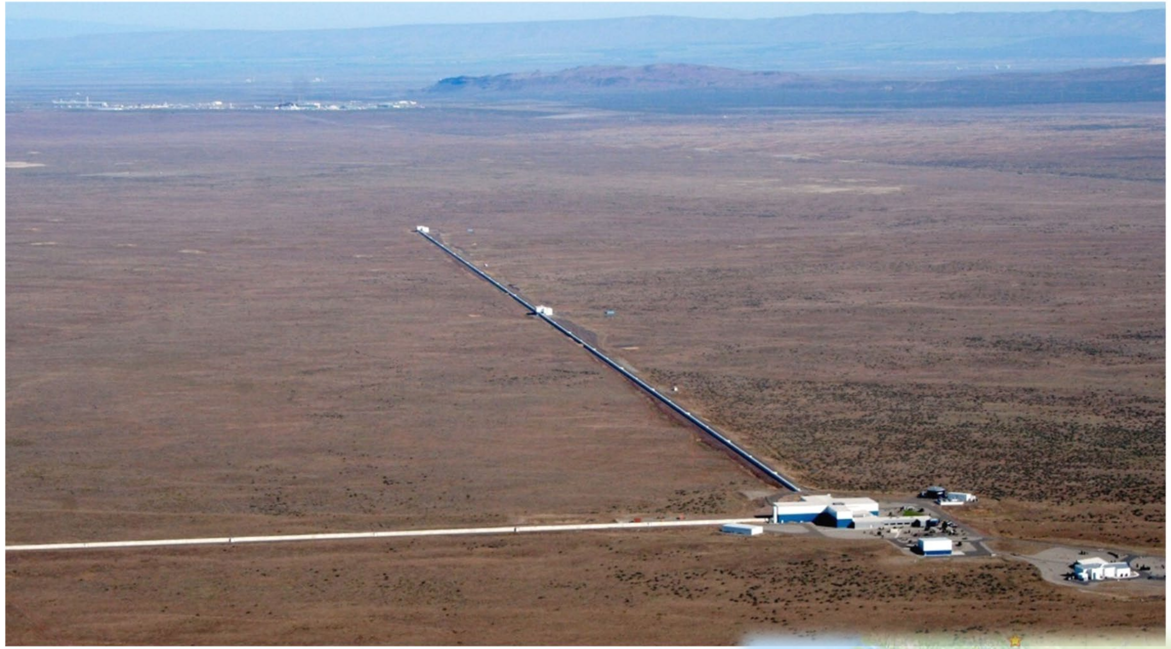


Already operated

Will begin operation soon

Project approved

LIGO



4km X 4km arm lengths

Virgo

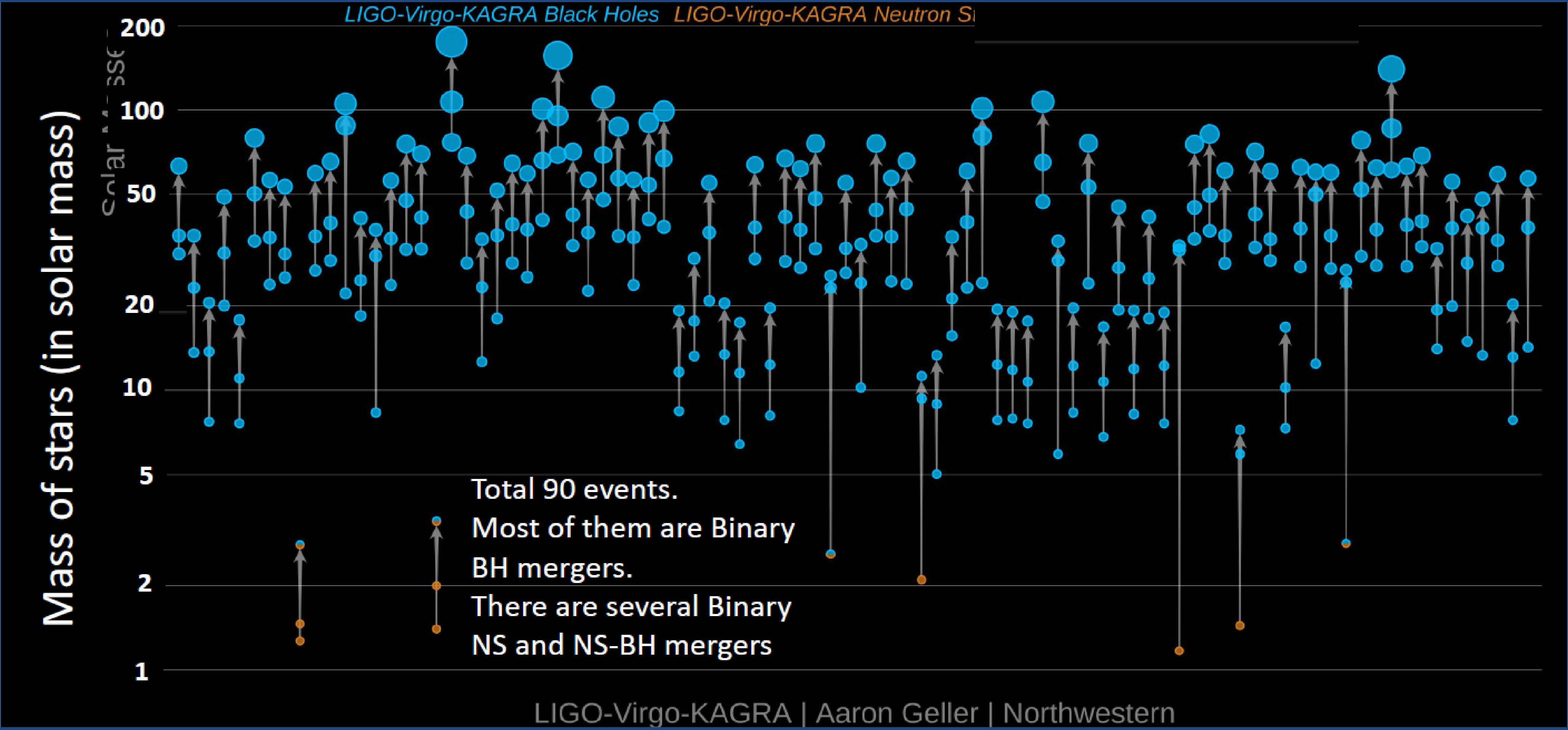
http://fs.huntingdon.edu/jlewis/syl/ircomp/MapsItaly.htm

3km X 3km arm lengths

(Virgo began operation in Aug. 2017!)

LIGO-Virgo observation summary

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



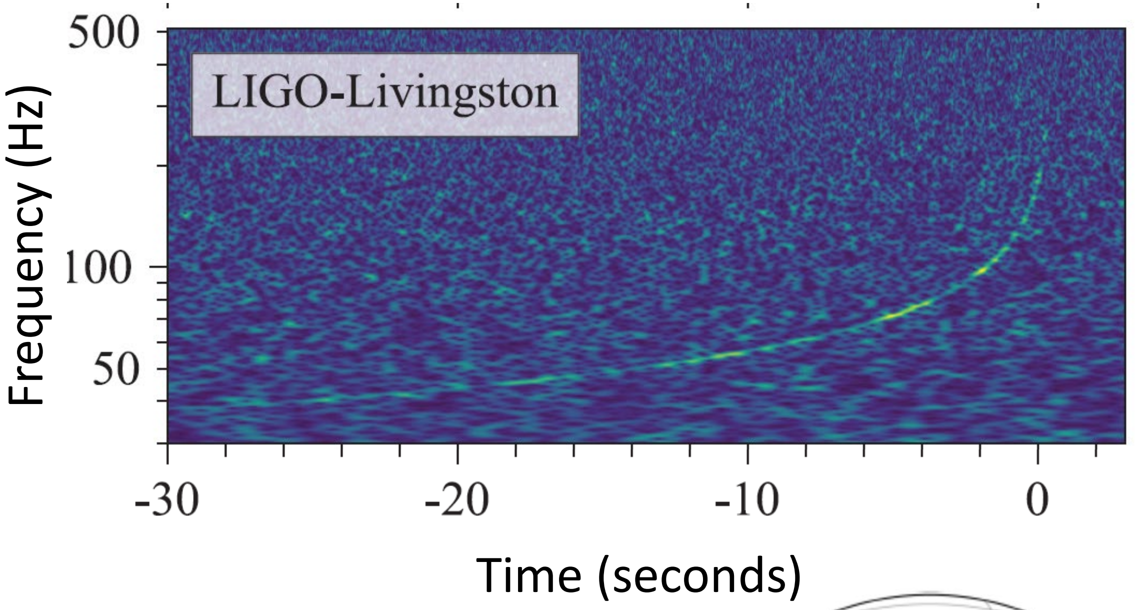
Total 90 events.

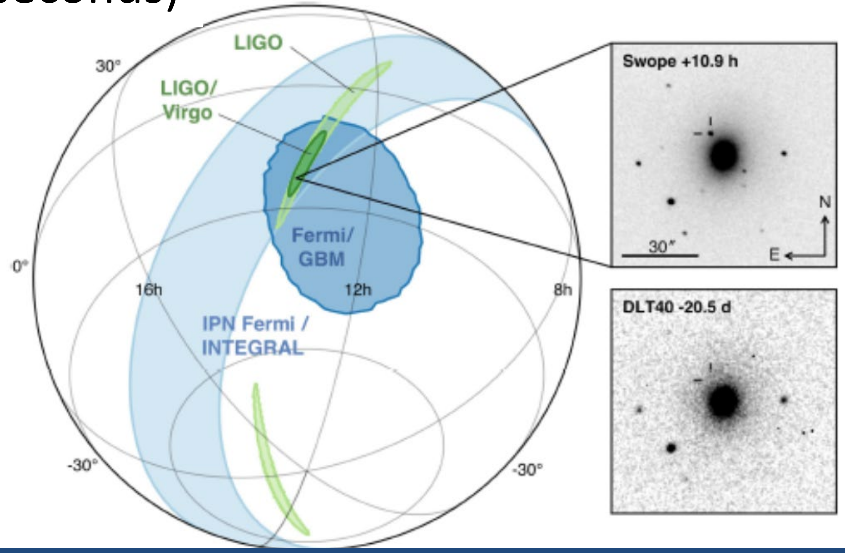
Most of them are Binary BH mergers.

There are several Binary NS and NS-BH mergers

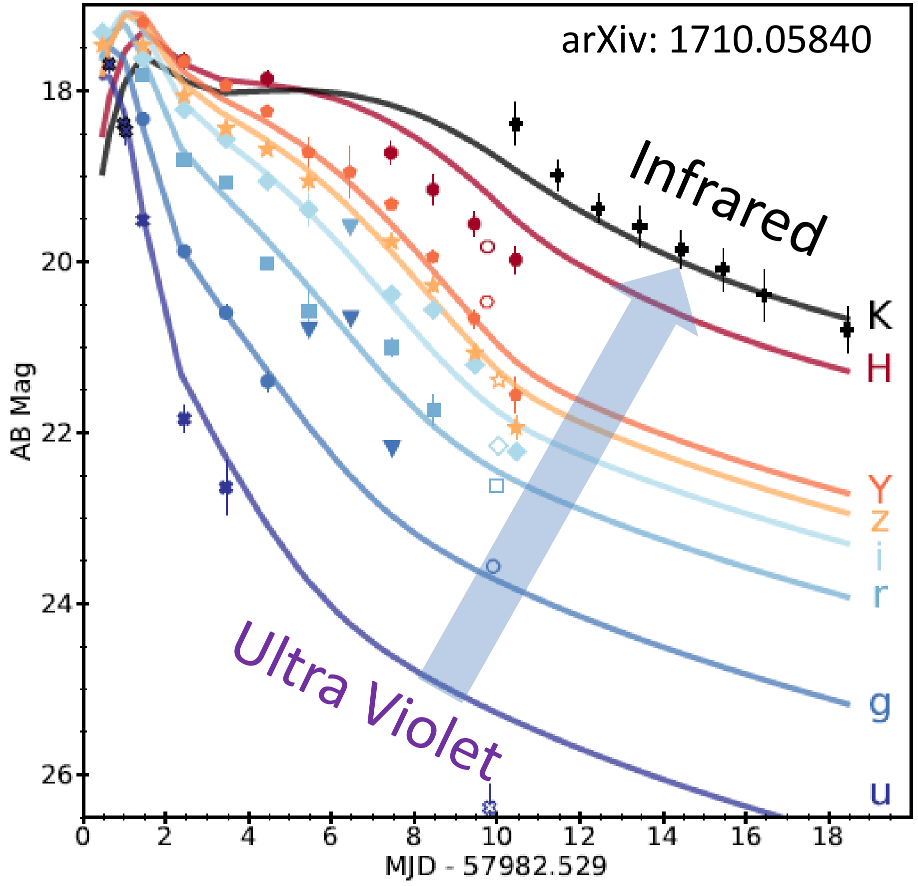
Multi-messenger astronomy with GW

Aug. 17, 2017



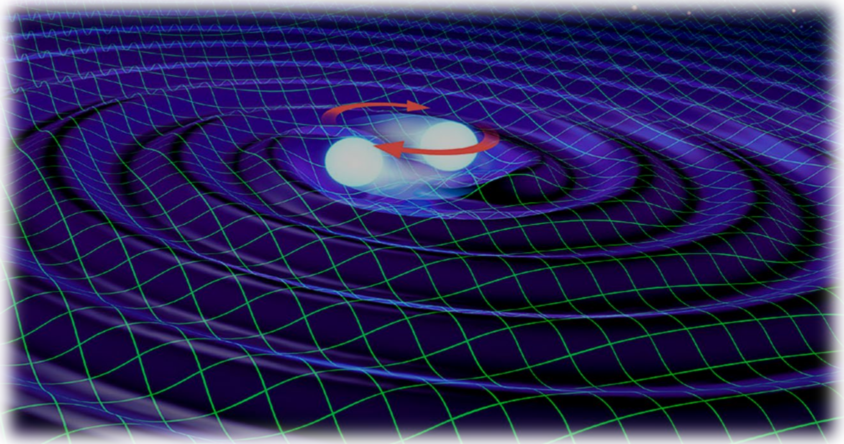


Pointing the binary neutron star merger event by LIGO and Virgo and the discovery of the optical counterpart



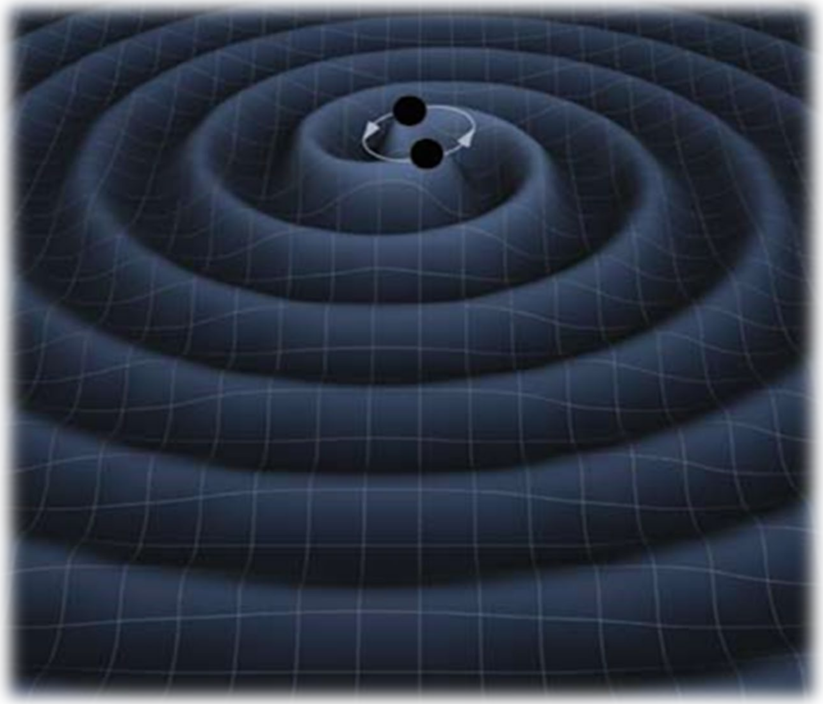
Consistent with many heavy metals (such as gold or platinum) generation!

Common goals of ground-based GW detectors



Merger of binary neutron stars

- ➔ We want to understand the origin of the heavy metals in the Universe.
- ➔ We want to understand neutron stars better.
- ➔ ….



Merger of binary blackholes

- ➔ How the blackholes were created?
- ➔ …

Supernova explosion

- ➔ How the heavy stars finish their life?
- ➔ ….

Not easy to detect GWs

If strong gravitational waves come to the solar system, the distance between the Sun and the Earth will change by about ***0.00000001cm (10^{-8}cm).***
Therefore every gravitational wave detector has to be sensitive to this length change…

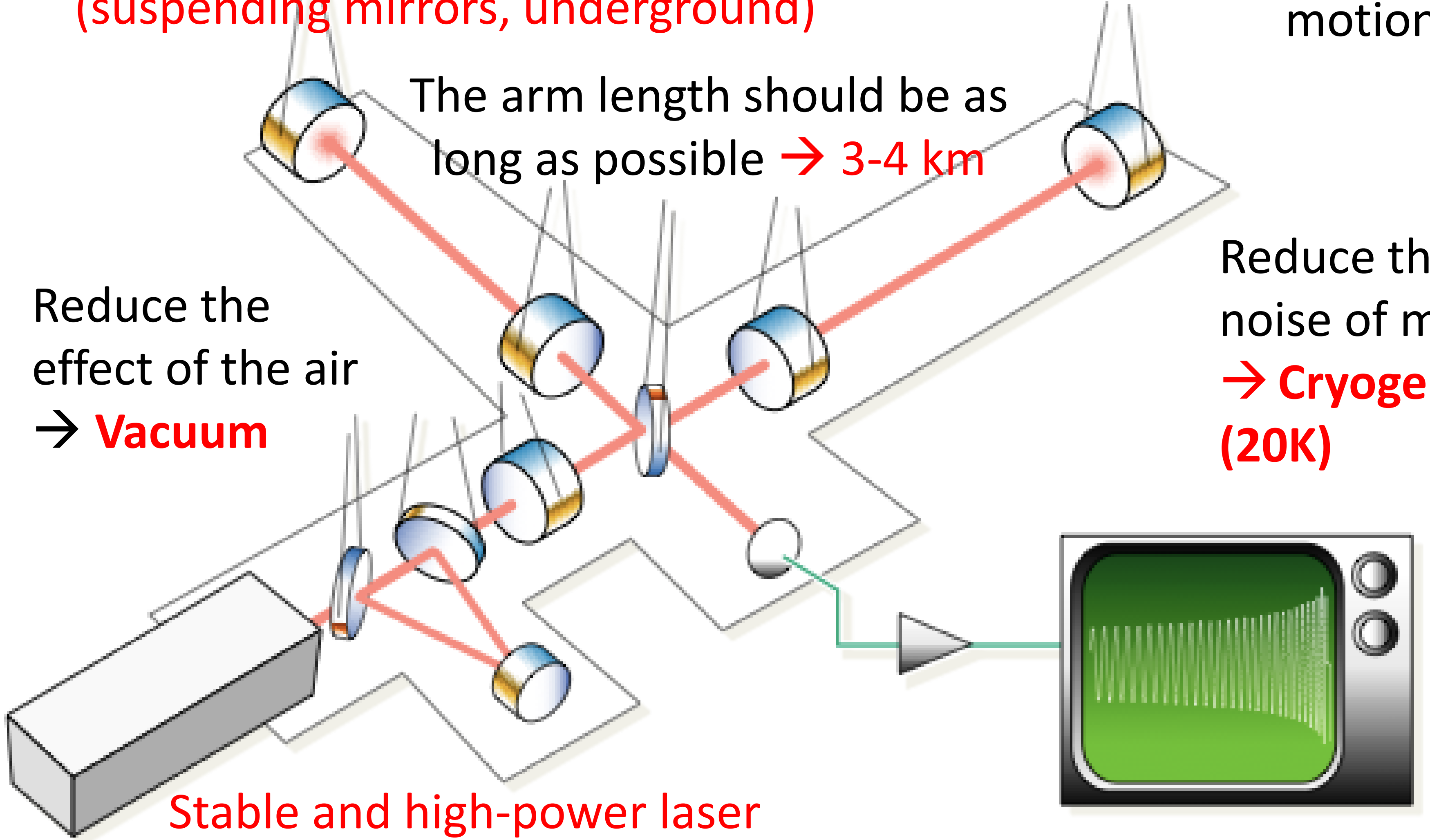
Please note that the present GW detectors have the arm length of only 3-4 km.
Therefore, these detectors must be sensitive to the length change of ***0.0000000000000001cm (10^{-16}cm)*** in 3-4 km.

realizing high sensitivity

Isolate the mirrors from seismic noises
→ **Vibration isolation system**
(suspending mirrors, underground)

The arm length should be as long as possible → 3-4 km

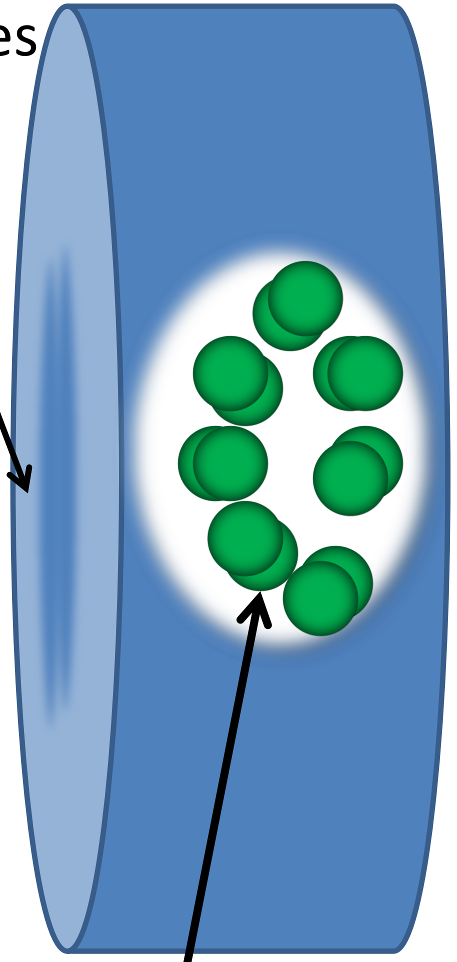
Reduce the effect of the air
→ **Vacuum**



Stable and high-power laser

The surface of the mirror is fluctuating due to the thermal motion of molecules

Reduce the thermal noise of mirrors
→ **Cryogenic mirrors (20K)**



Molecules

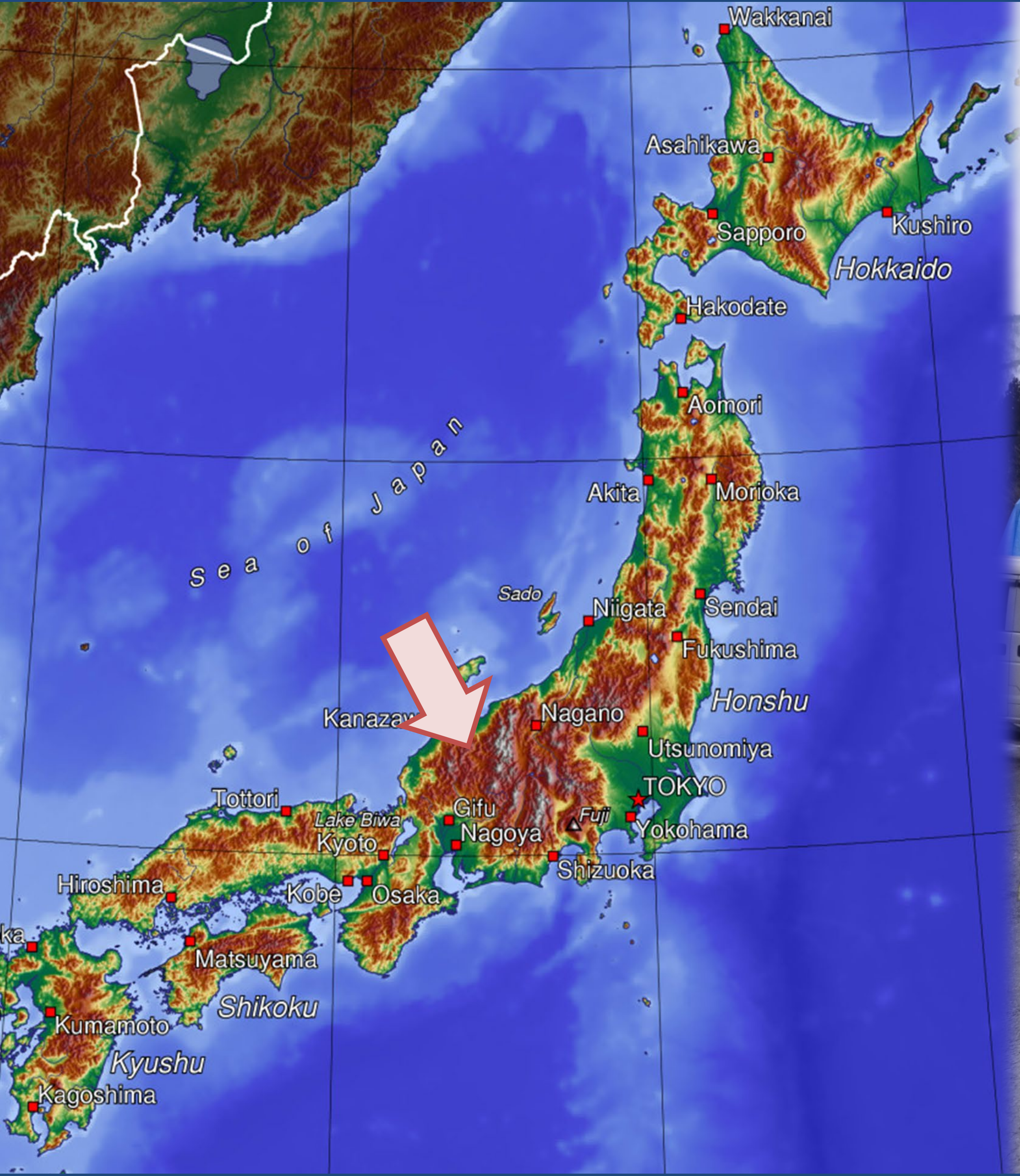
The KAGRA project

KAGRA collaboration

8 countries/regions, ~150 authors

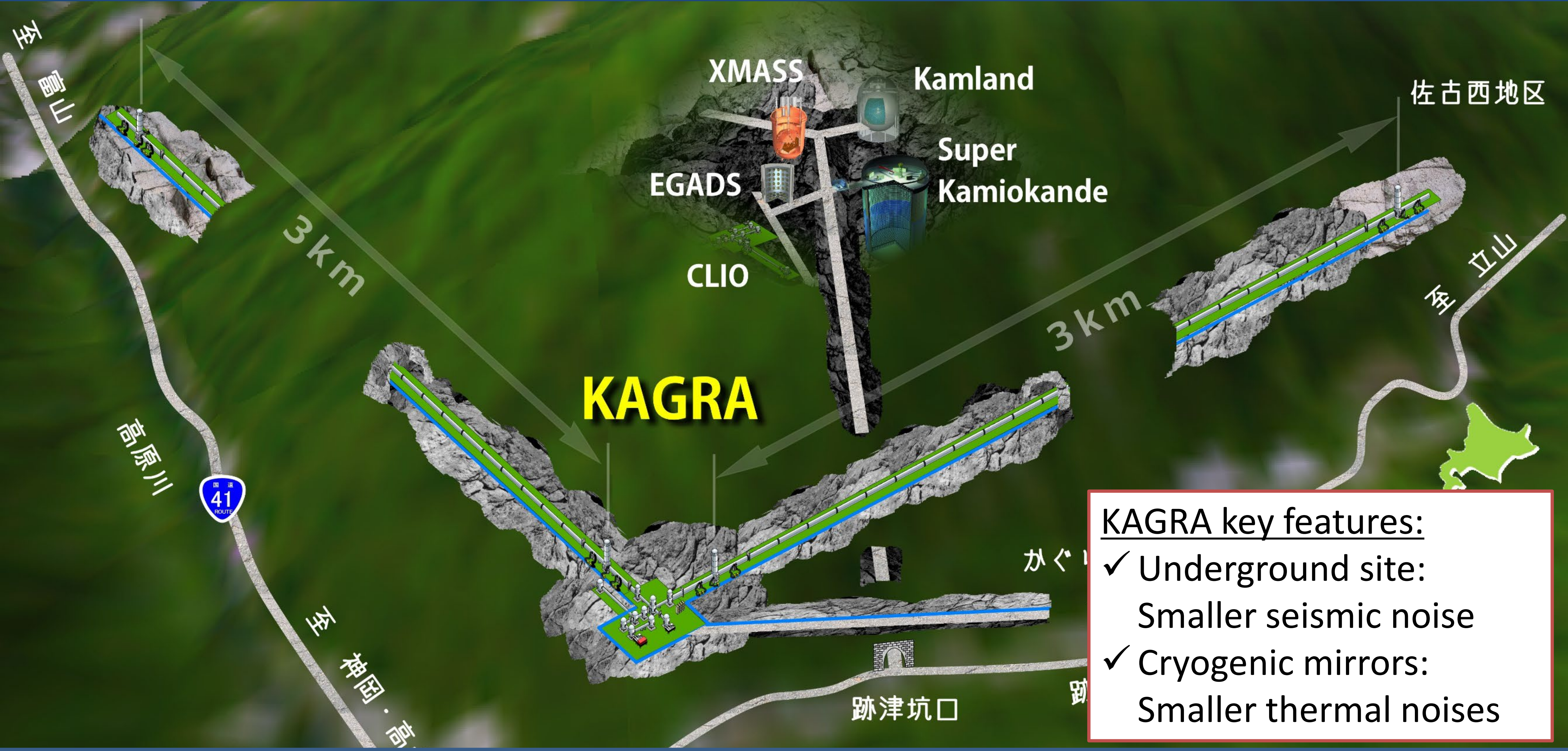
(and ~500 collaborators from 17 countries/regions)

Location of KAGRA



(Sorry, an old photo during the construction)

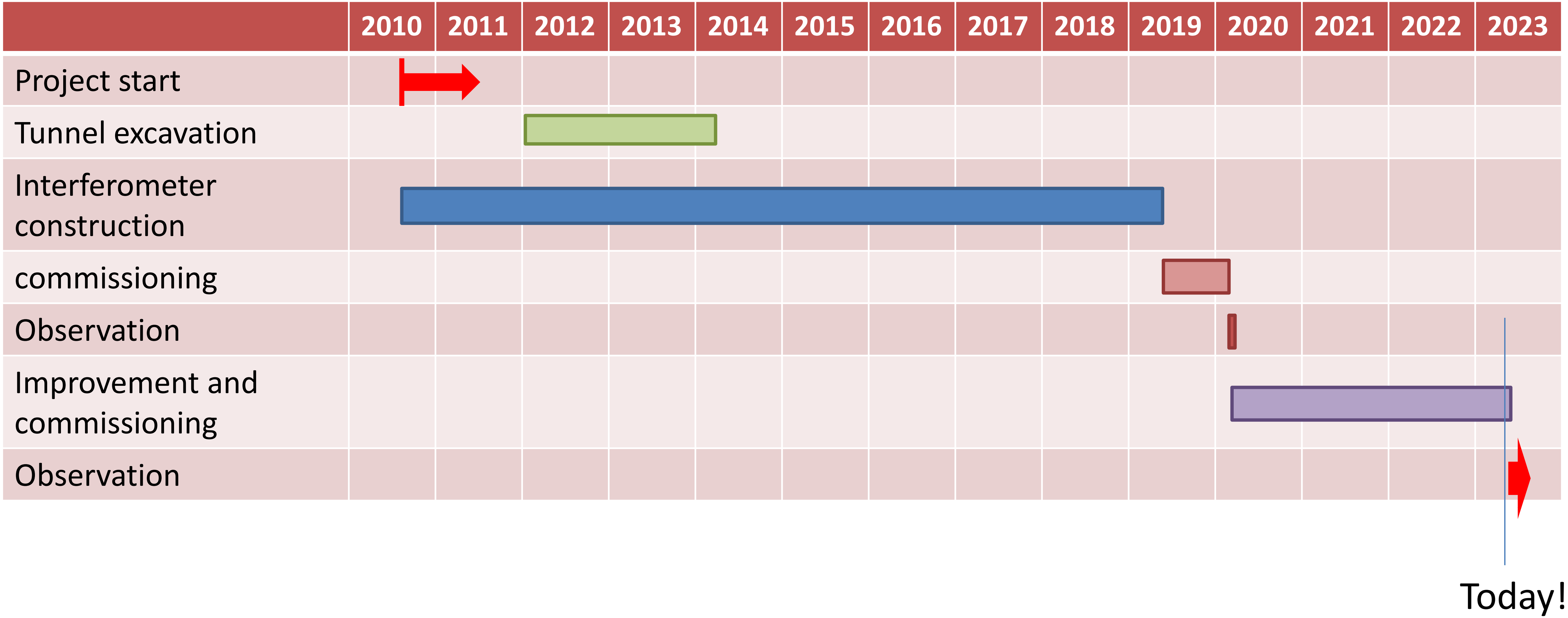
Location of KAGRA



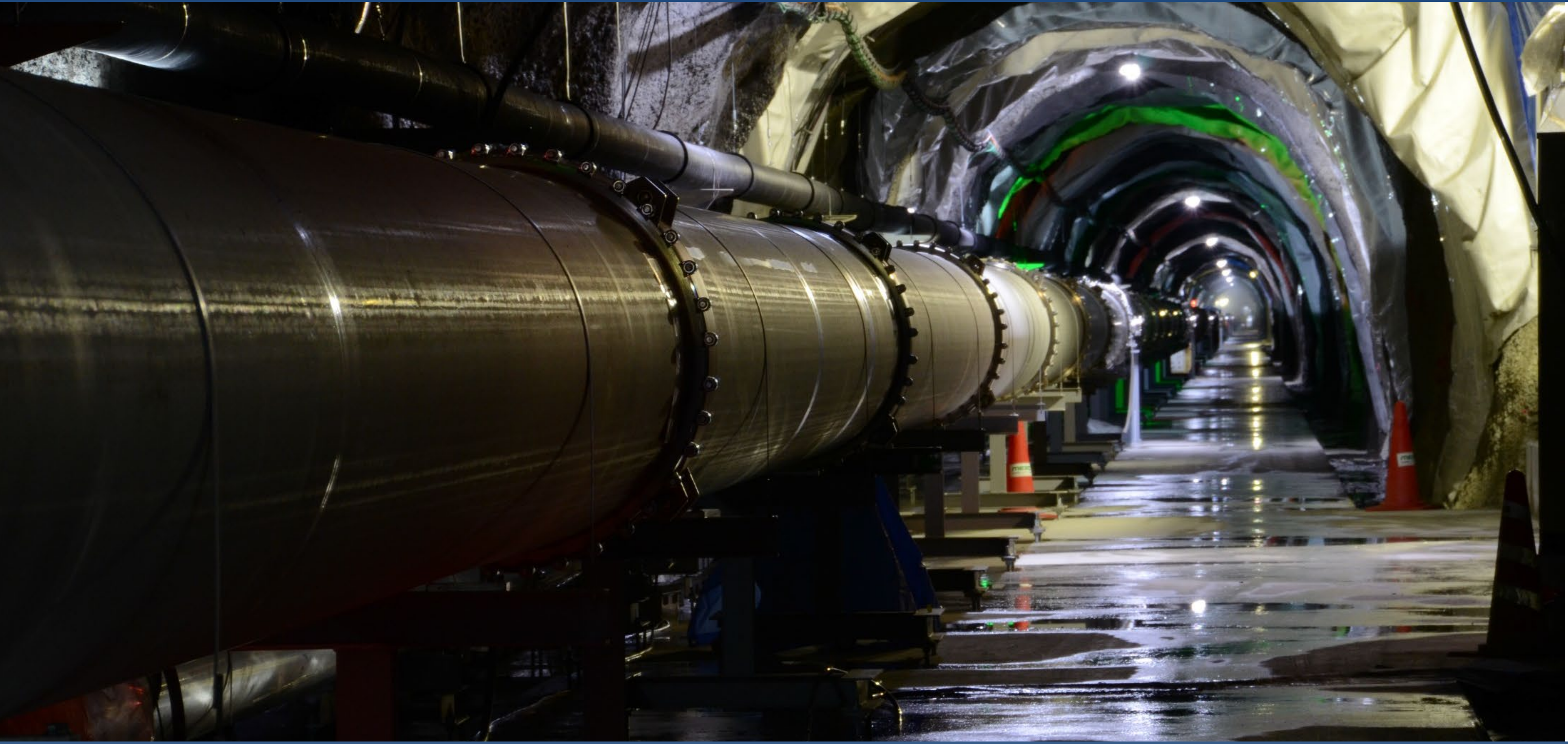
KAGRA key features:

- ✓ Underground site: Smaller seismic noise
- ✓ Cryogenic mirrors: Smaller thermal noises

Project history (Construction and Operation)



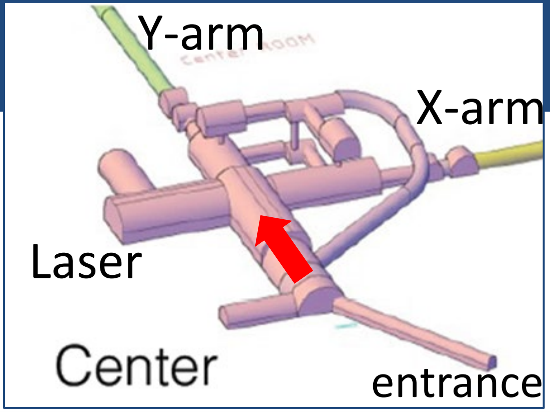
3km long vacuum tube (Feb. 2015)



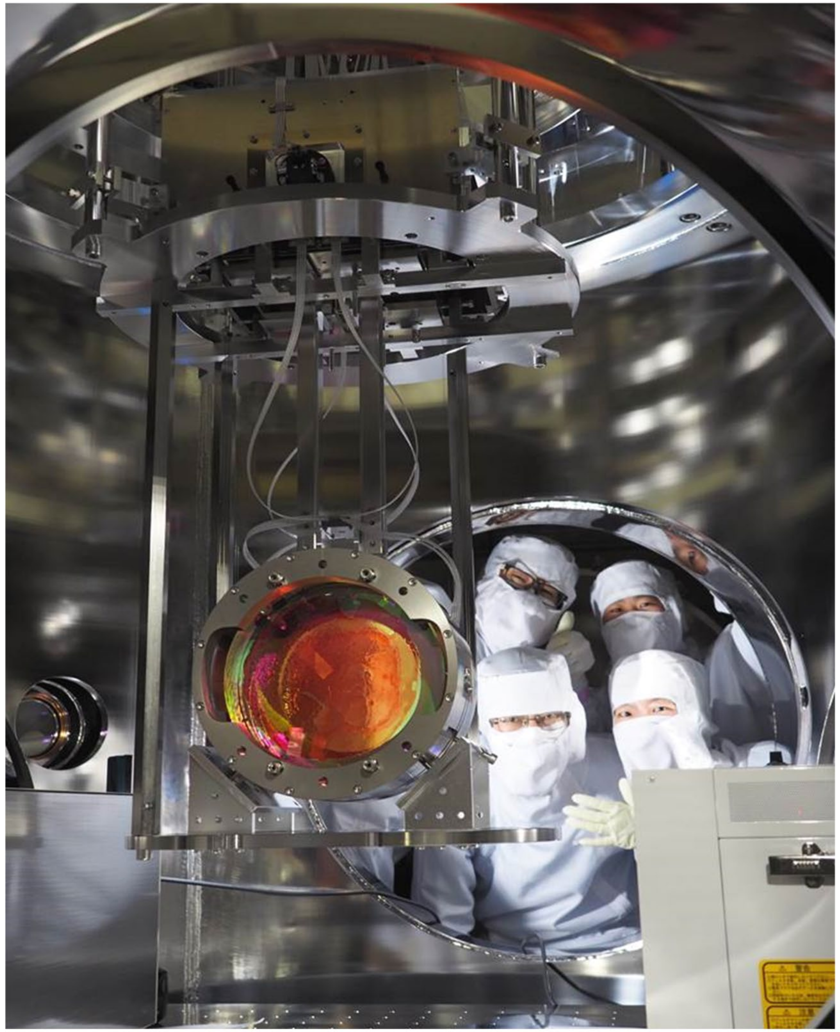
Center area

Fall 2015

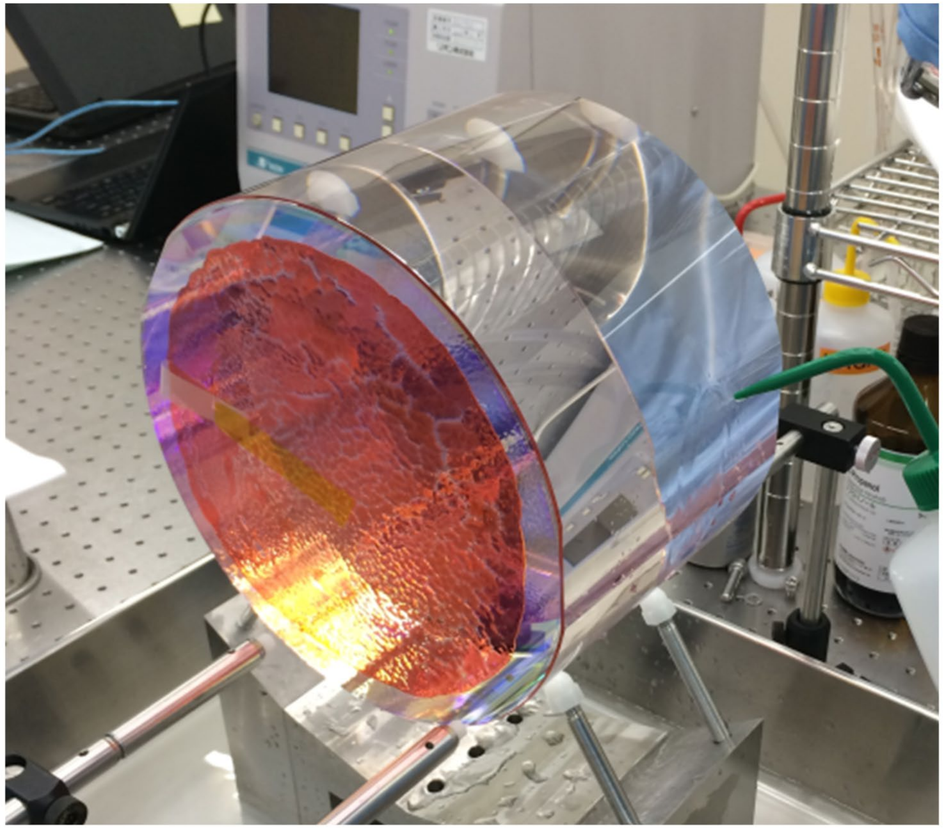
September 2019 (construction completed in the clean booths.)



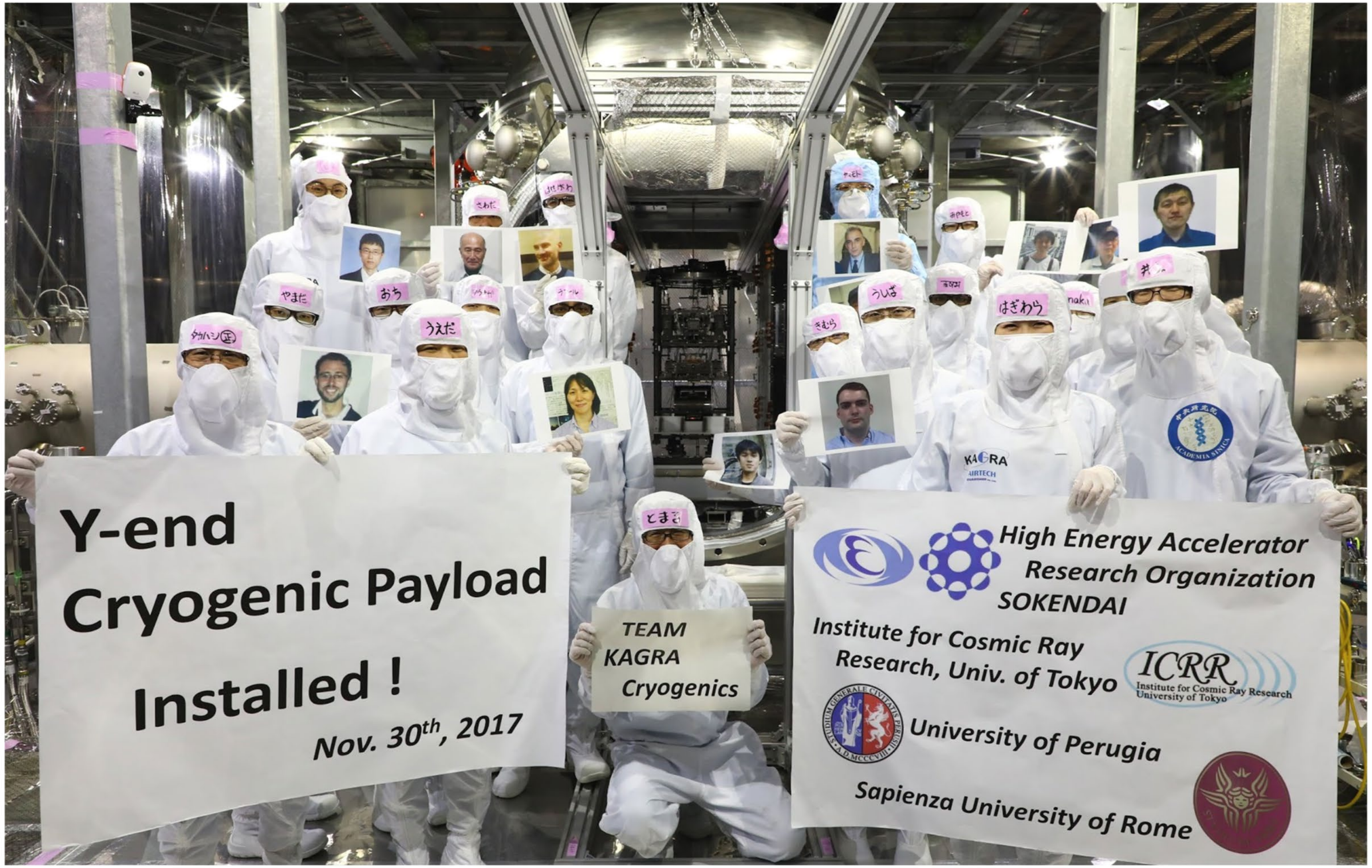
Installation works (until spring 2019)



Installation of cryogenic mirrors in KAGRA

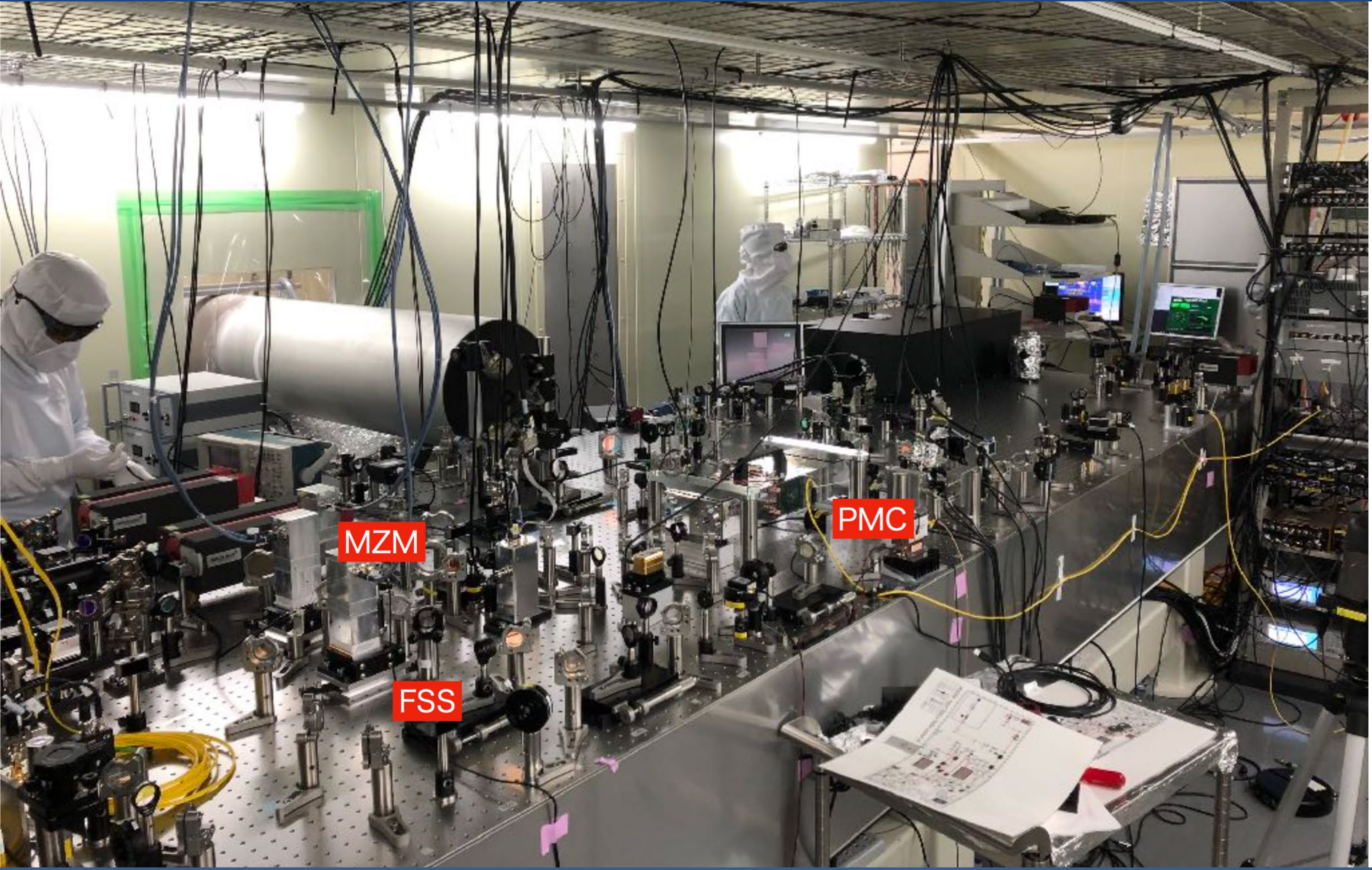


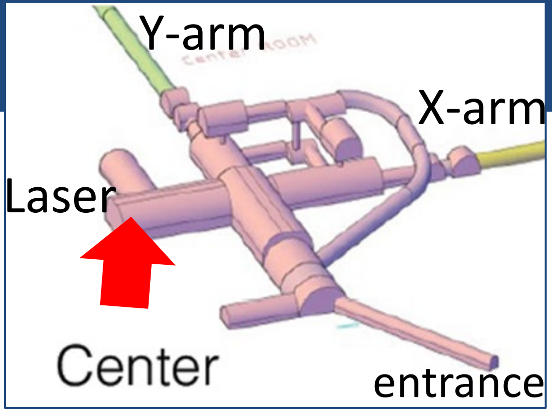
Preparation of cryogenic mirror
（22cm(ϕ), 15cm (t), 23kg）
➔ To the KAGRA site



Installation of the first cryogenic mirror（Nov.30, 2017）
(The last one (4th mirror) installed on Nov. 9, 2018)

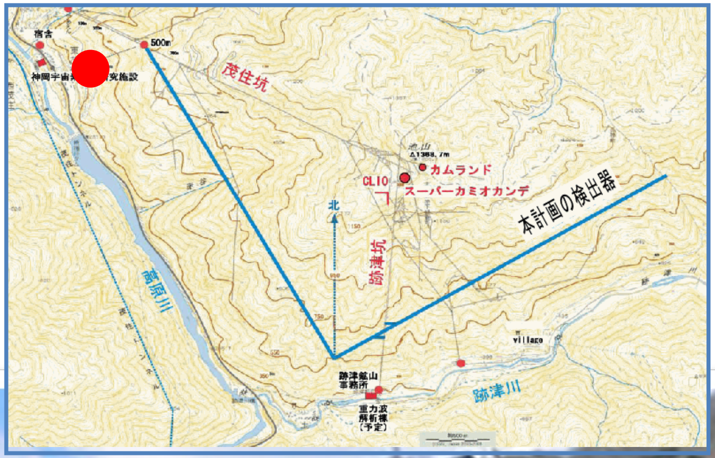
Laser room





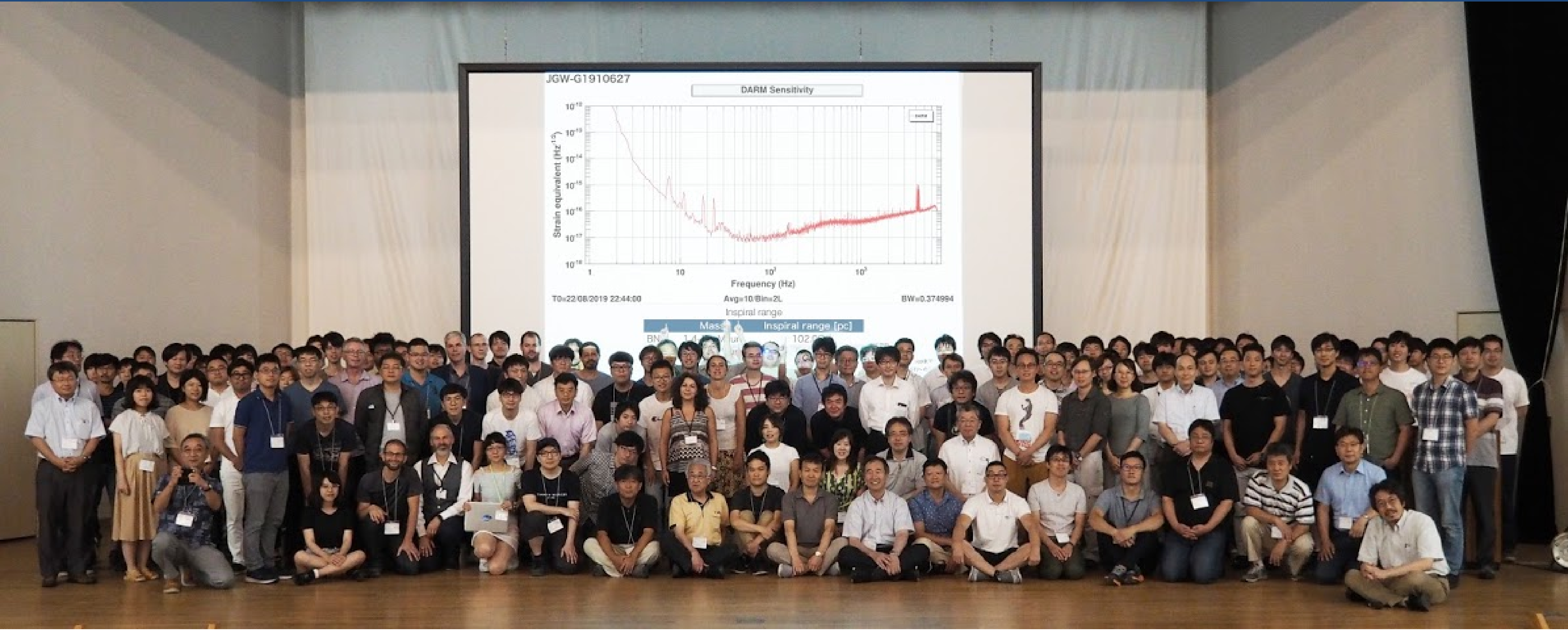
Intensity stabilization,
Frequency stabilization,
....

Office and the KAGRA control room at the surface



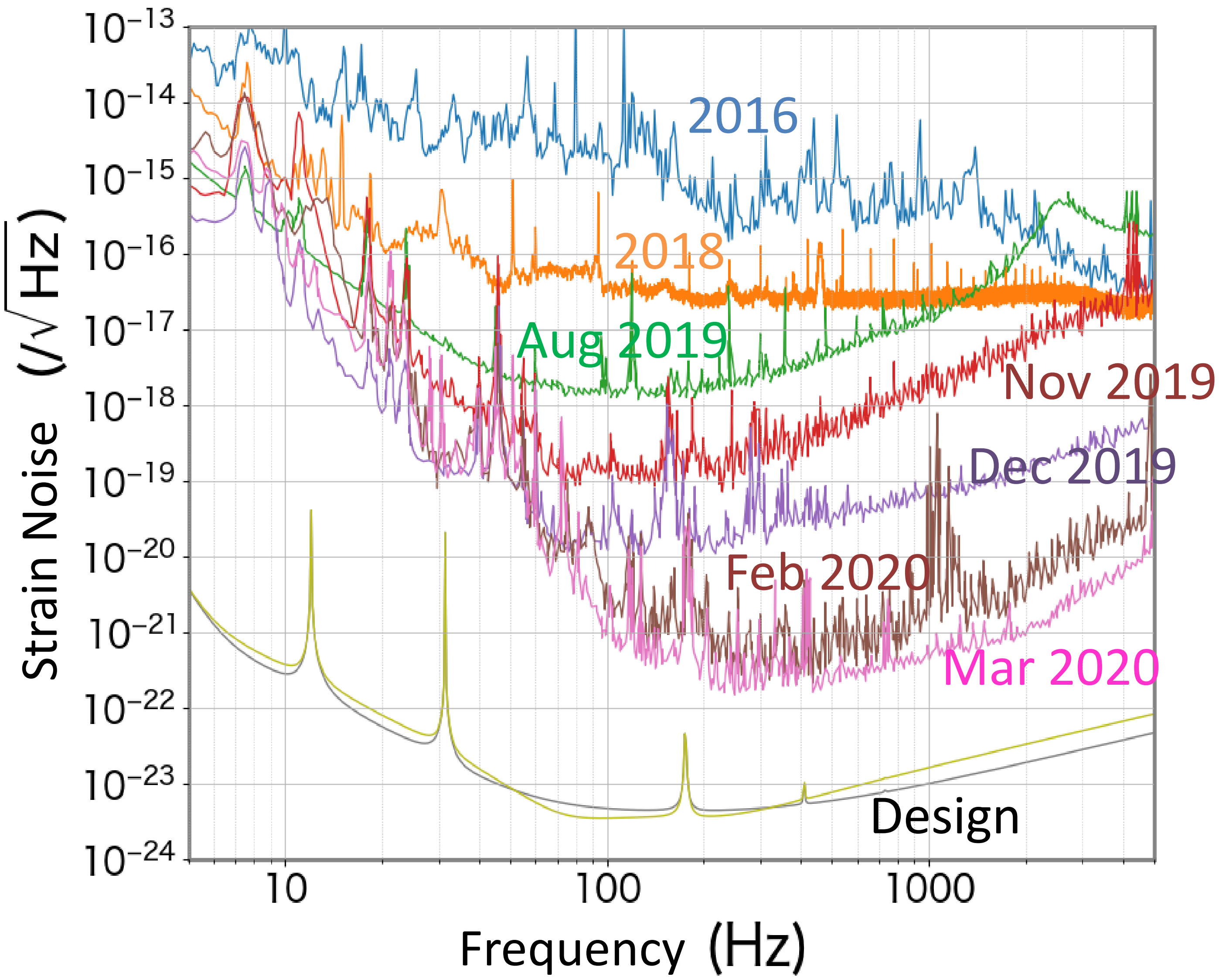
The interferometer commissioning is carried out at the surface facility.

KAGRA collaboration



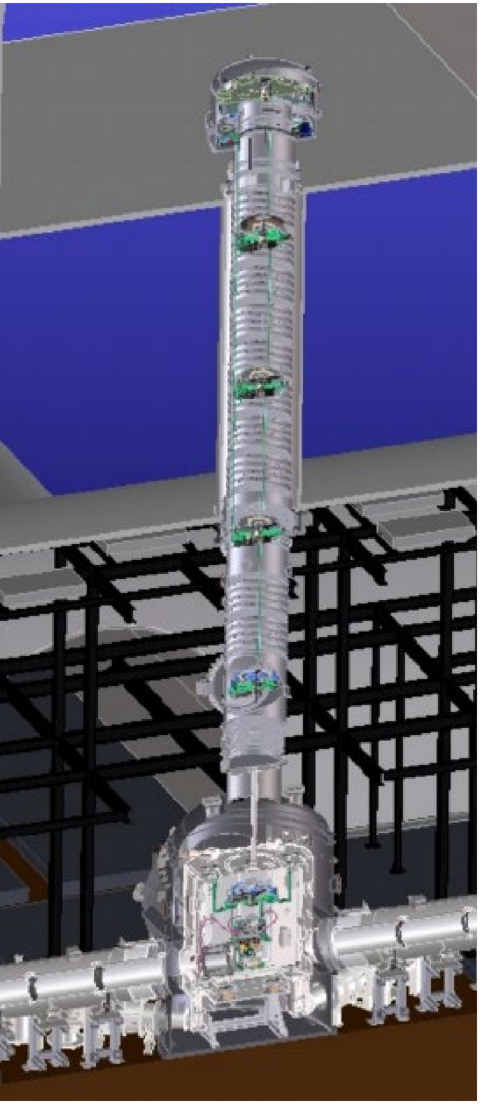
KAGRA is an international collaboration based largely on Asian countries/regions. We work together for the KAGRA project and for the gravitational wave astronomy!

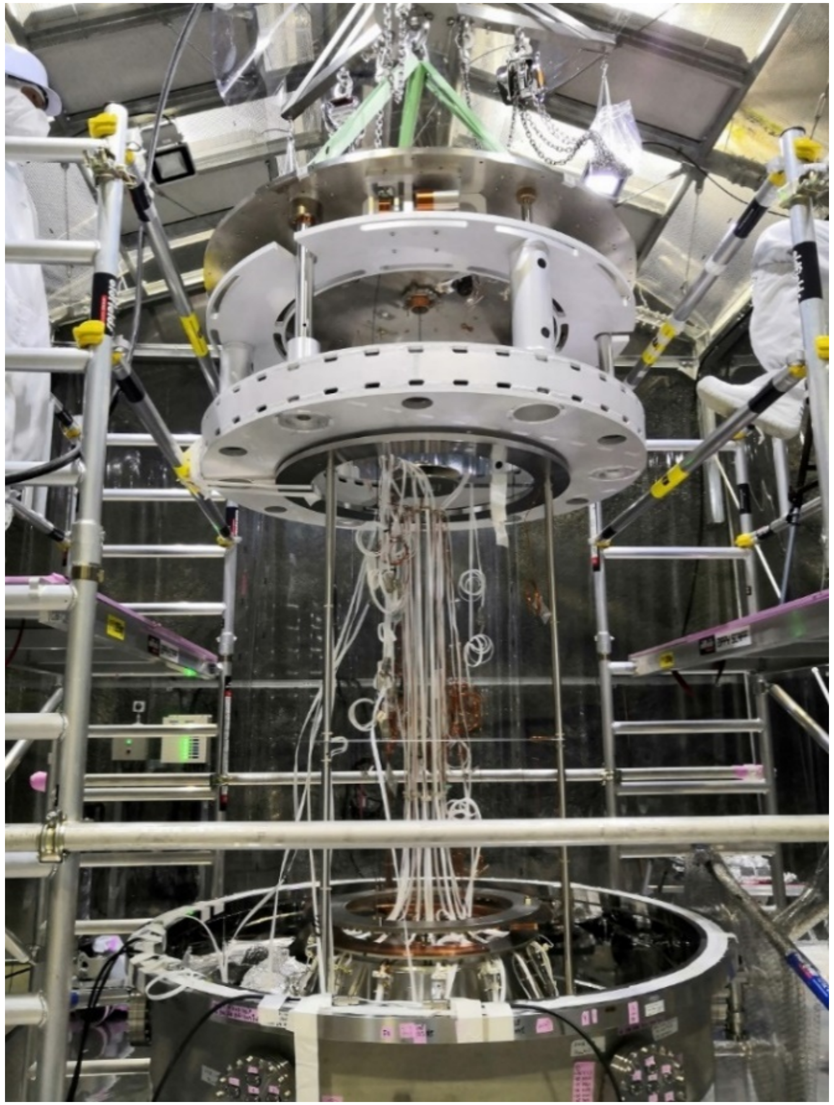
KAGRA sensitivity history until spring 2020



- 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.
- Started the improvement work, giving up the observation.

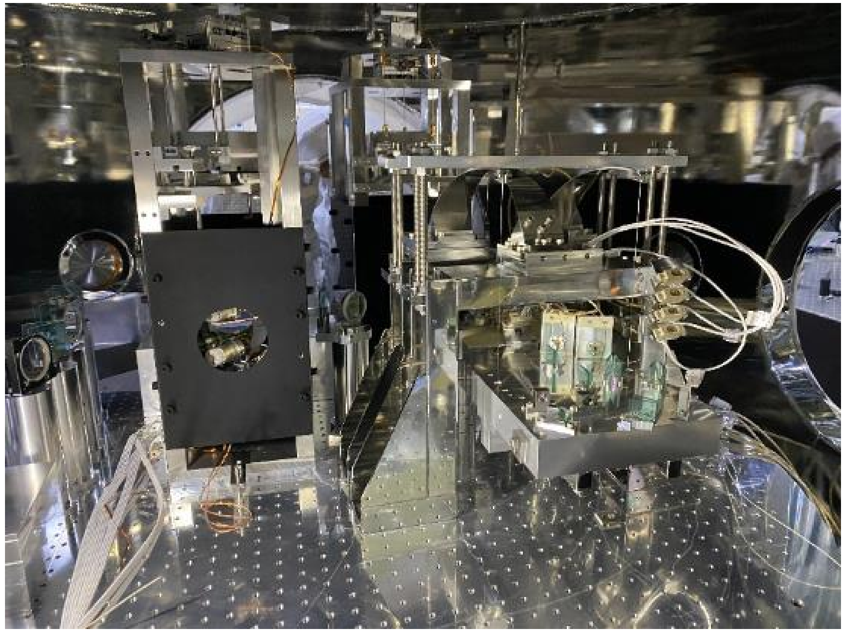
KAGRA improvement works





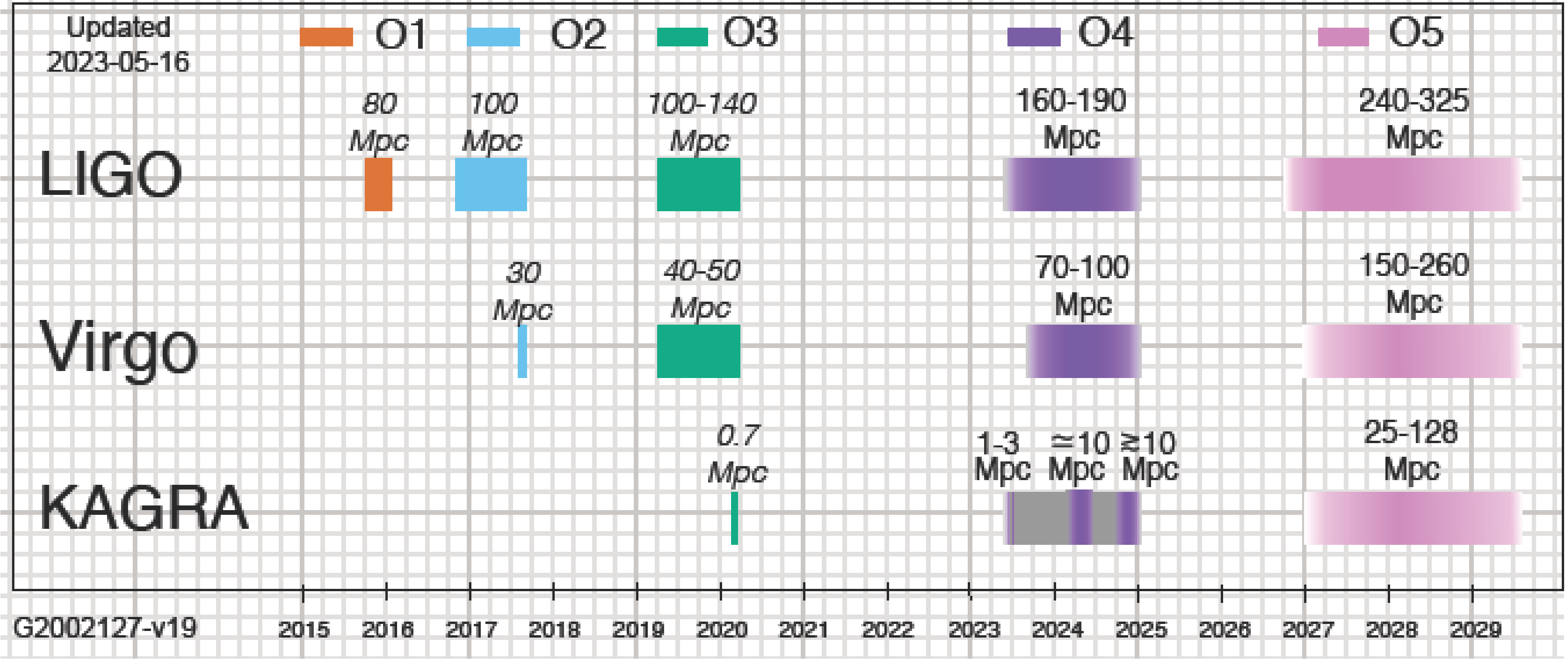
Re-installation of the vibration isolation system

Testing the vibration isolation system



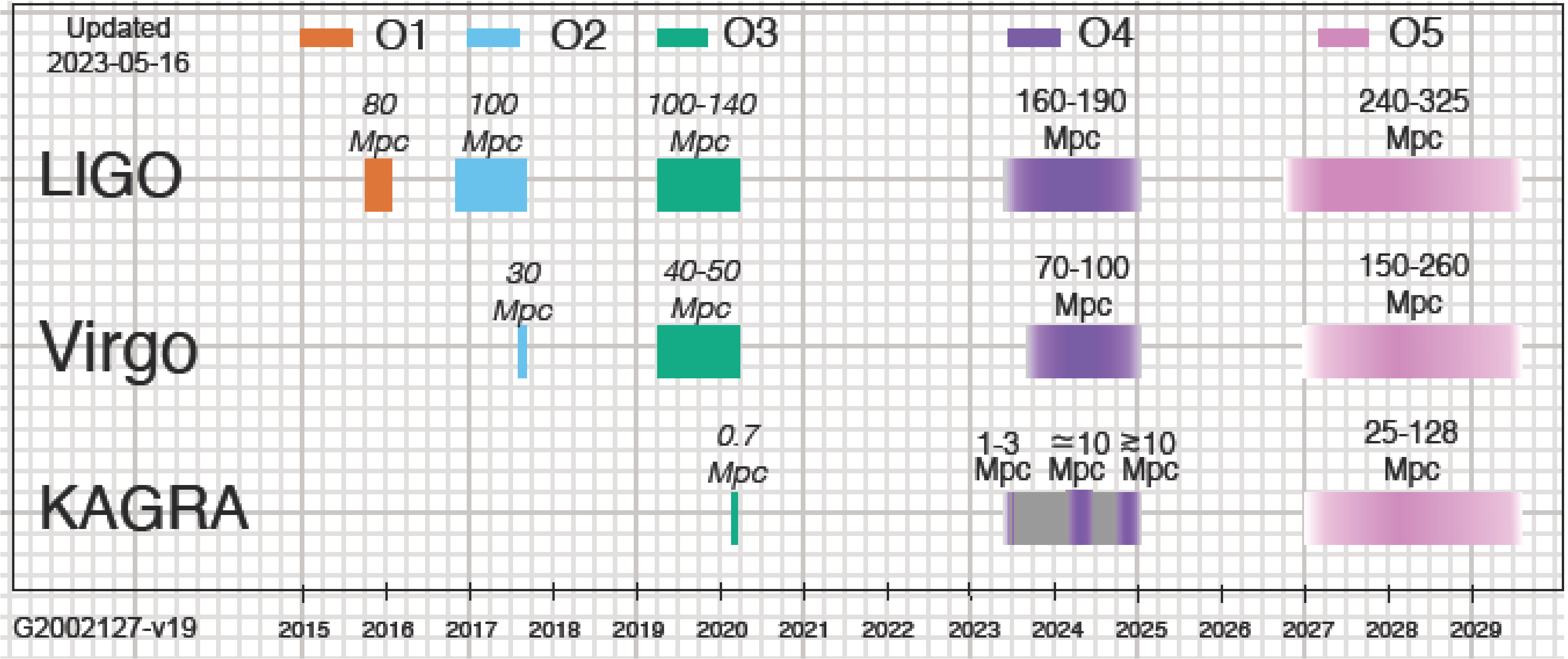
Re-instalation of the output mode cleaner

KAGRA Now



- ✓ KAGRA started the O4 observation on May 24, 2023!
- ✓ After 1 month of observation, KAGRA will stop the observation and try to improve the sensitivity further. KAGRA will rejoin O4 in the spring of 2024.
- ✓ We hope that we can see the GW signal during O4.

Near future



- ✓ After O4, KAGRA will further improve the sensitivity to really contribute to the GW astronomy.
- ✓ After O5, KAGRA would like to improve the sensitivity further, and contribute to the GW astronomy significantly.

KAGRA's contribution to the GW science

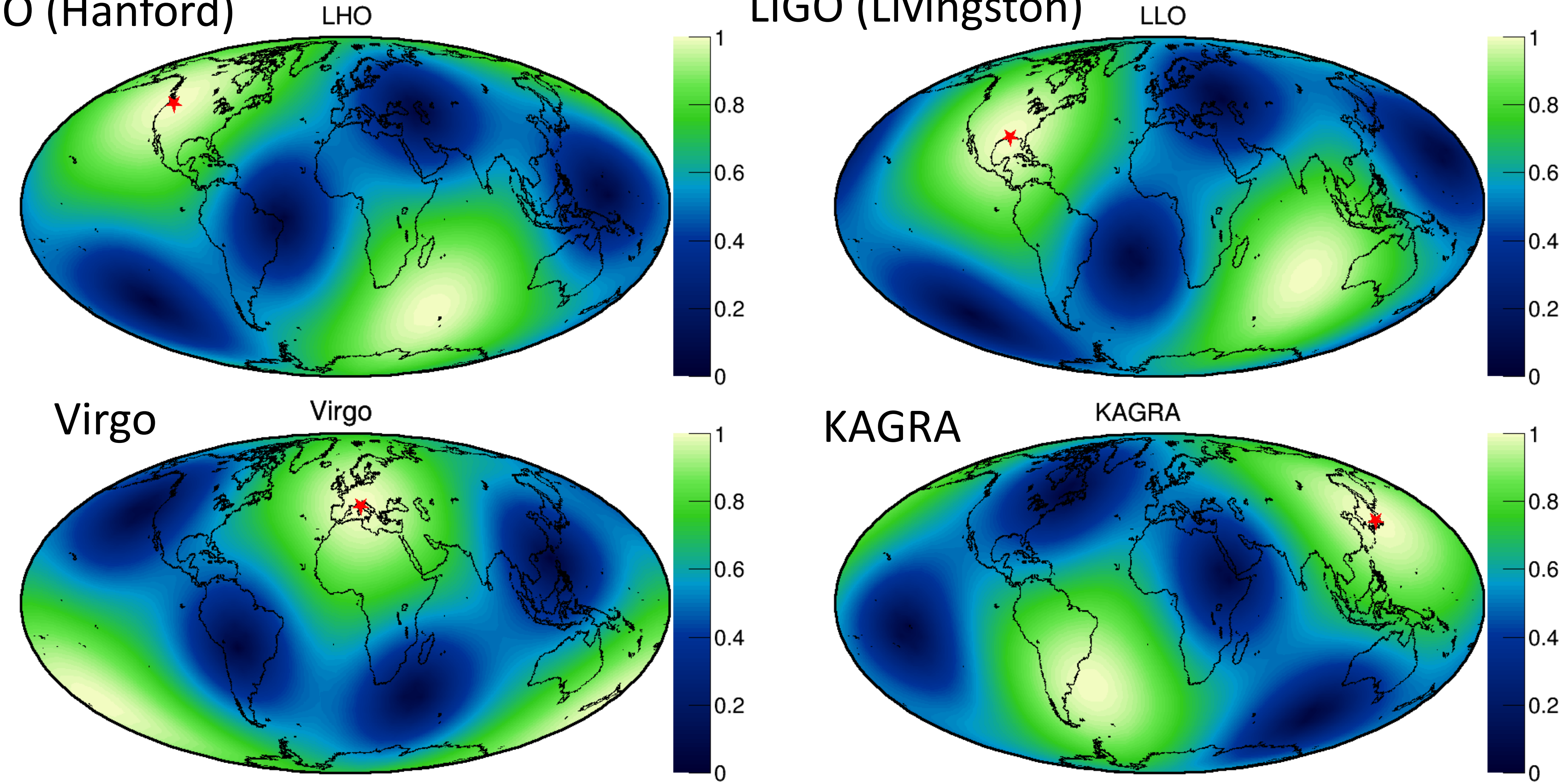
Importance of Global GW Network: Detector antenna patterns

LIGO (Hanford)

LIGO (Livingston)

Virgo

KAGRA



KAGRA is complementary in the sensitive direction to other detectors.

Importance of Global GW Network: Sky localization

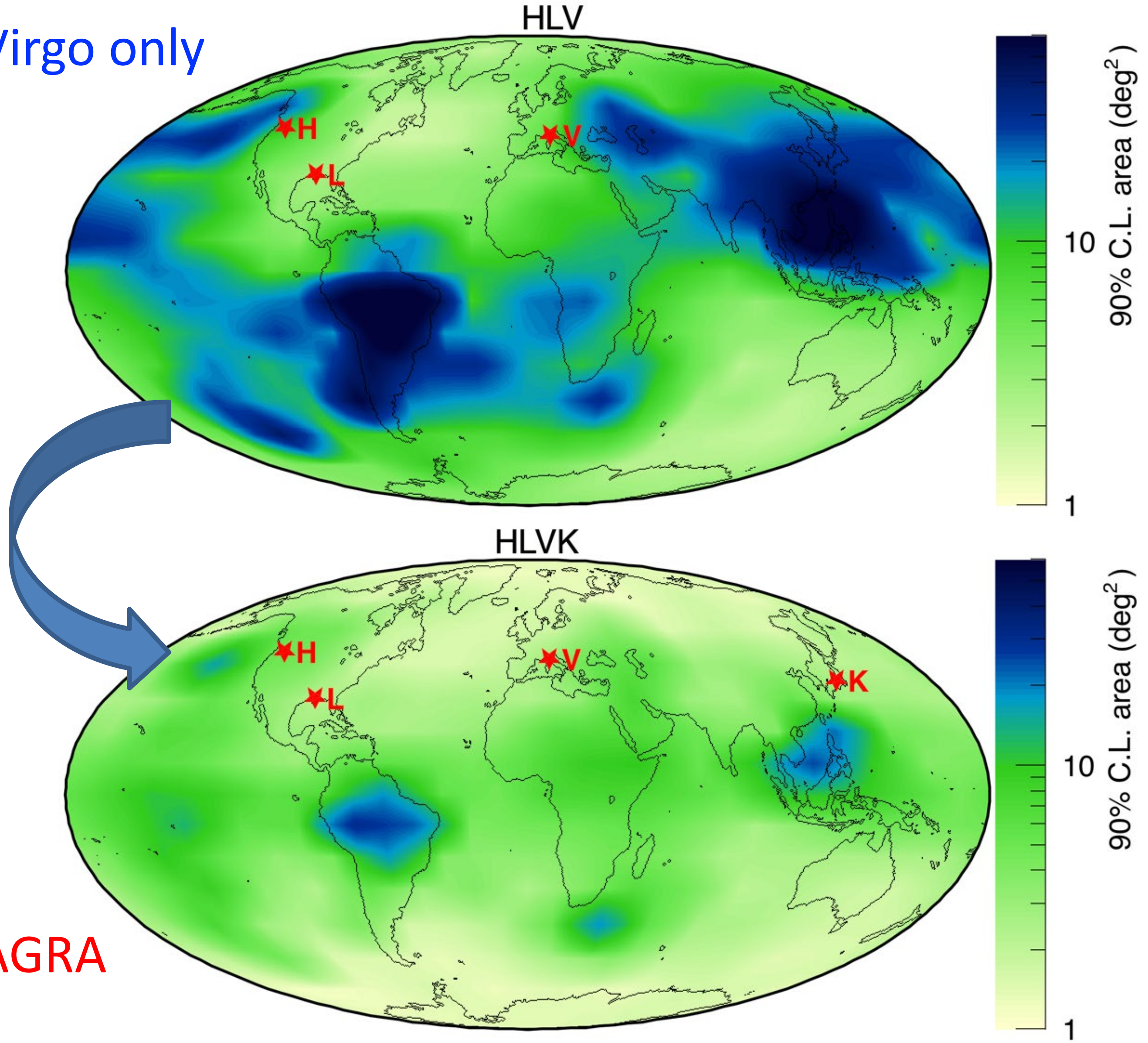
- Assuming the sensitivities of;

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

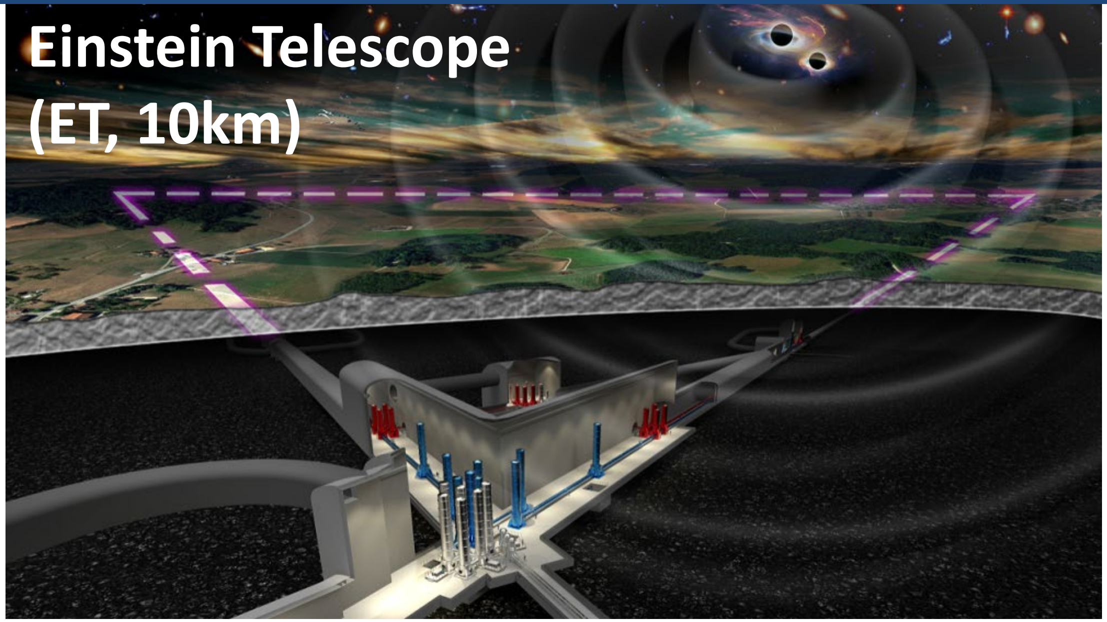
LIGO-Virgo only



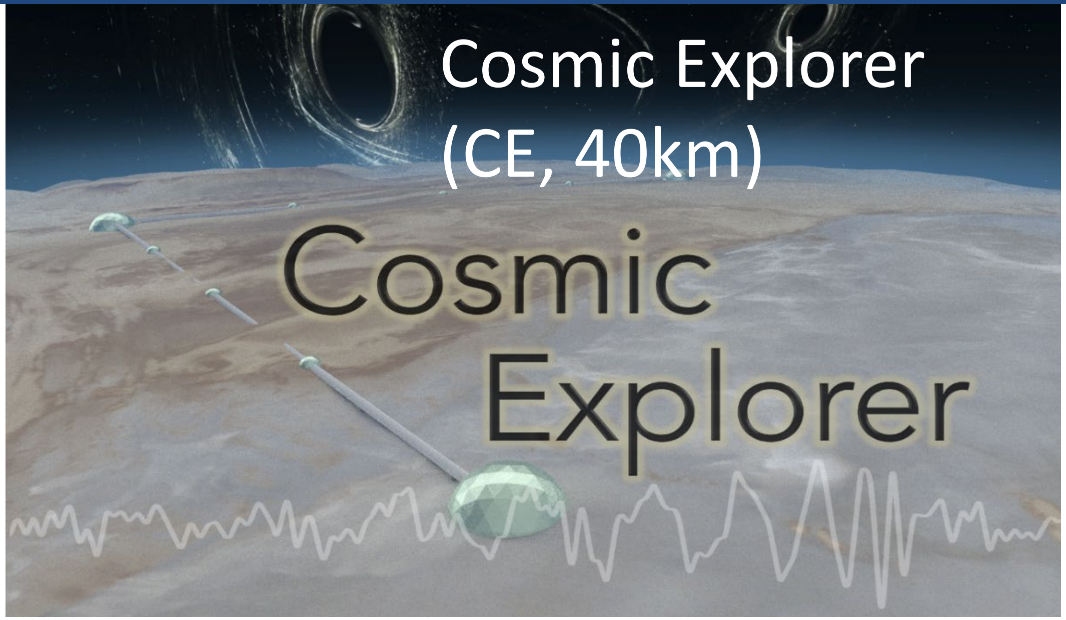
Adding KAGRA

Future ground-based GW detectors

Future of ground-based GW detectors and KAGRA



https://www.et-gw.eu/

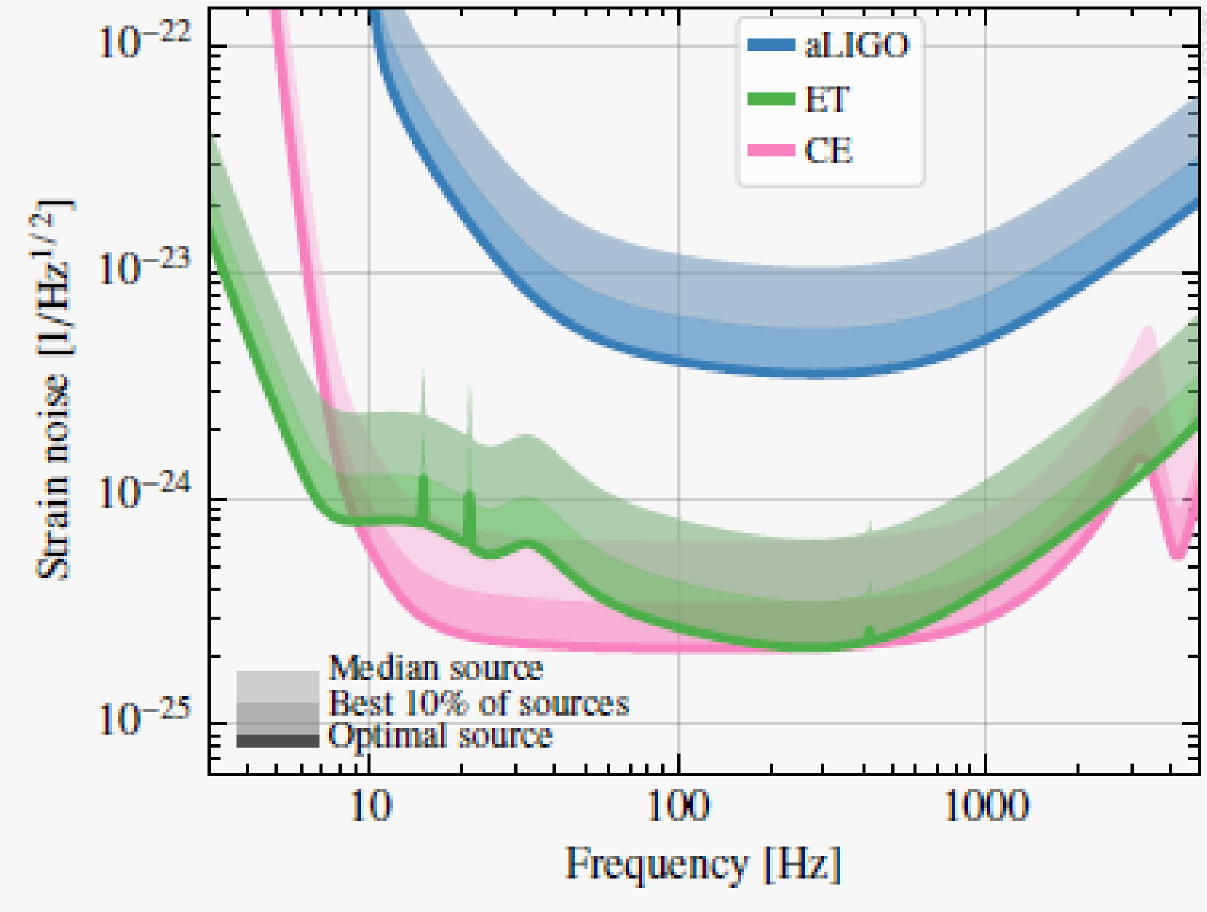


https://cosmicexplorer.org/

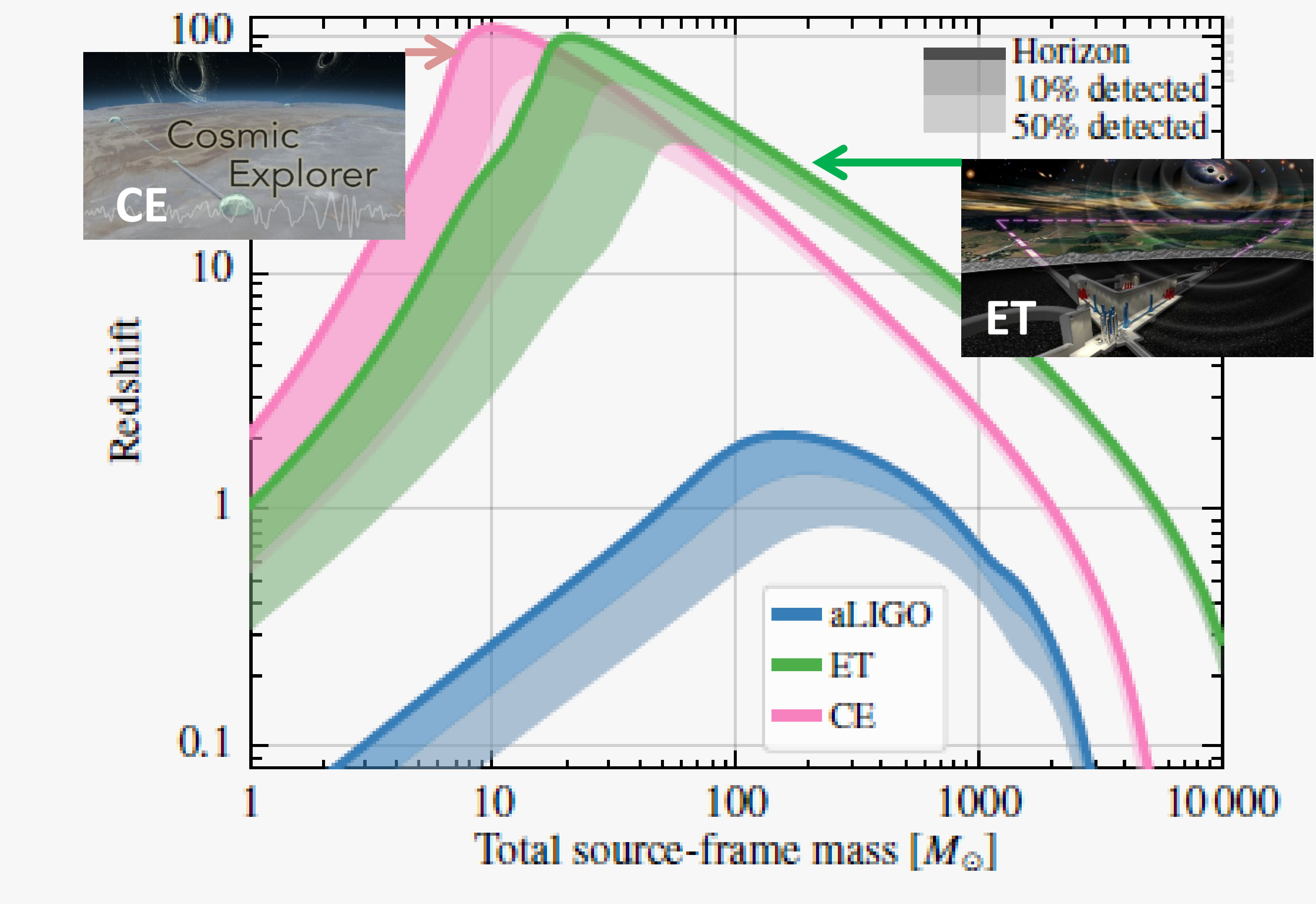
- ✓ Since the present generation of ground-based GW detectors have been so successful, there have been intense activities to design and propose the next generation detectors (ET and CE).
- ✓ These future detectors will use cryogenic mirrors to improve the sensitivity. One of them (ET) will be constructed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

Sensitivity: future ground-based GW detectors

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



Sensitivity (GW strain noise) for future detectors (ET and CE) compared with LIGO.



Astrophysical reach for equal mass binaries.

Summary

- Gravitational wave astronomy is a new and exciting scientific field. It will unveil the secrets of the Universe.
- KAGRA is a unique gravitational wave detector with cryogenic mirrors and the underground site.
- KAGRA would like to contribute to the global network of gravitational wave detectors and to the science of gravitational wave astronomy.
- KAGRA started the observation on May 24, 2023. Really exciting moment!

Sensitivity history