GGI, Florence, Italy, June 28, 2024

Gravitational waves and the KAGRA project


LIGO

Virgo

KAGRA

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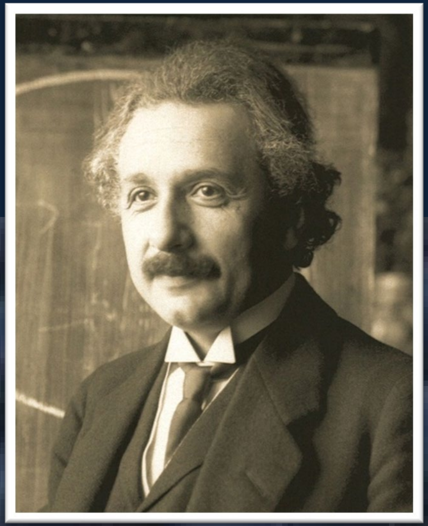
Outline

- *Introduction*
- *Possible Sources of Gravitational Waves*
- *Detecting Gravitational Waves*
- *The KAGRA Project*
- *Gravitational Wave Network*
- *KAGRA's contribution to the GW science*
- *Future*
- *Summary*

Introduction

Gravitational waves

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



A. Einstein
（by F. Schmutzer, Wikipedia）

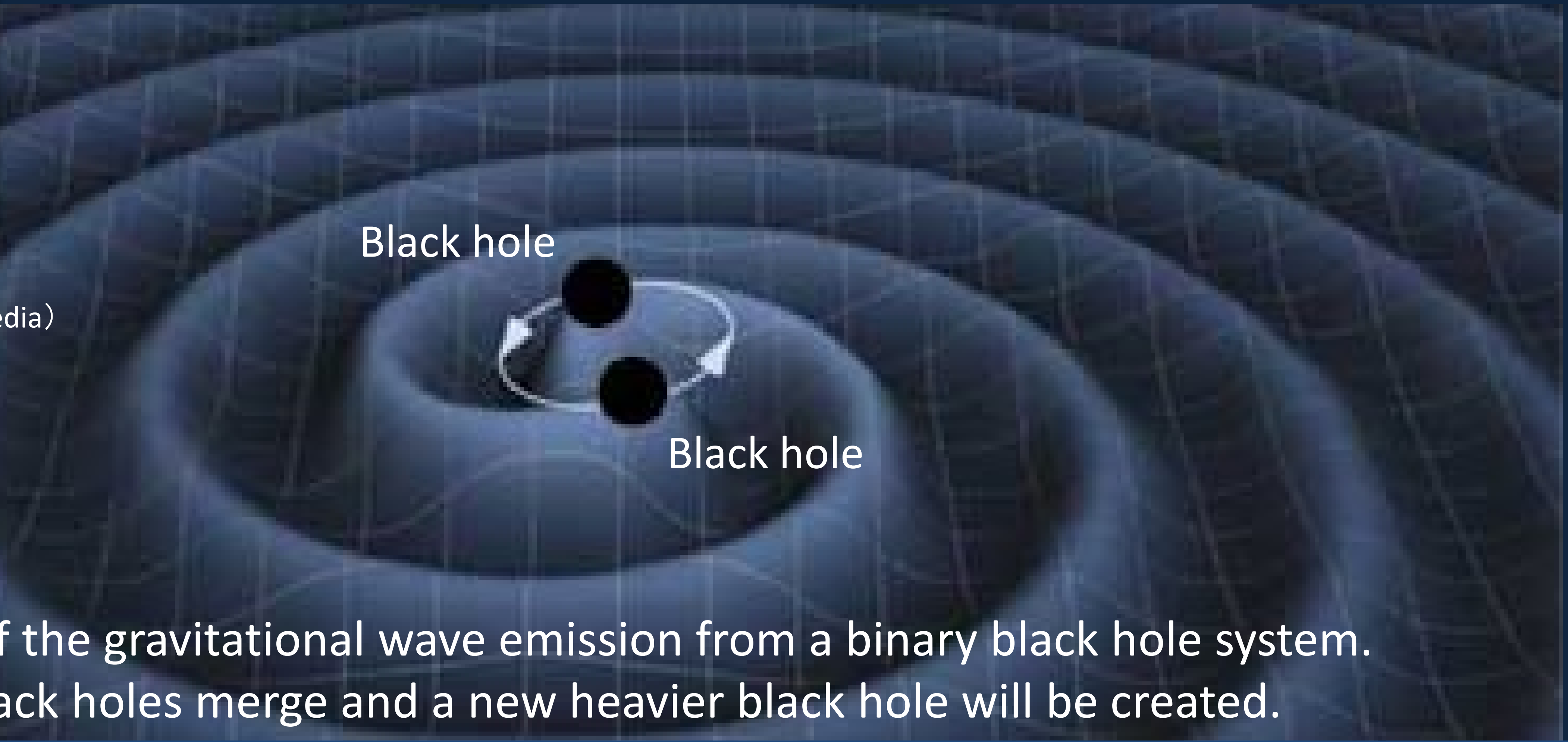
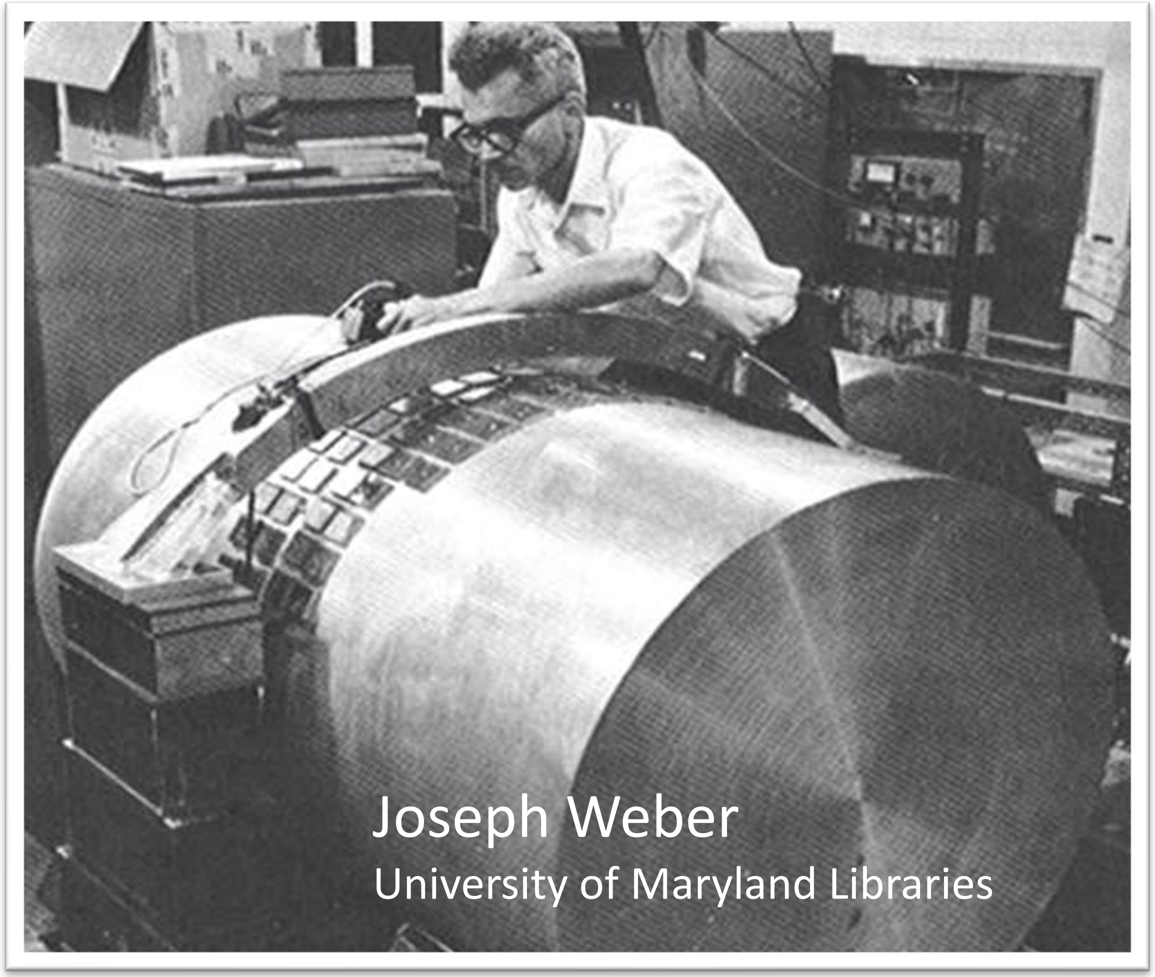


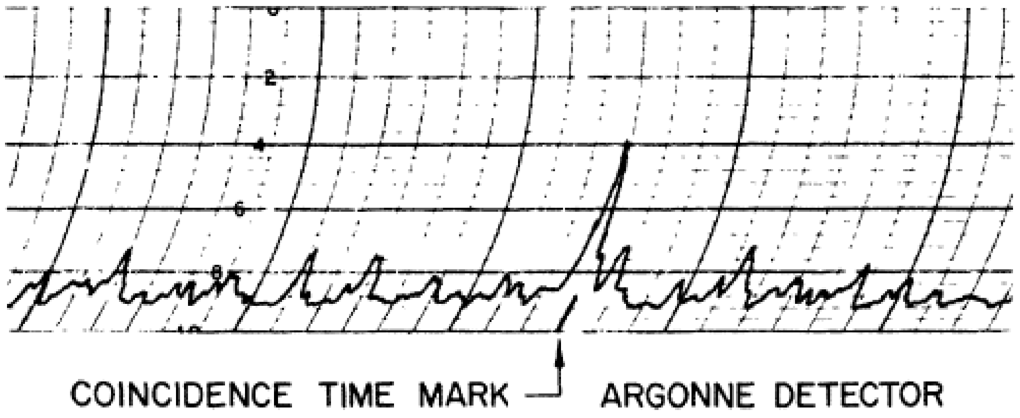
Image of the gravitational wave emission from a binary black hole system.
These back holes merge and a new heavier black hole will be created.

Early days of gravitational wave experiments

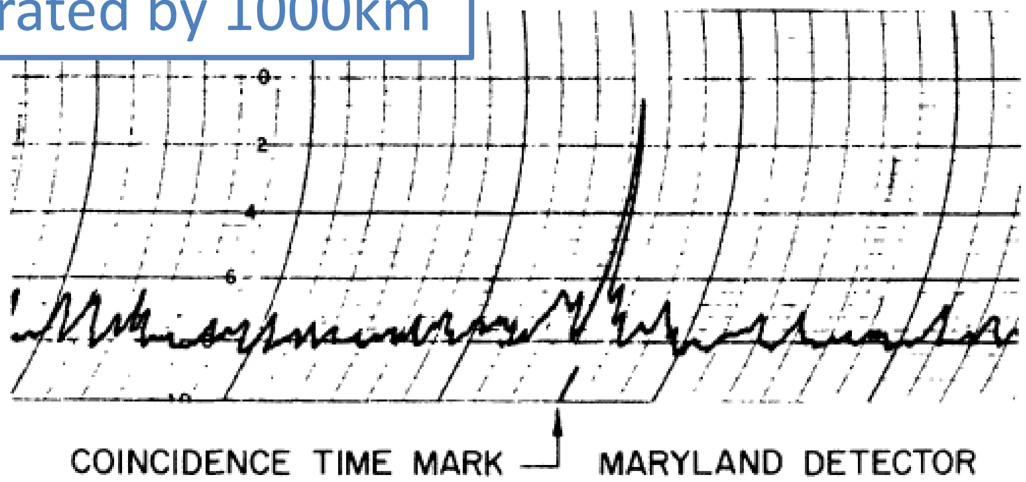


1969

J. Weber, PRL 22, 1320 (1969)

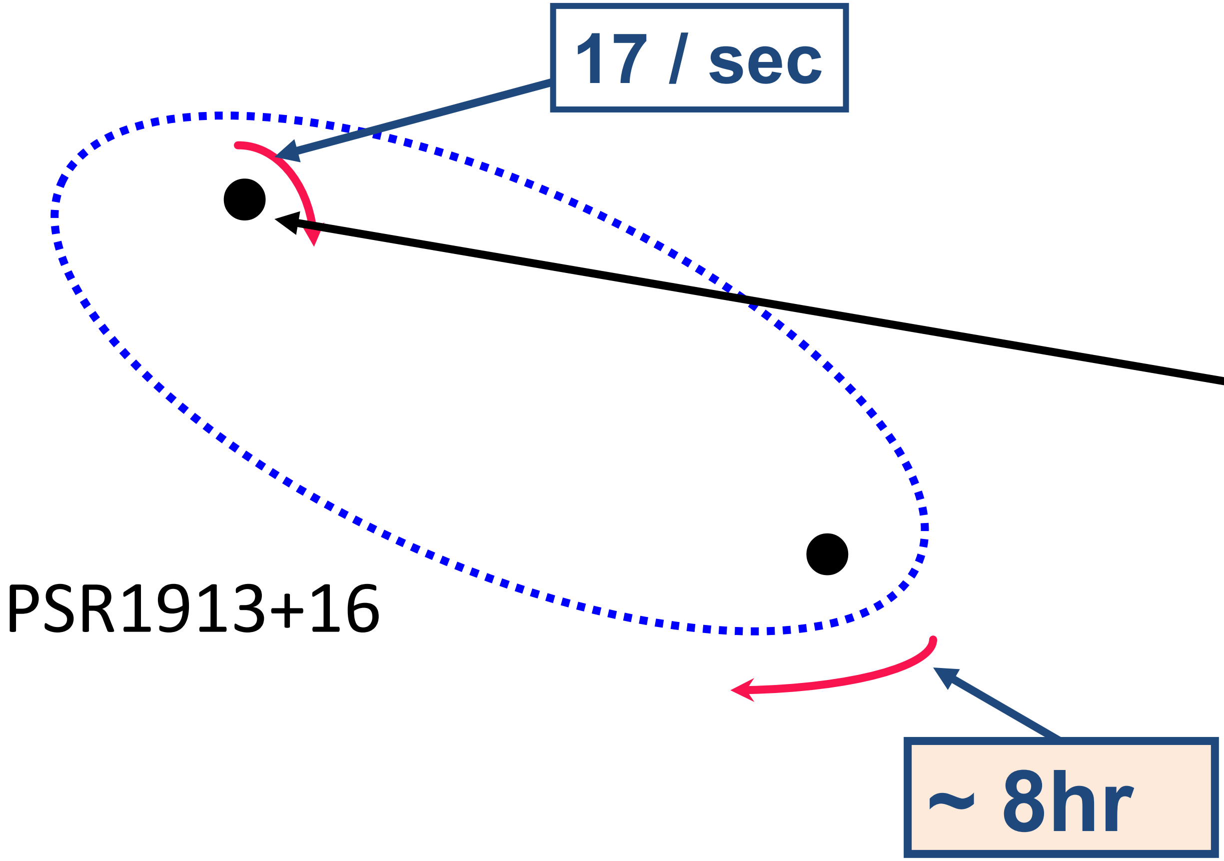


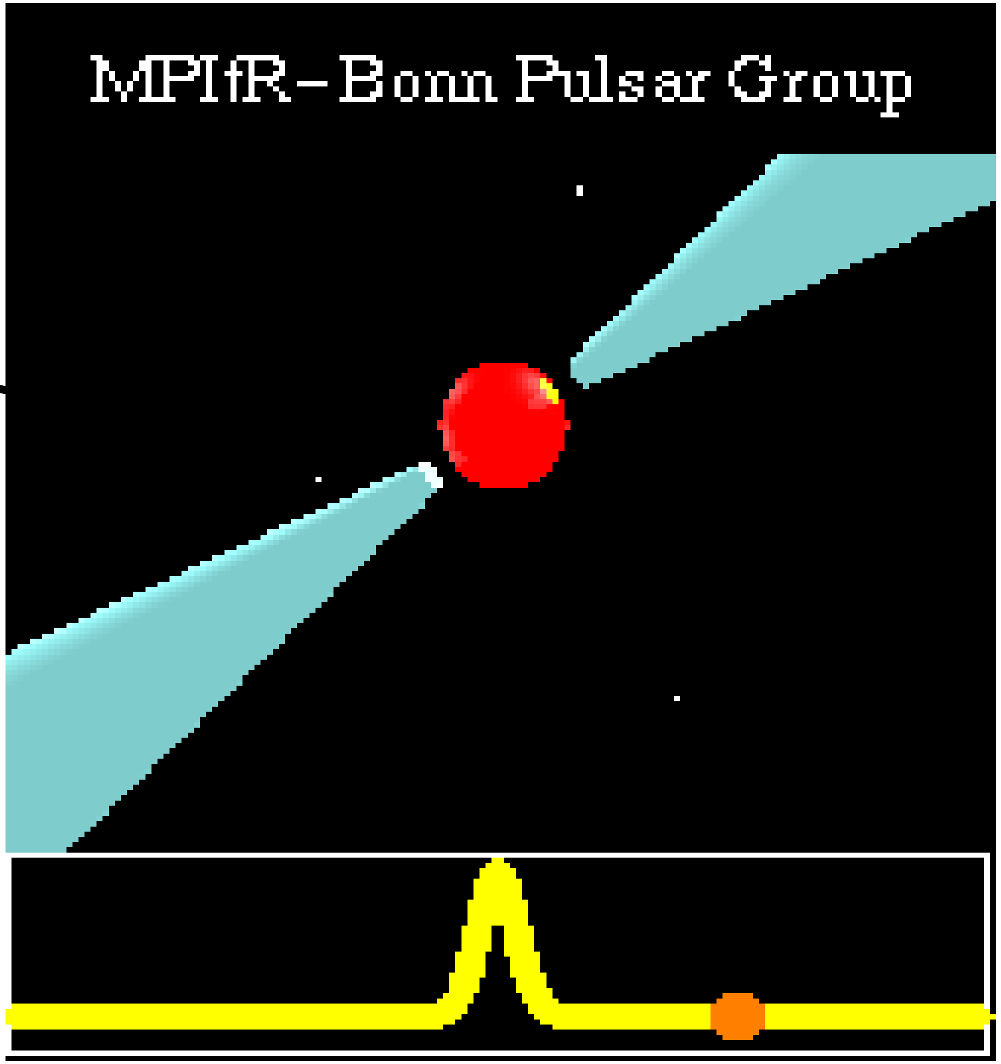
Separated by 1000km



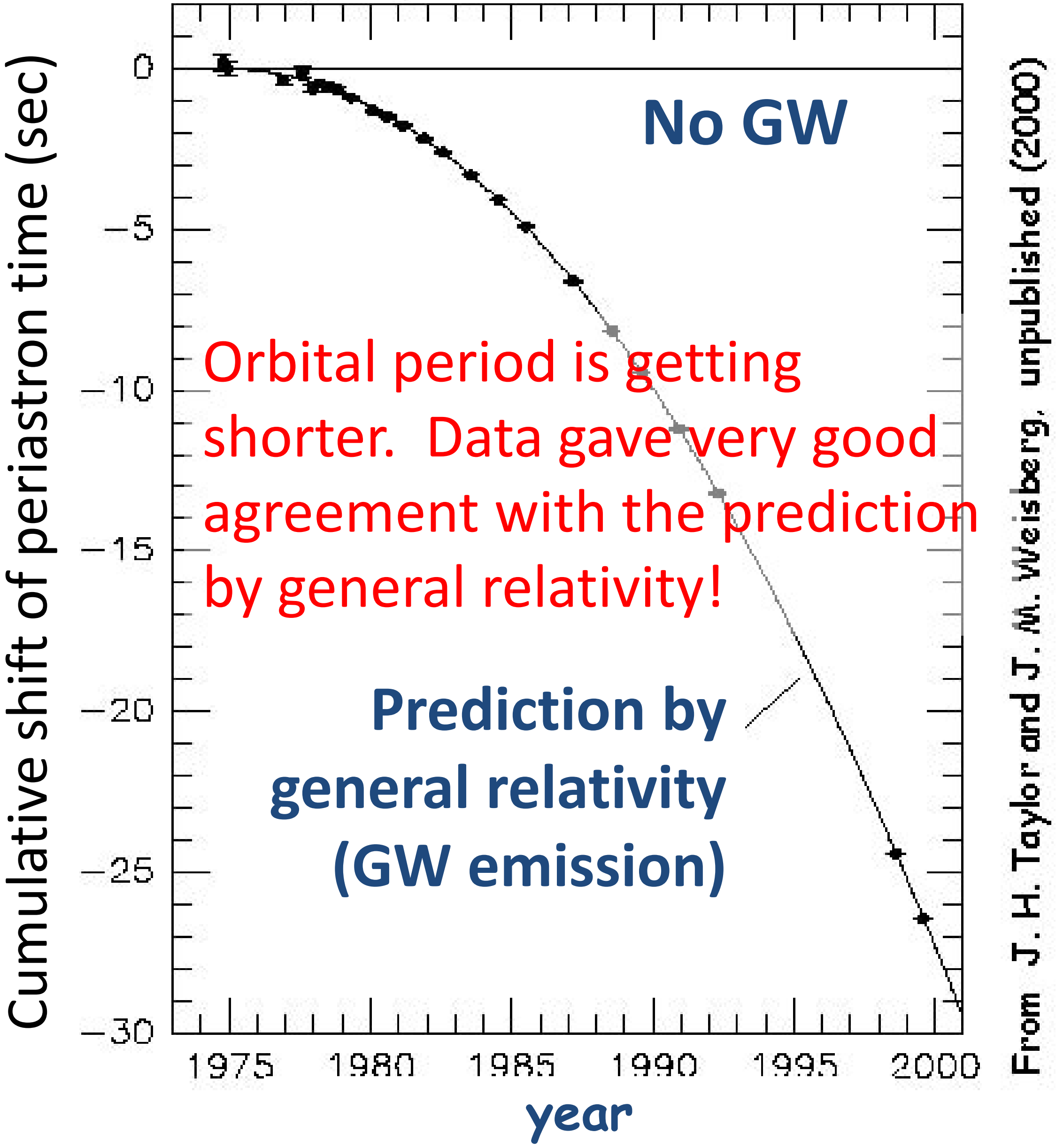
- ✓ No one was able to re-observe similar signals.
- ✓ However, this experiment motivated the detection of gravitational waves.

Binary neutron stars





Evidence for GW: binary neutron stars



The Nobel Prize in Physics 1993

Photo from the Nobel Foundation archive.
Russell A. Hulse

Photo from the Nobel Foundation archive.
Joseph H. Taylor Jr.

https://www.nobelprize.org/prizes/physics/1993/speedread/

Hulse and Taylor's observations, although indirect, provided the strongest proof yet for gravitational radiation. Their findings have provided the impetus to develop a series of gravity-wave detectors, which aim to catch gravitational radiation from astronomical phenomena like black holes or two merging neutron stars through more direct means, as their passing waves wash over Earth.

Proposal to use laser interferometer

The Weber's detector had a disadvantage that the frequency of the GWs that can be observed was limited to the resonance frequency. Therefore, in 1972, Rainer Weiss proposed a laser interferometer to observe GWs[1].

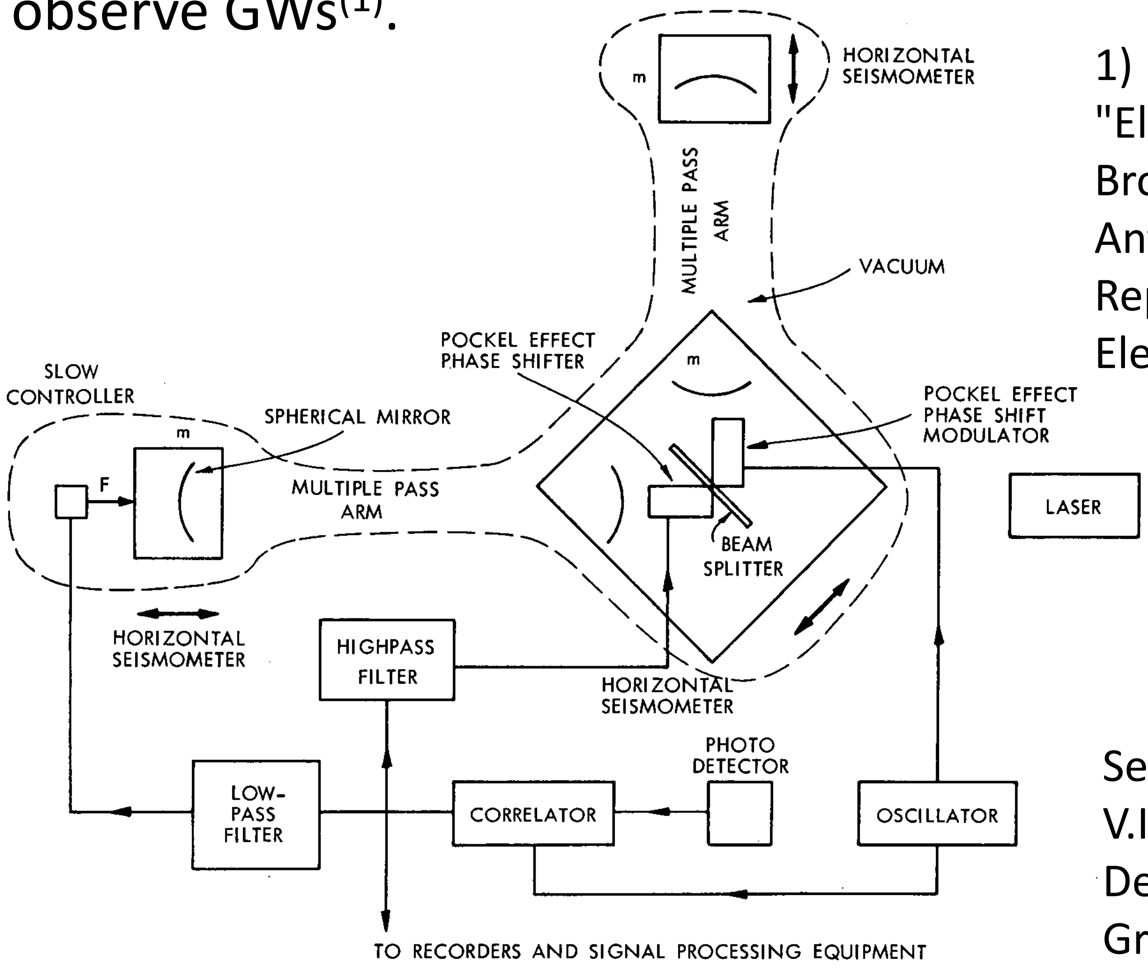


Fig. V-20. Proposed antenna.

1) R. Weiss (1972). "Electromagnetically Coupled Broadband Gravitational Antenna". Quarterly Progress Report, Research Laboratory of Electronics, MIT 105: 54.

See also, M.E. Gertsenshtein, V.I. Pustovoit, "On the Detection of Low Frequency Gravitational Waves", Sov.Phys.JETP 16 (1962) 433

Rainer Weiss (Wikipedia)

Then, …

https://physicsworld.com/a/rainer-weiss-50-years-ligo-gravitational-waves/
https://medium.com/big-science-at-stfc/gravitational-waves-discovery-a-timeline-b2ddbd172e1c
https://en.wikipedia.org/wiki/Virgo_interferometer

- In 1974, Rainer Weiss met Kip Thorne and convinced Thorne that a laser-based instrument would give them the best chance of finding gravitational waves. They started working on the project that would become LIGO.
- In 1979, the National Science Foundation funded Caltech and MIT to carry out a feasibility study of interferometric detection.
- In 1985, the Virgo project was conceptualized by Adalberto Giazotto (Italy) and Alain Brillet (France).
- 1990–1999: Construction of LIGO at Hanford, Washington, and Livingston, Louisiana was approved, funded and completed. LIGO is inaugurated in 1999.
- The Virgo project was approved in 1992 by the French CNRS and in 1993 by the Italian INFN. The construction of the detector started in 1996 at the Cascina site near Pisa, Italy, and was completed in 2003.
- 2002–2010: LIGO began operations. But no gravitational waves were observed.
- Virgo had several science runs between 2007 and 2011 without detection.
- Both LIGO and Virgo had a long shutdown to improve the sensitivities (Advanced LIGO and Advanced Virgo projects).

The first detection of GW (GW150914)

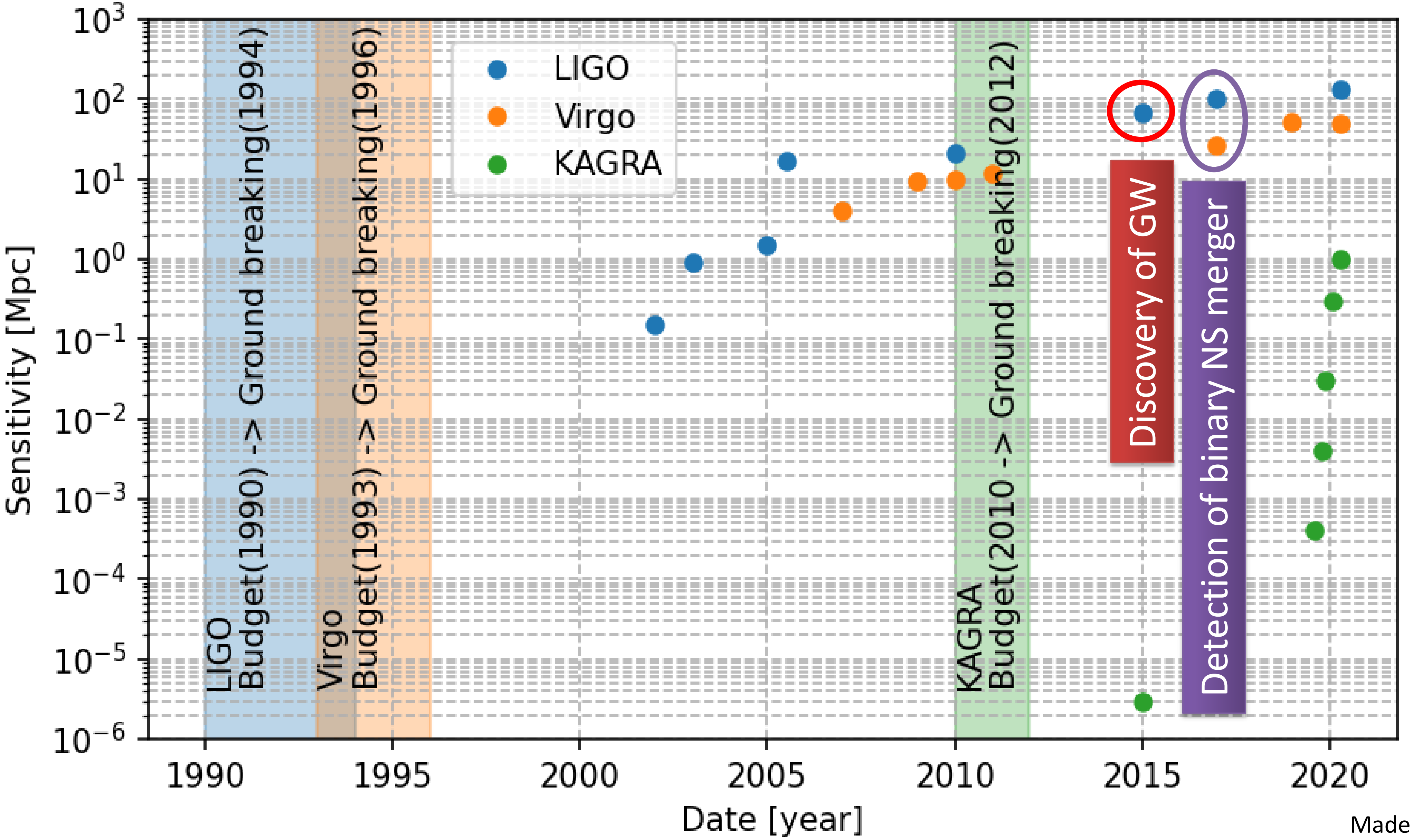
LIGO Scientific Collaboration and Virgo Collaboration, PRL, **116**, 061102 (2016)

Feb. 11, 2016

"Ladies and gentlemen, we have detected gravitational waves. We did it."

Dr. France Cordova, Director of NSF: … Since the mid-1970s,NSF has been founding the science that ultimately led LIGO's construction. And in 1992, when then NSF director, Walter Massey and the National Science Board approved LIGO's initial funding, it was the largest investment NSF had ever made. It was a big risk, but NSF is the agency that takes these kinds of risks.

Sensitivity history

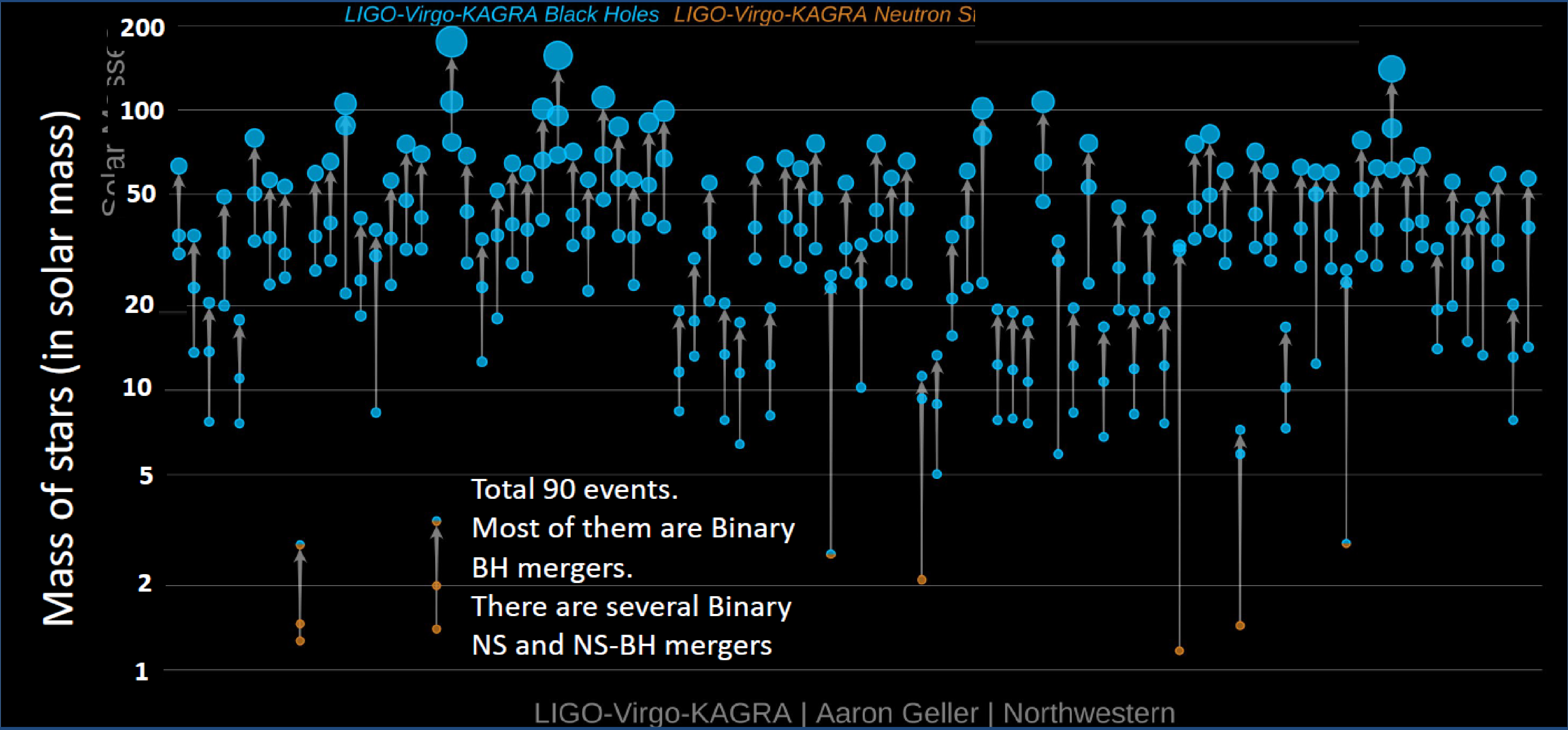


Made by KAGRA collab.

Possible sources of Gravitational Waves

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.

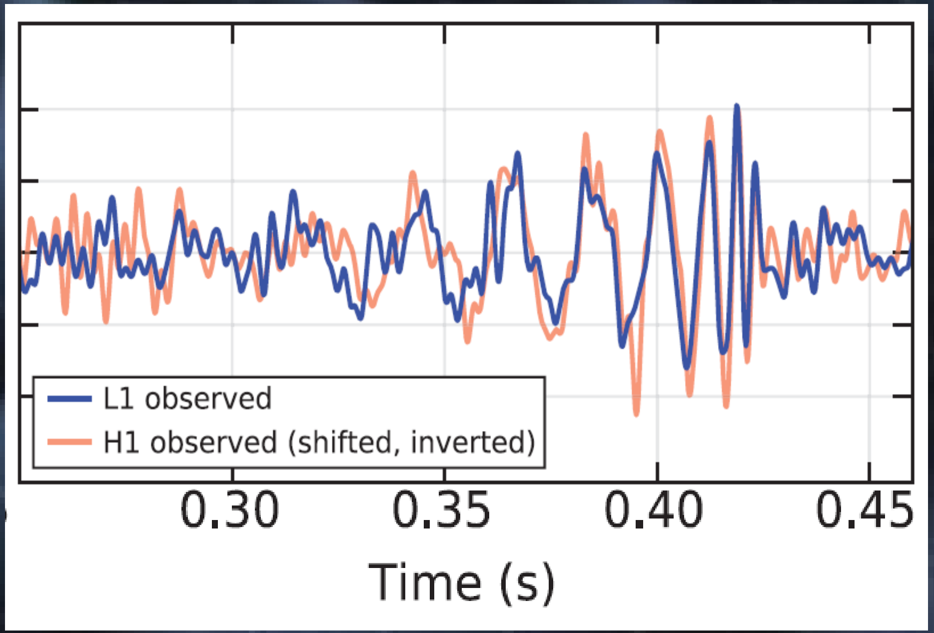
There are several Binary NS and NS-BH mergers

Merger of binary blackholes

✓We already learned that blackholes merge and create a heavier blackhole.

✓We would like to know how these blackholes themselves were created in the Universe.

✓….



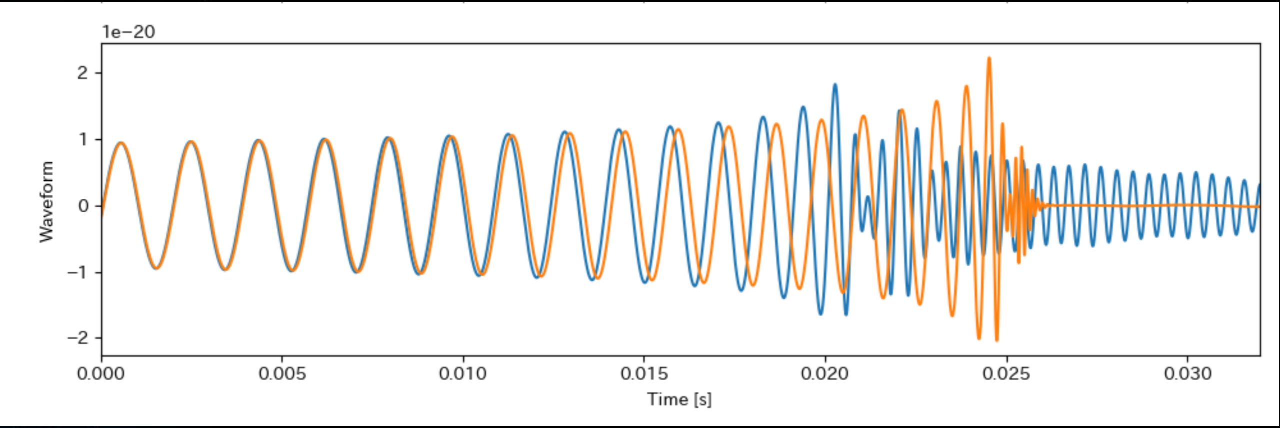
Merger of binary neutron stars

✓We would like to know if a blackhole is created immediately after the merger of the binary neutron stars.

✓We would like to know if heavy metals, such as gold, are produced during the merger of binary neutron stars. (In 2017, the GW signal of binary neutron star merger was observed for the first time, and this observation partially confirmed the origin of them.)

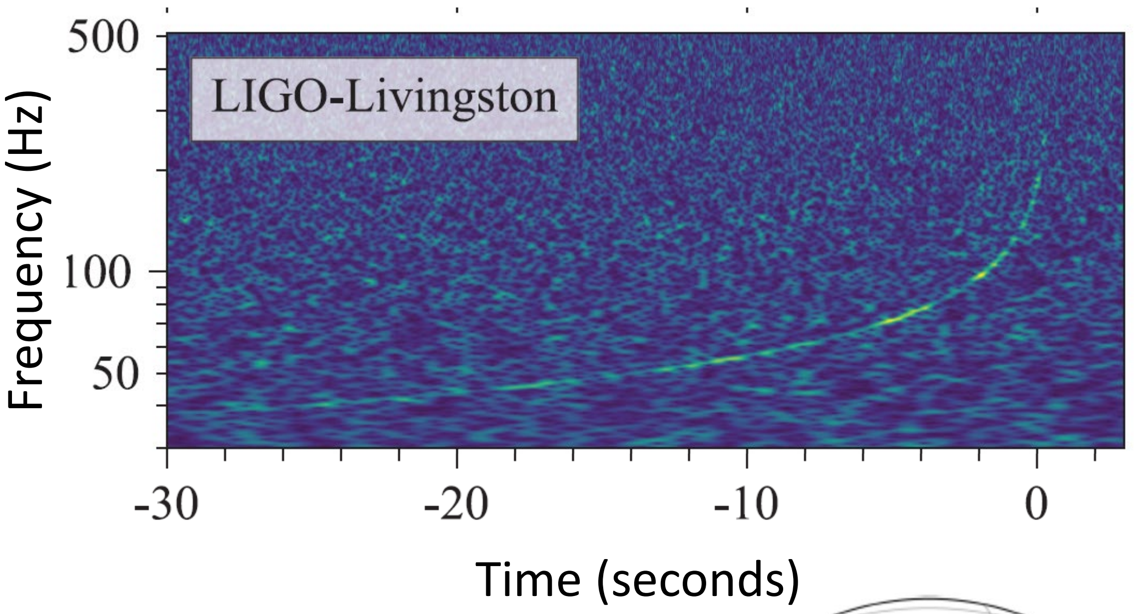
✓We would like to understand the short gamma ray bursts.

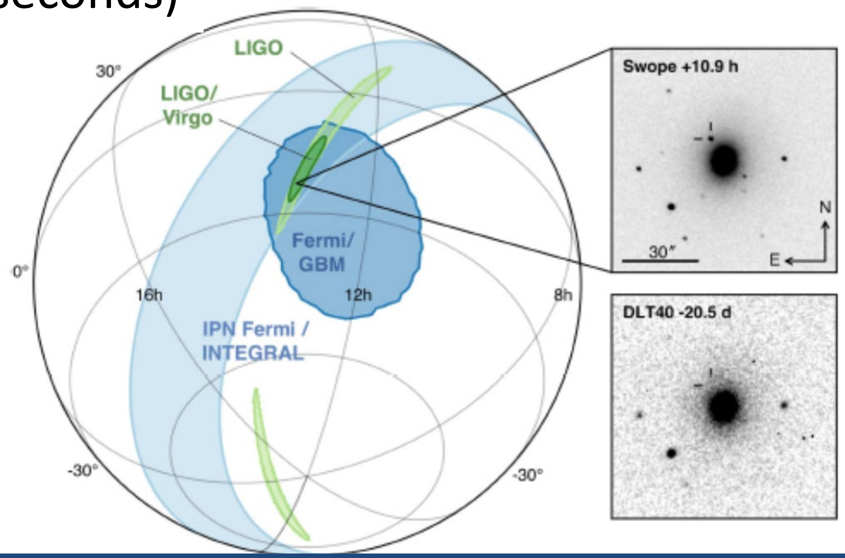
✓….



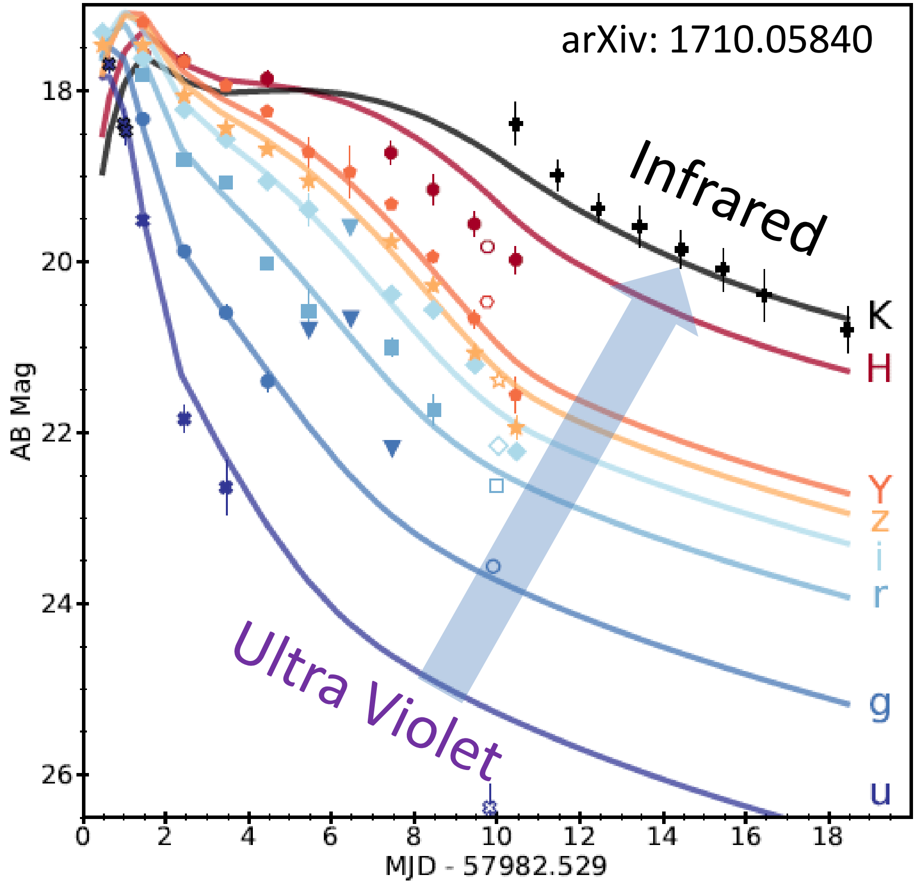
Multi-messenger astronomy with GW

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!

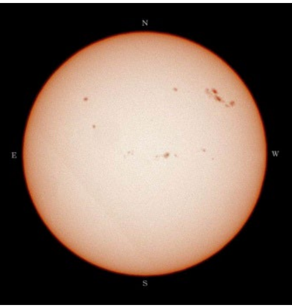
Supernova explosion

✓We would like to know how the heavy stars finish their life
✓ ….

@Anglo Australian Observatory

Detecting Gravitational Waves

Not easy to detect GWs



150,000,000 km

If strong gravitational waves come to the solar system, the distance between the Sun and the Earth will change by about ***10^{-8}cm.***

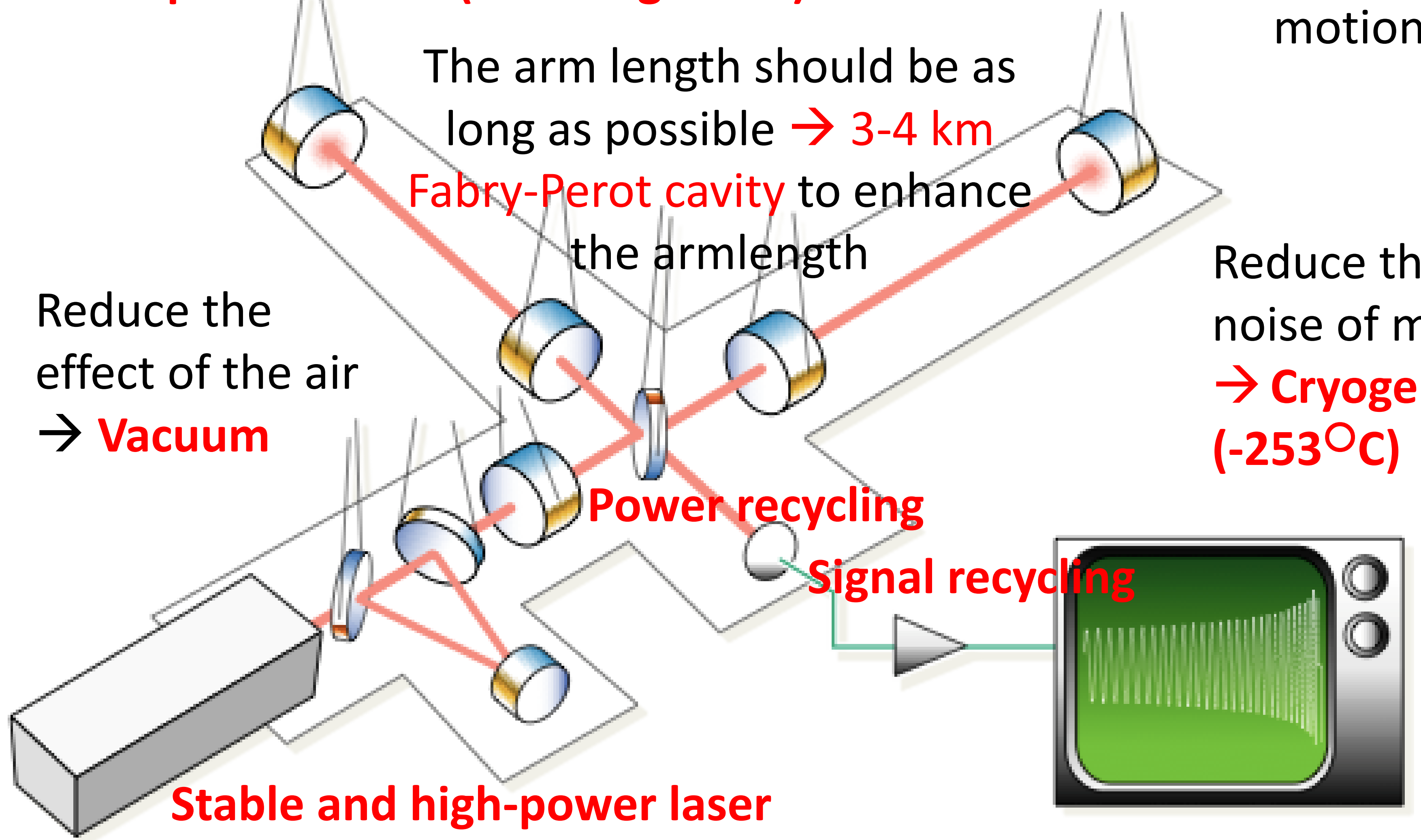
The present GW detectors have the arm length of only 3-4 km. Therefore, these detectors must be sensitive to the length change of ***10^{-16}cm*** in 3-4 km.

Realizing high sensitivity

Isolate the mirrors from seismic noises
→ **Suspend mirrors (+ underground)**

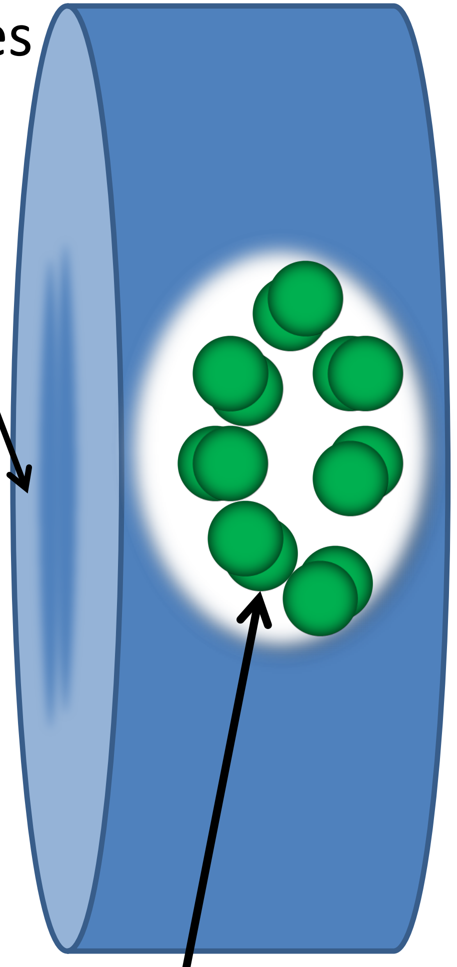
The arm length should be as long as possible → 3-4 km
Fabry-Perot cavity to enhance the armlength

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



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

Reduce the thermal noise of mirrors
→ **Cryogenic mirrors (-253°C)**



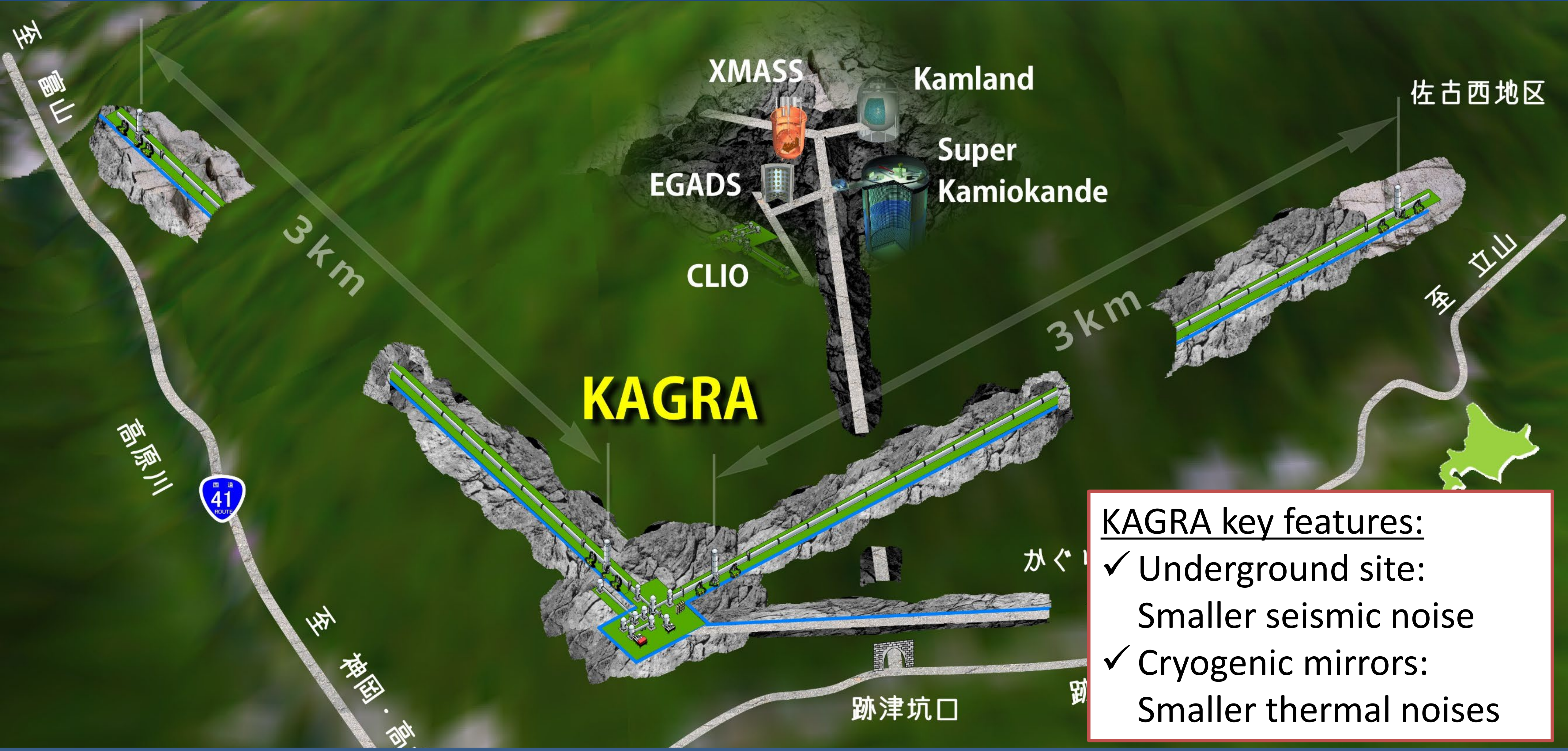
The KAGRA project

KAGRA collaboration

8 countries/regions, ~160 authors

(and ~400 collaborators from 17 countries/regions)

Location of KAGRA



KAGRA key features:

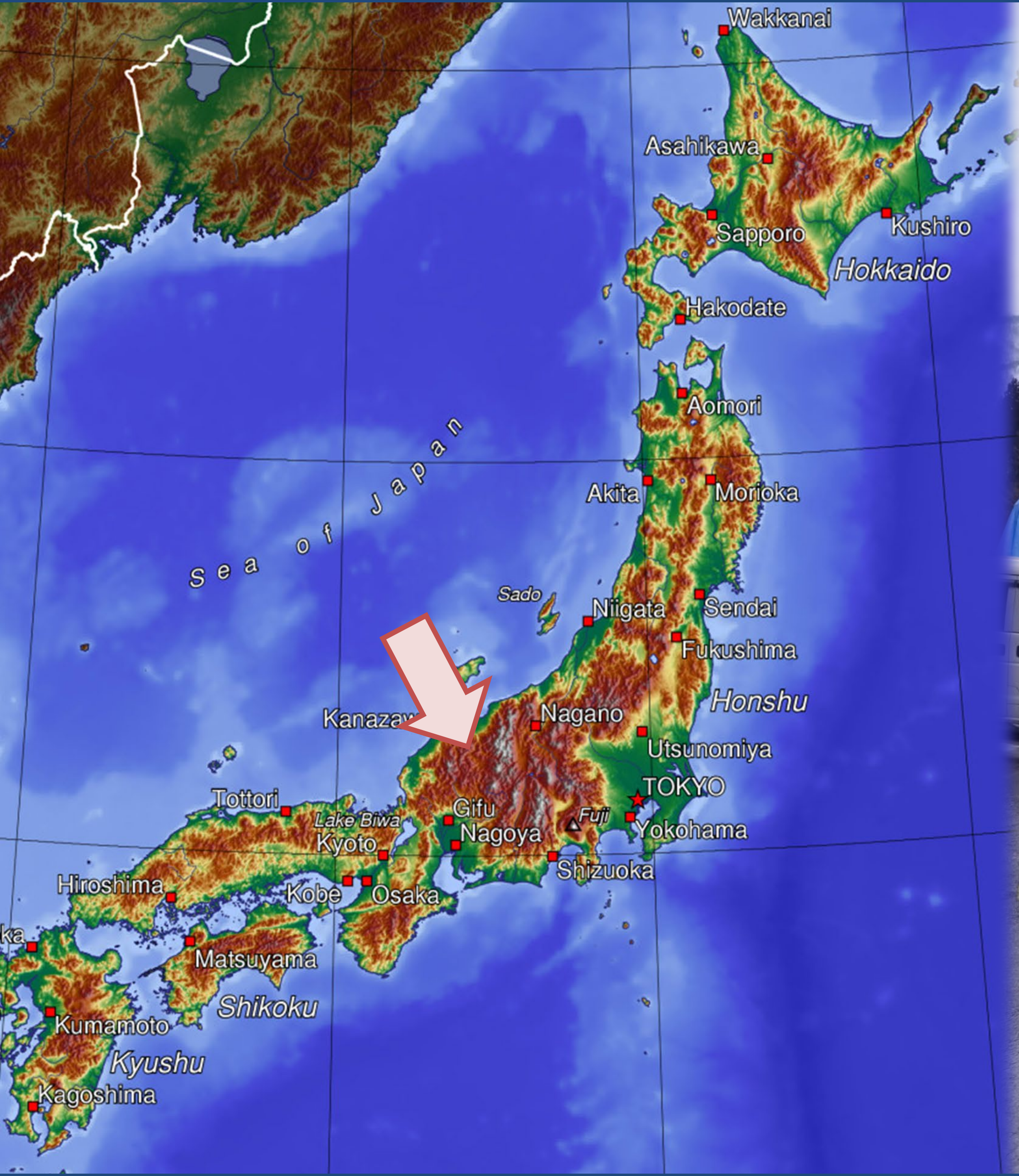
✓ Underground site:
Smaller seismic noise

✓ Cryogenic mirrors:
Smaller thermal noises

My personal history: From neutrinos to gravitational waves

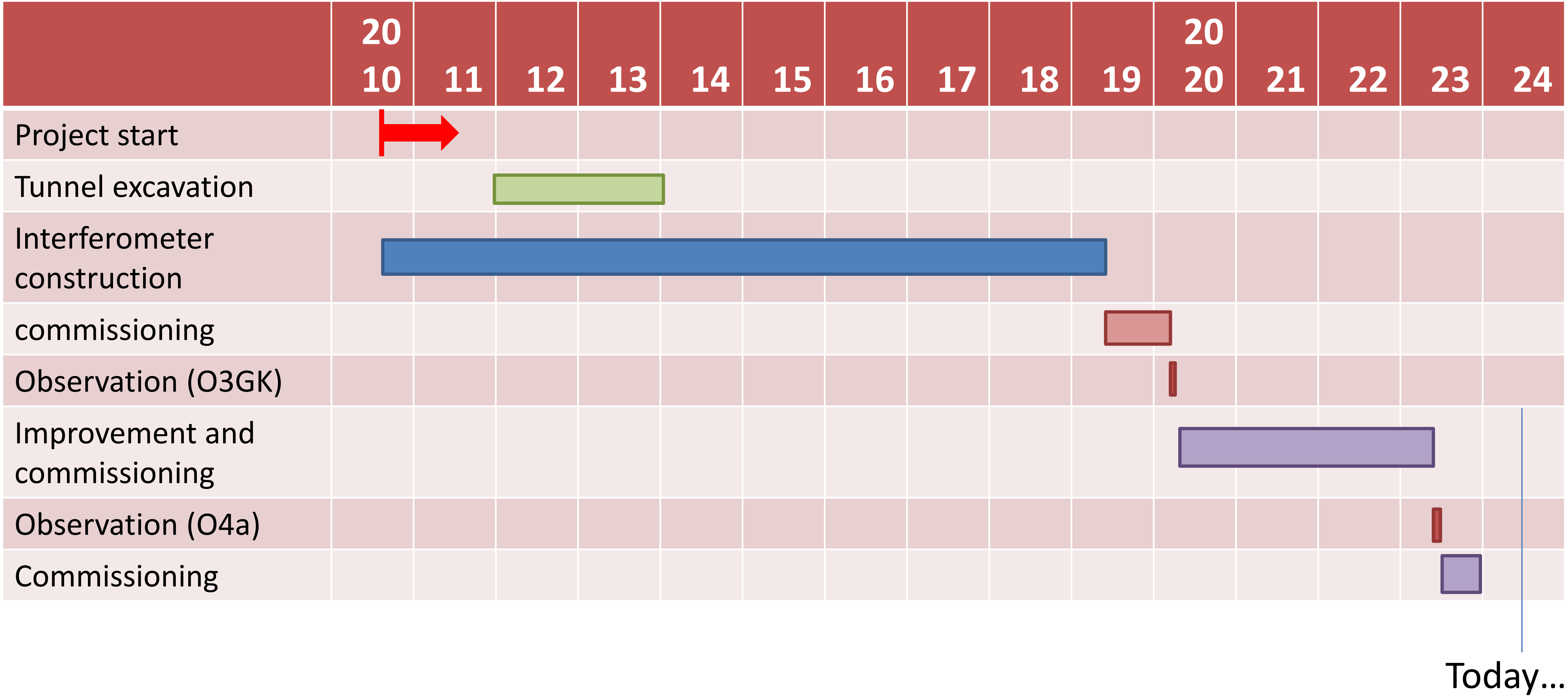
- I studied neutrinos for more than 20 years.
- After the discovery of neutrino oscillations in 1998 and after some more studies for several more years, I was feeling that I finished what I should do in my neutrino research.
- On the other hand, there are still many exciting sciences that we would like to study. In particular, gravitational waves had not yet discovered at that time. I was fascinated by the research on gravitational waves and the studies of the Universe with gravitational waves.
- KAGRA’s mission was clear: KAGRA should contribute to the GW astronomy as a detector far from LIGO and Virgo. KAGRA should develop the cryogenic technology and contribute to the next generation GW detectors.
- In 2008, I was appointed as the director of the Institute for Cosmic Ray Research. It was clear that I could no longer contribute to neutrino research much. Still, I wanted to be involved in exciting research. Therefore, I decided to participate in the gravitational wave project KAGRA with my partial time.

Location of KAGRA

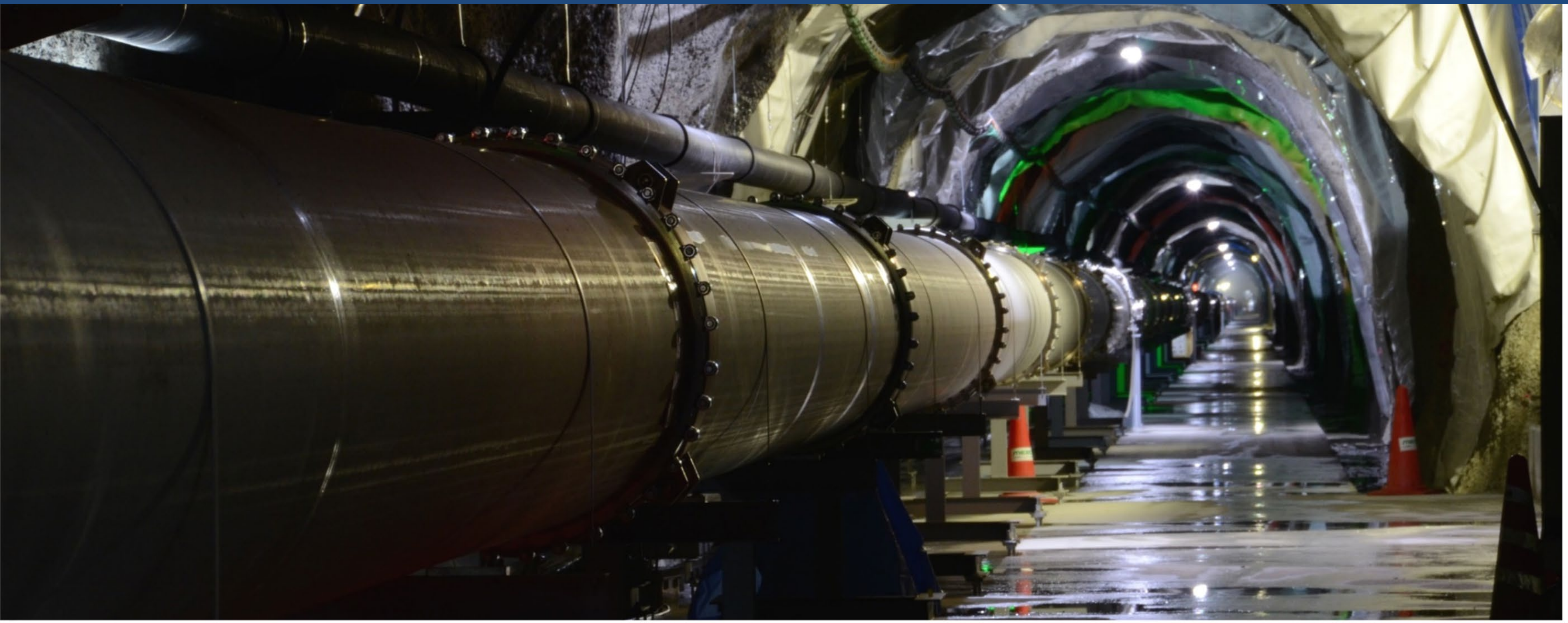


(A slightly old photo during the construction)

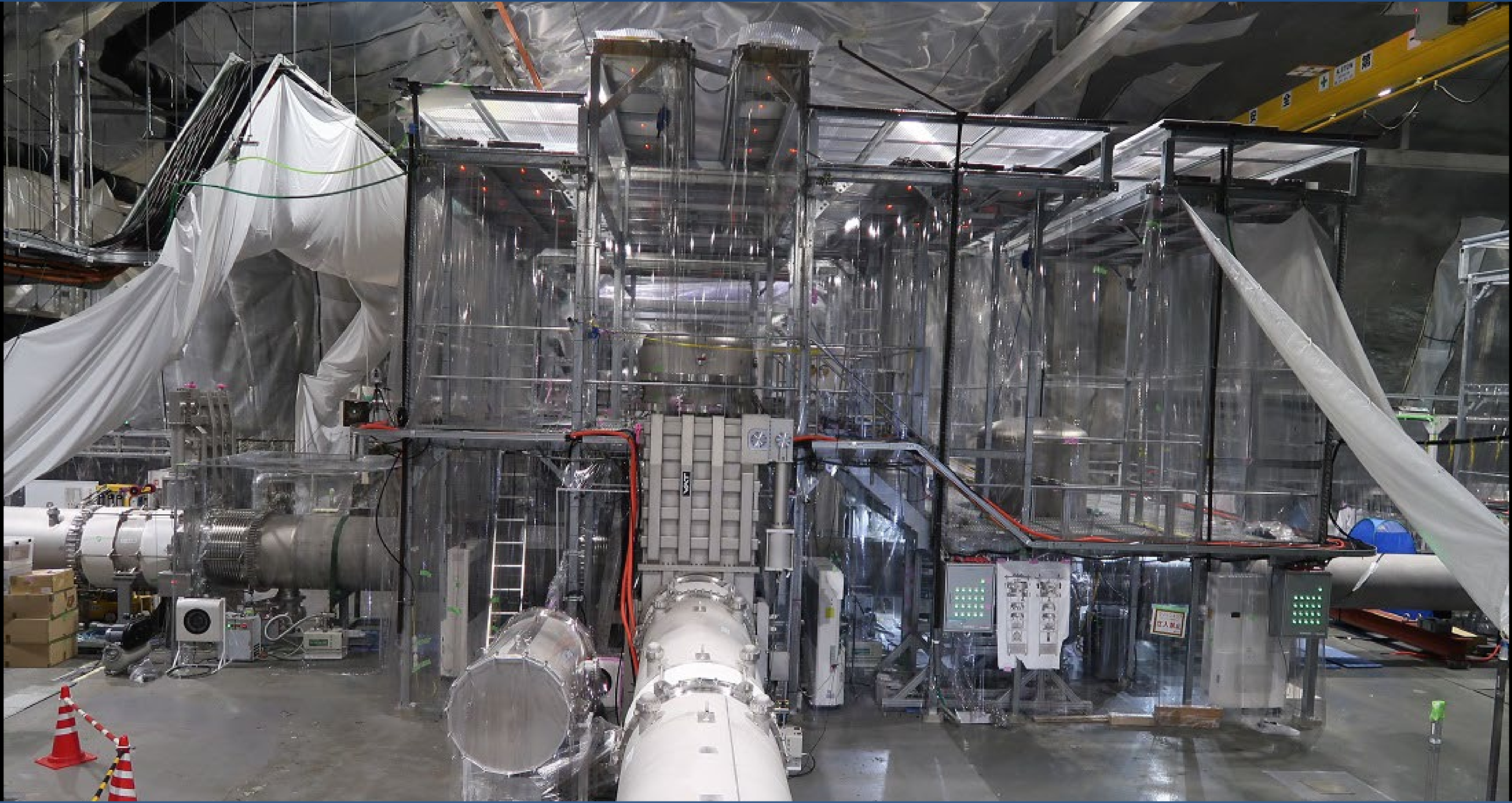
KAGRA project history



3km long vacuum tubes (Feb. 2015)

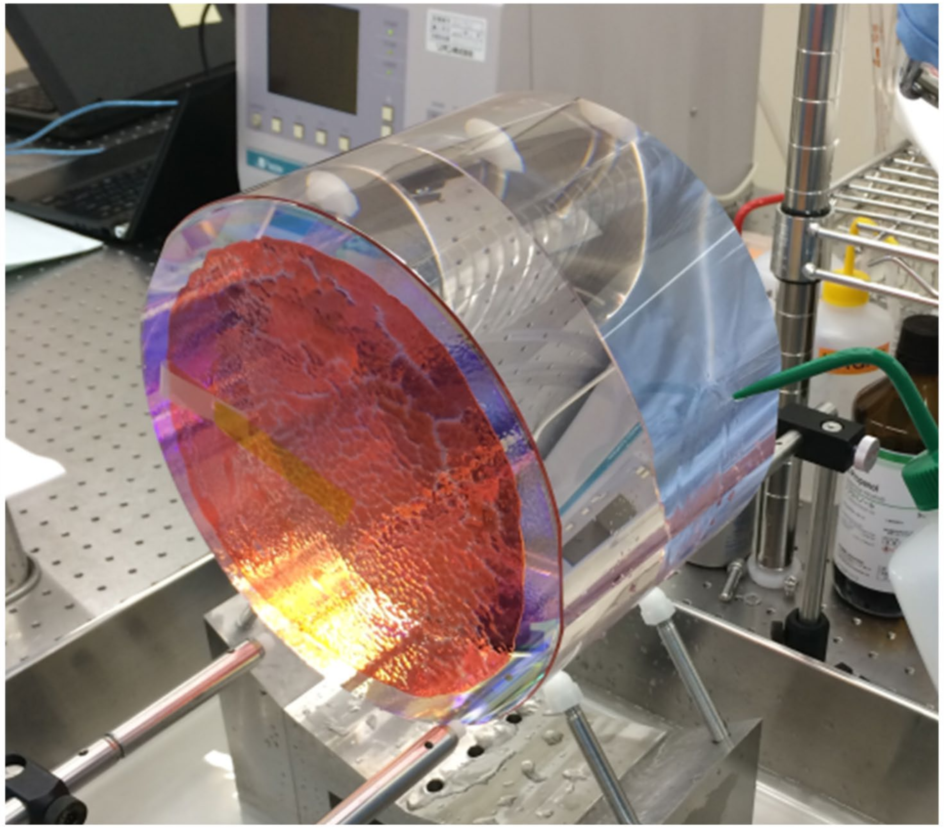


Center area



Installation works (until spring 2019)

Vibration isolation system



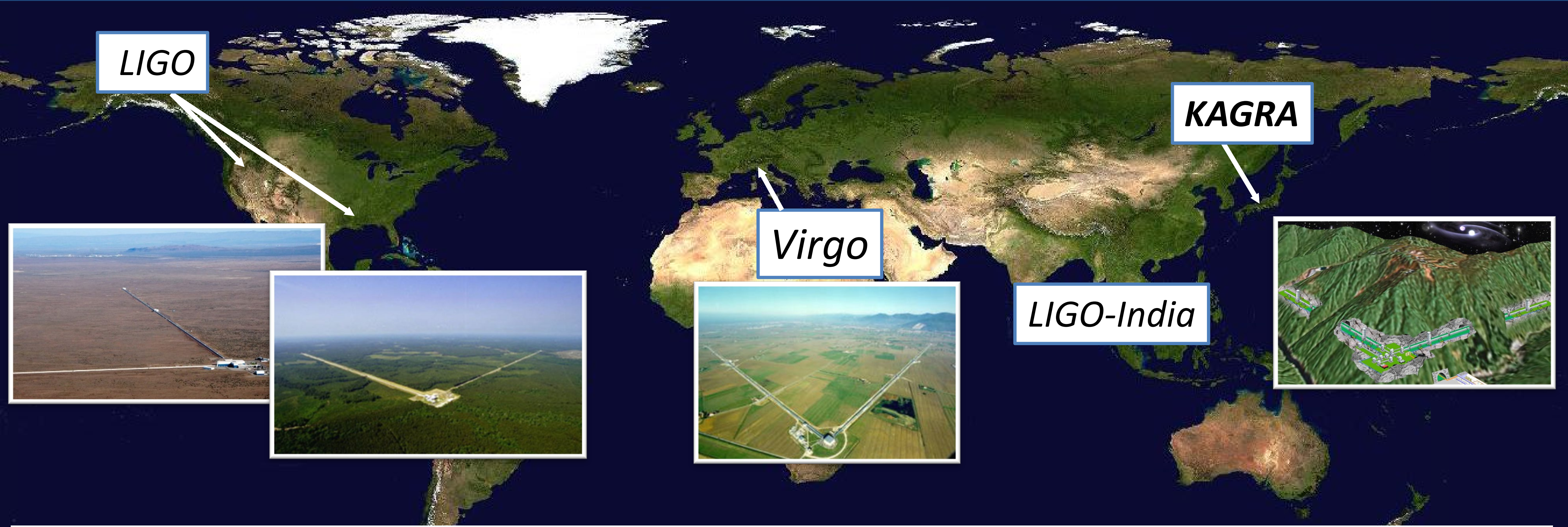
Preparation of cryogenic mirror
（22cm(ϕ), 15cm (t), 23kg）
➔ To the KAGRA site

Office and the KAGRA control room at the surface

The interferometer commissioning is carried out at the surface facility.

Gravitational Wave Network

Joining the global GW network



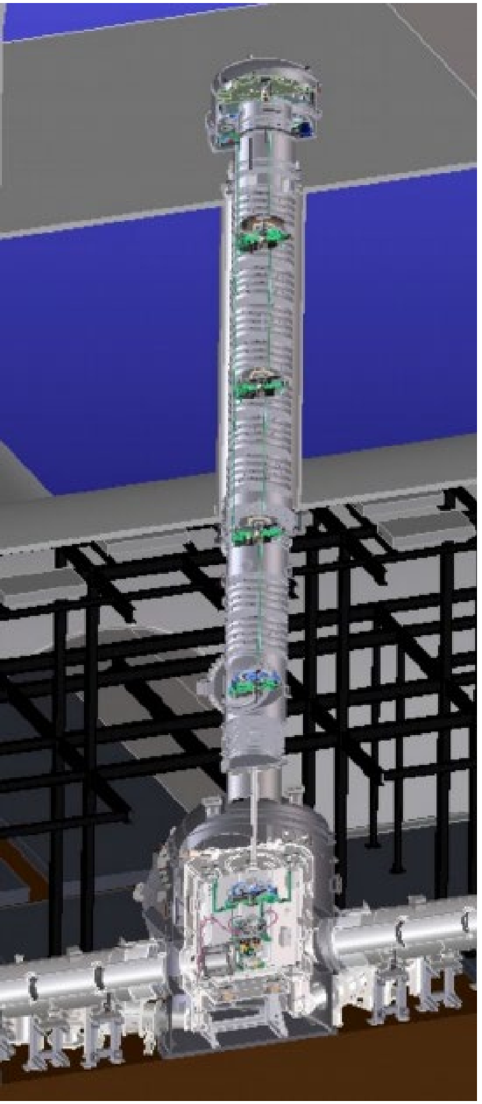
- To determine the location (direction) of the source, we need at least 3 detectors which are located far apart from each other.
- KAGRA decided to join the network observation with LIGO and Virgo. We are working together, namely, we observe GWs simultaneously and analyze the data as a team.

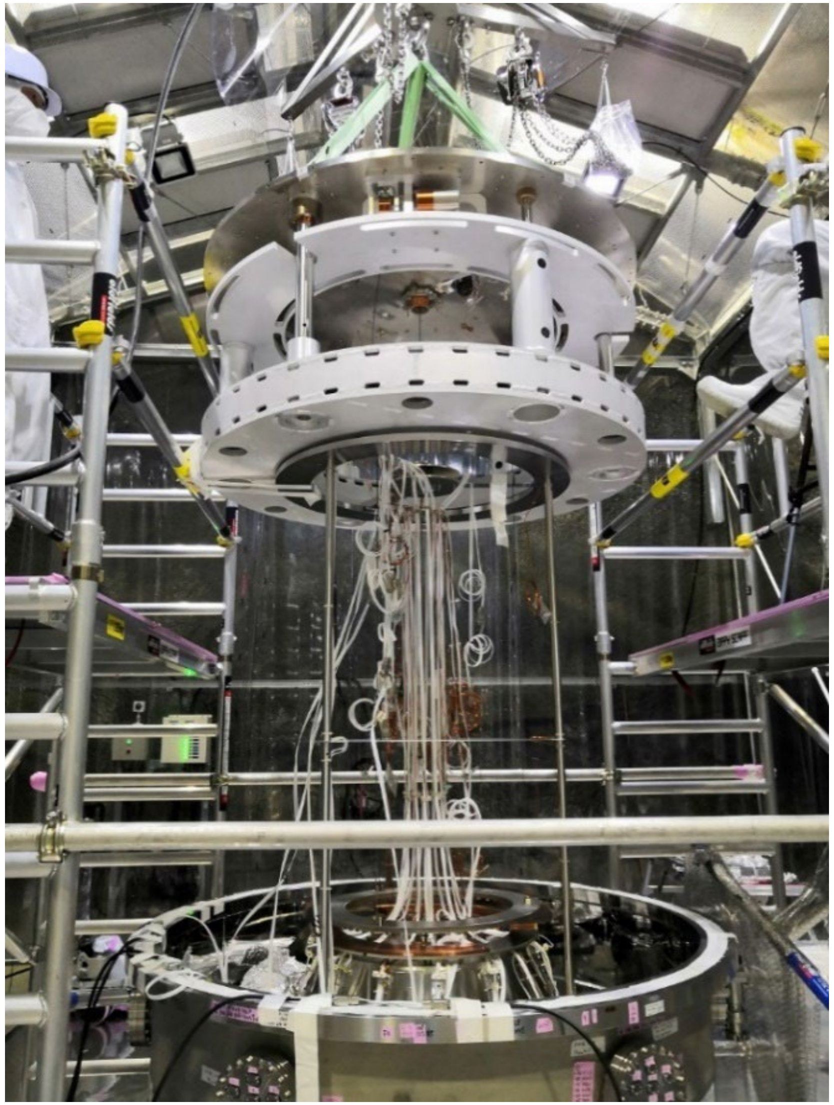
KAGRA history until spring 2020

(Feb. 25, 2020)

- In March 2020, after about a year of very intense commissioning, KAGRA achieved the sensitivity of 1Mpc, and officially joined the GW network with LIGO and Virgo.
- (COVID-19)
- KAGRA had 2 weeks of observation run then stopped.
- Started the improvement work.

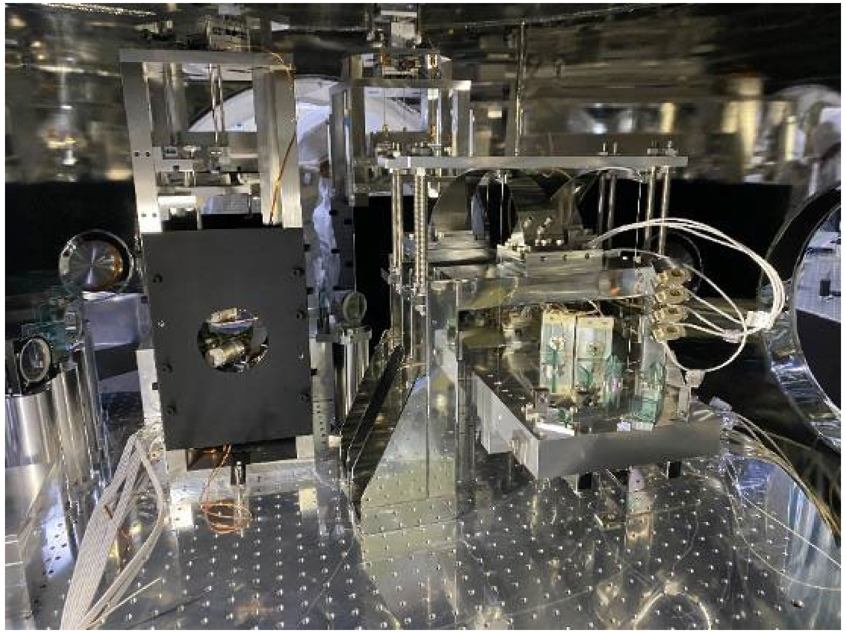
KAGRA improvement works (2020 – 2022)





Re-installation of the vibration isolation system

Testing the vibration isolation system

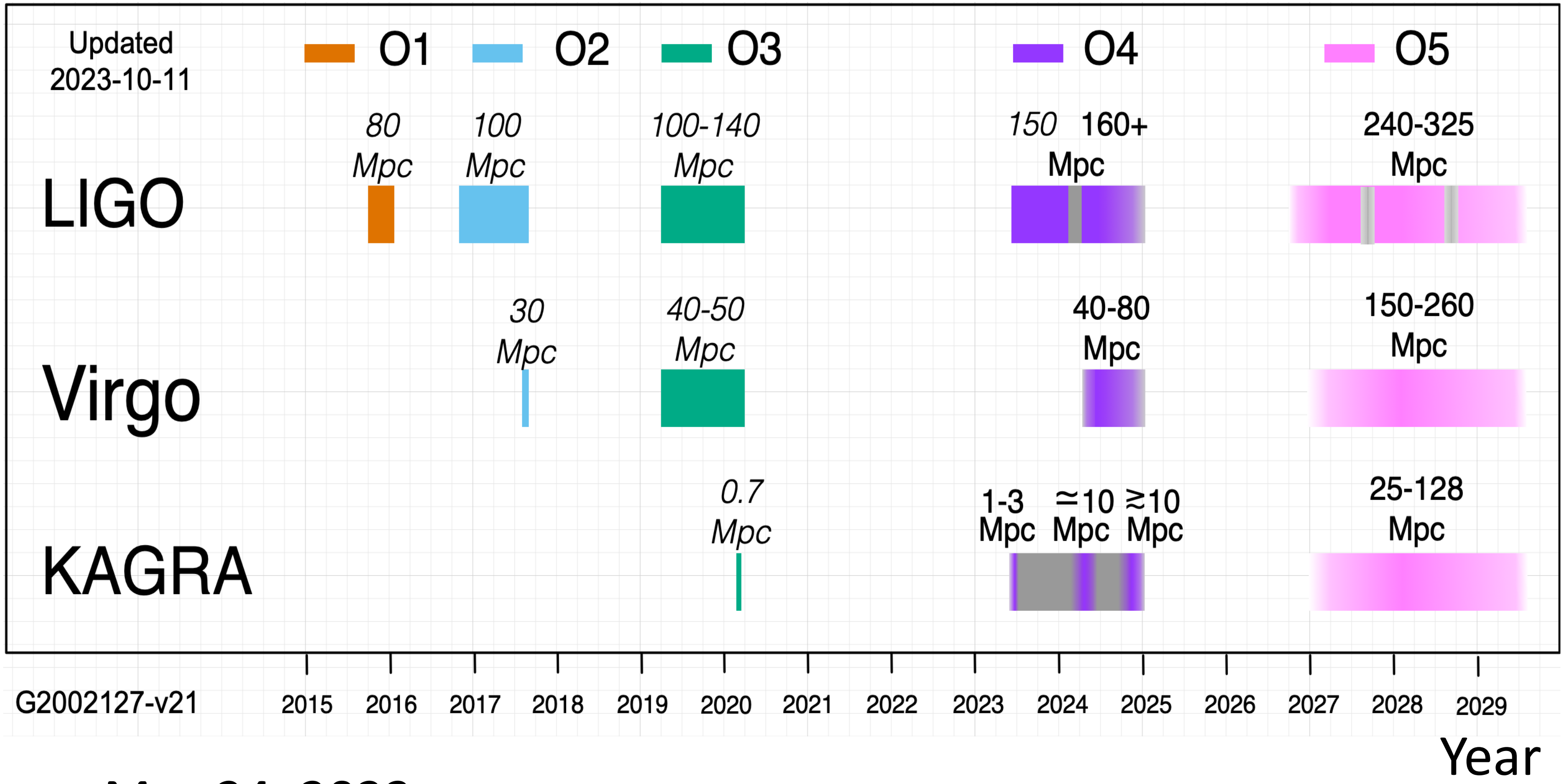


Re-instalation of the output mode cleaner

Observation in 2023

Observation history and plan of LIGO, Virgo and KAGRA (2023 version).

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



- ✓ KAGRA joined the observation on May 24, 2023.

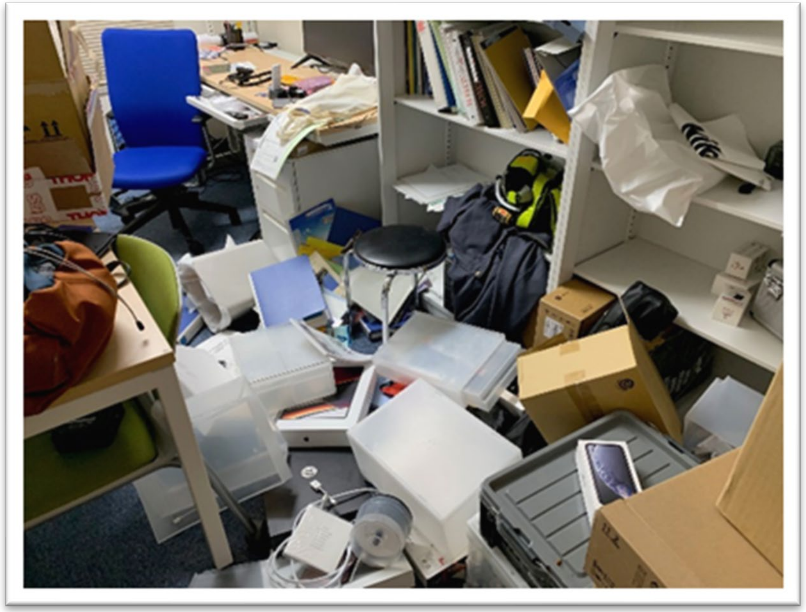
  Compared with KAGRA in 2020, the sensitivity was improved (0.7Mpc → 1.3 Mpc).
- ✓ After 1 month of observation, KAGRA stopped the observation and restarted working on the sensitivity improvement.
- ✓ KAGRA has been planning to rejoin the observation in the spring of 2024.

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)

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



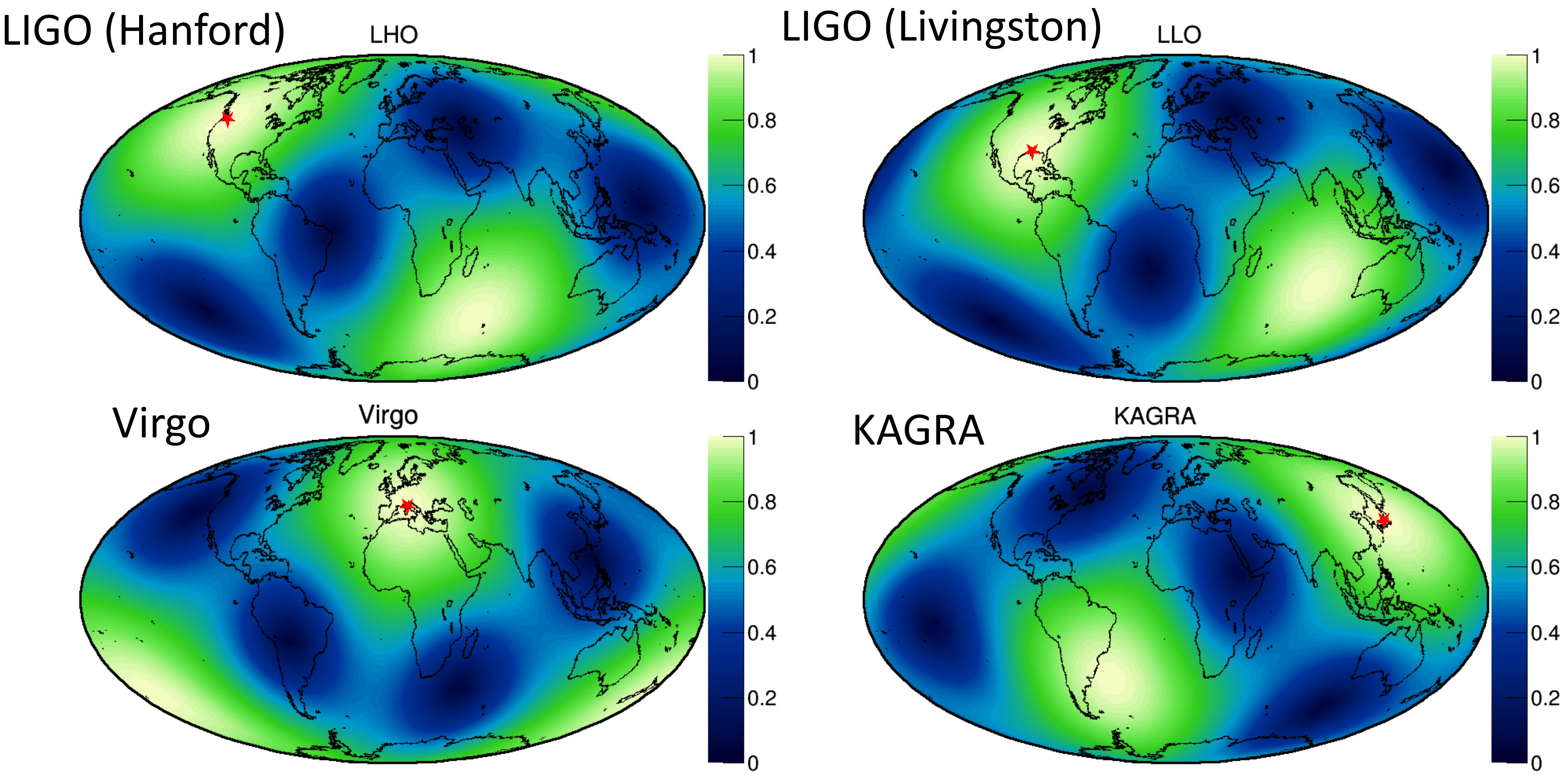
Inside the KAGRA surface building on Jan. 1

- I think we were fortunate, because we installed the KAGRA laser interferometer in underground. The effect of the earthquake was significantly smaller in underground.
- But there were still many damages in KAGRA.
- We started the recovery work

- We hope that KAGRA can rejoin the observation and contribute to the GW astronomy as soon as possible, hopefully in early 2025.

KAGRA’s contribution to the GW science

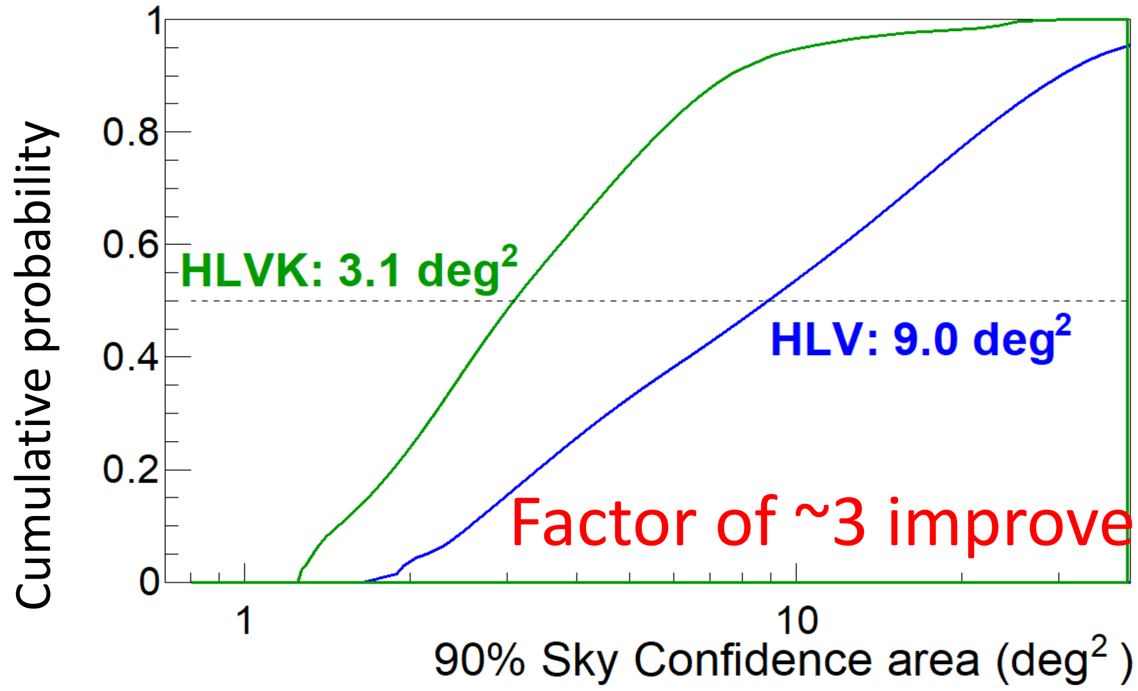
Importance of Global GW Network: Detector antenna patterns



KAGRA is complementary in the sensitive direction to other detectors.

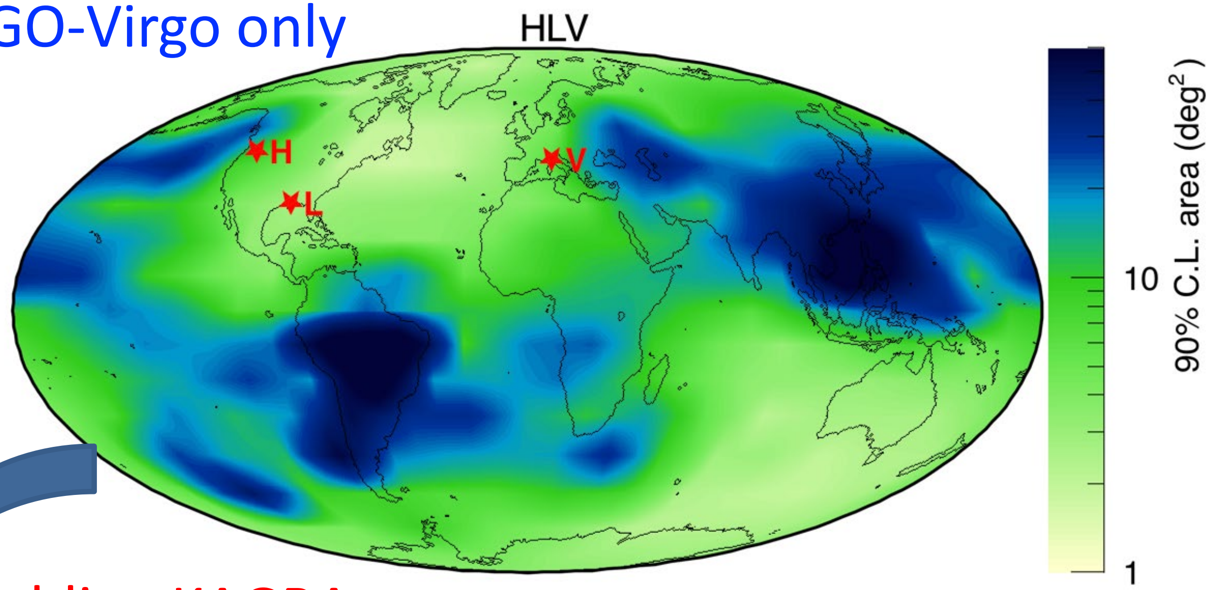
Importance of Global GW Network: Sky localization

- Assuming approximately the design sensitivities of LIGO, Virgo and KAGRA;
  LV: *LIGO-P1200087,* K: *JGW-T1707038*
- Also, assuming NS-NS merger ($1.4\ M_{Sun}$ -$1.4\ M_{Sun}$) at 150 Mpc

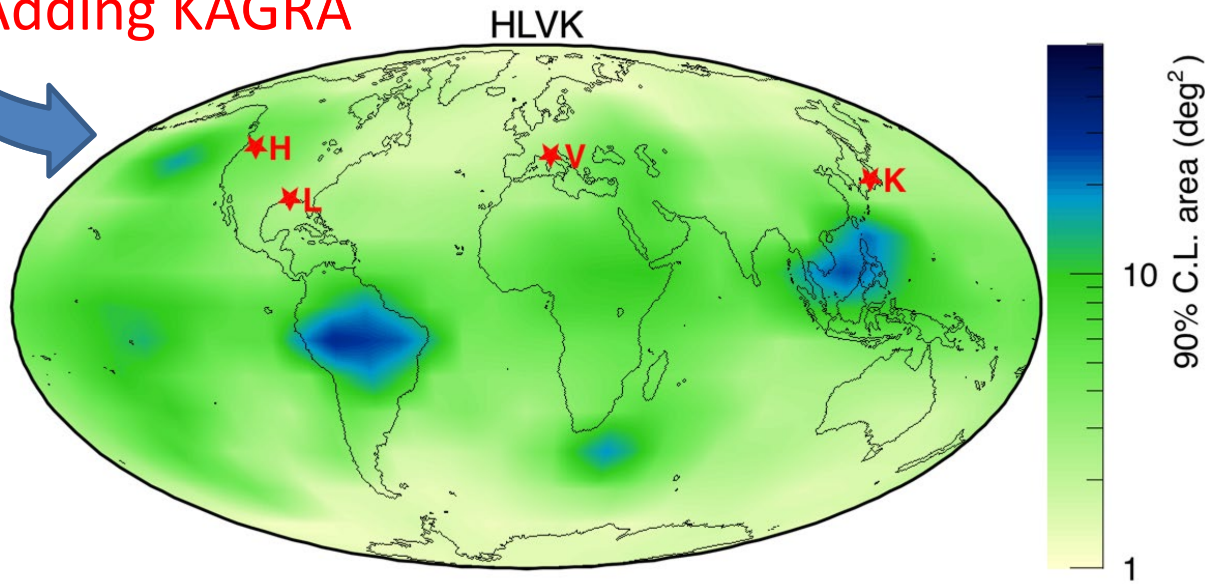


Factor of ~3 improvement

LIGO-Virgo only

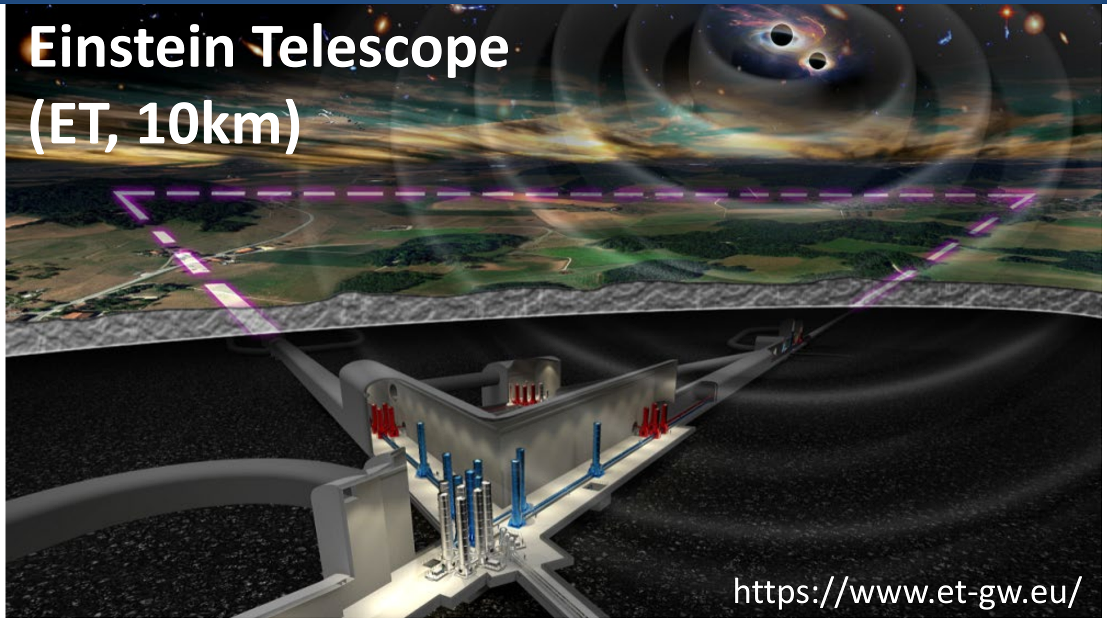


Adding KAGRA



Future

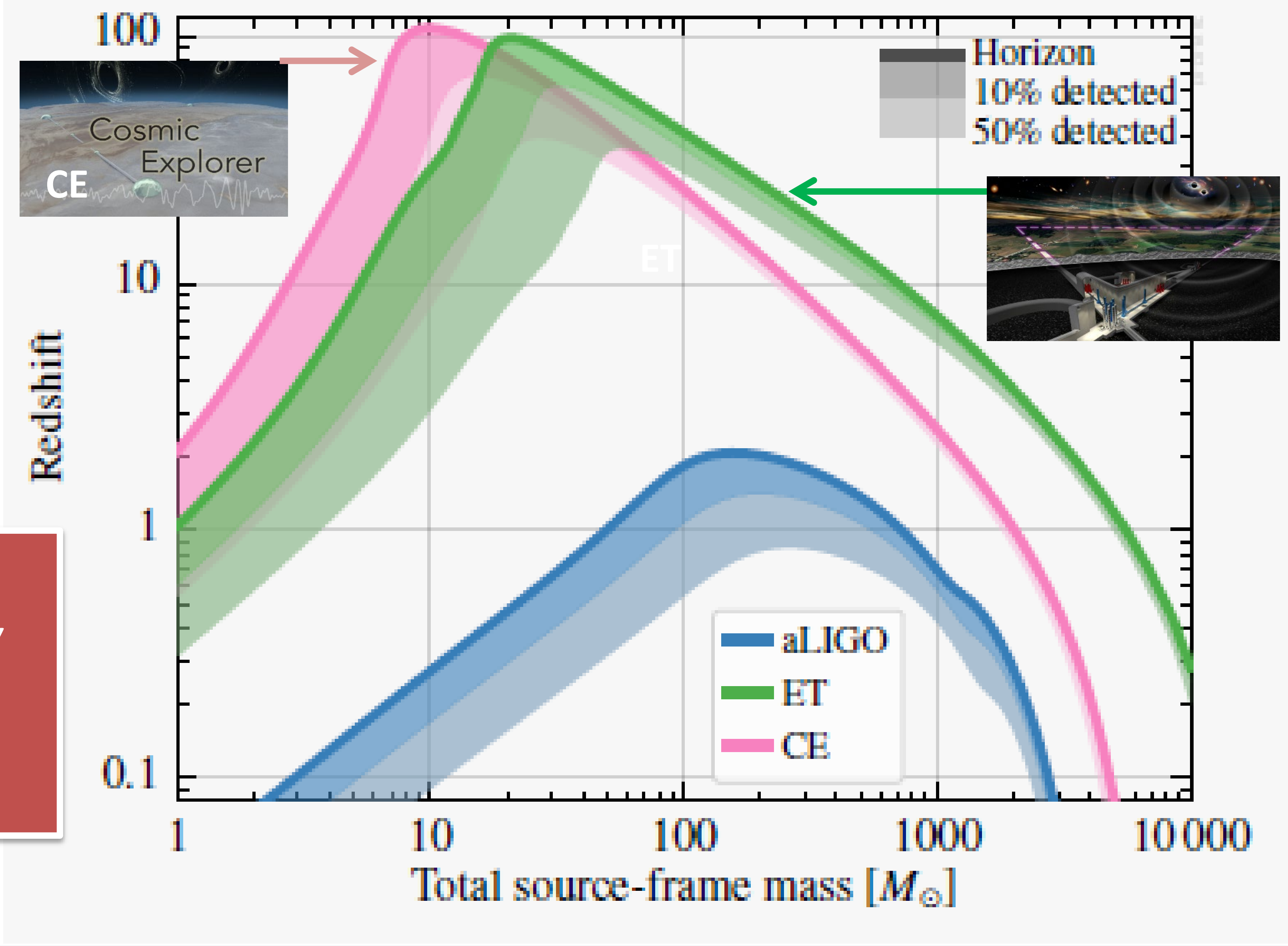
Future GW detectors and KAGRA



- ✓ 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 future detectors (at least ET) 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 of the underground site and the technology in the cryogenic mirrors.

Sensitivity: future GW detectors

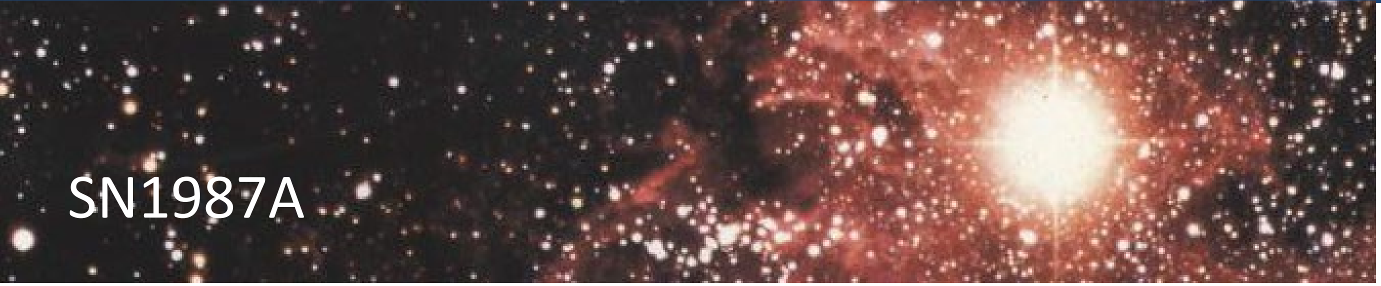
Astrophysical reach for equal mass blackhole binaries.



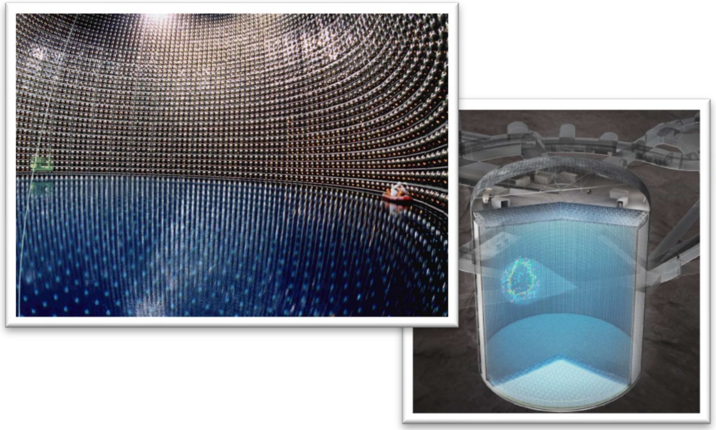
The next generation global gravitational wave observatory, The Science Book, Vicky Kalogera et al., GWIC 2021

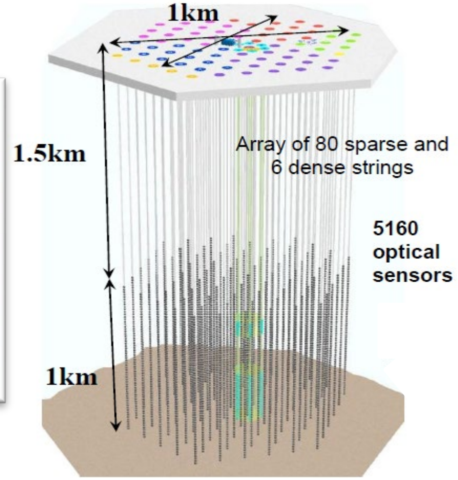
The science with these future GW detectors will be really exciting!

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 !

+optical observations,
+ Simulations

Summary

- There are very interesting history in the detection of GWs.
- Gravitational wave astronomy is a new and exciting scientific field. Many more fundamental discoveries will be ahead of us.
- KAGRA is a unique gravitational wave detector with cryogenic mirrors and the underground site.
- KAGRA would like to recover, as soon as possible, from the damage of the earthquake on Jan. 1, 2024, and contribute to the gravitational wave astronomy as soon as possible.