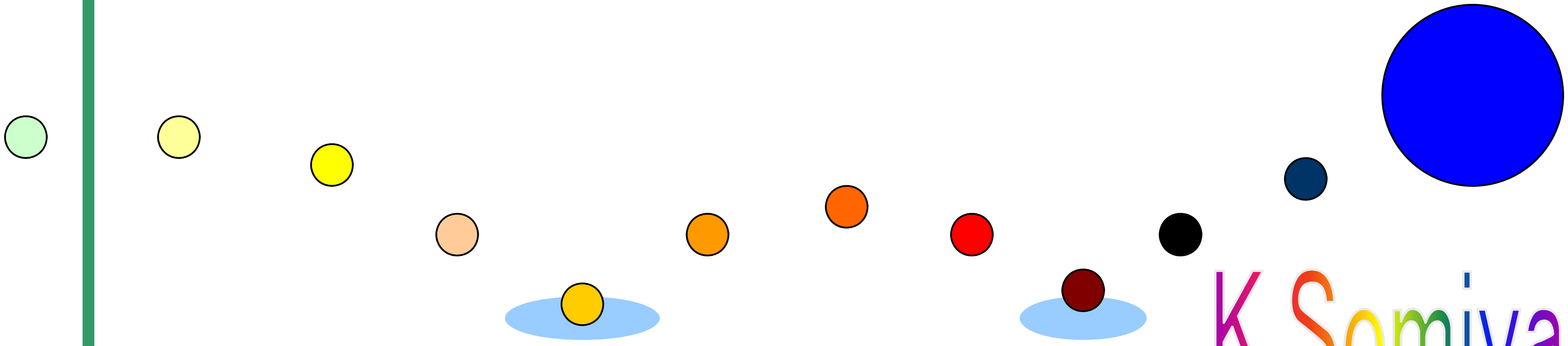
Status of KAGRA

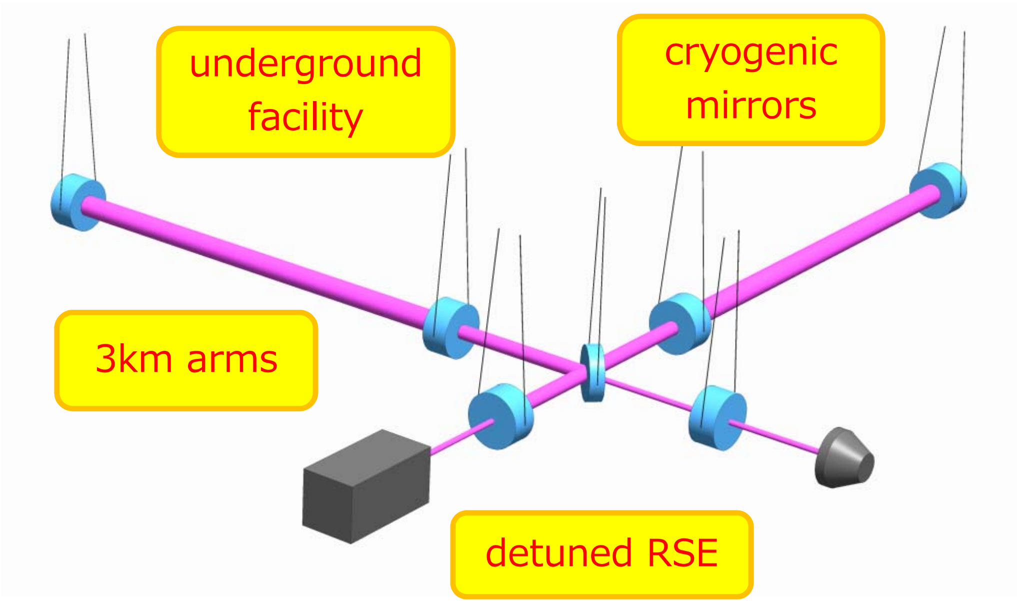
ET meeting @ Birmingham
Mar 28, 2017

K.Somiya on behalf of KAGRA collaboration



K.Somiya

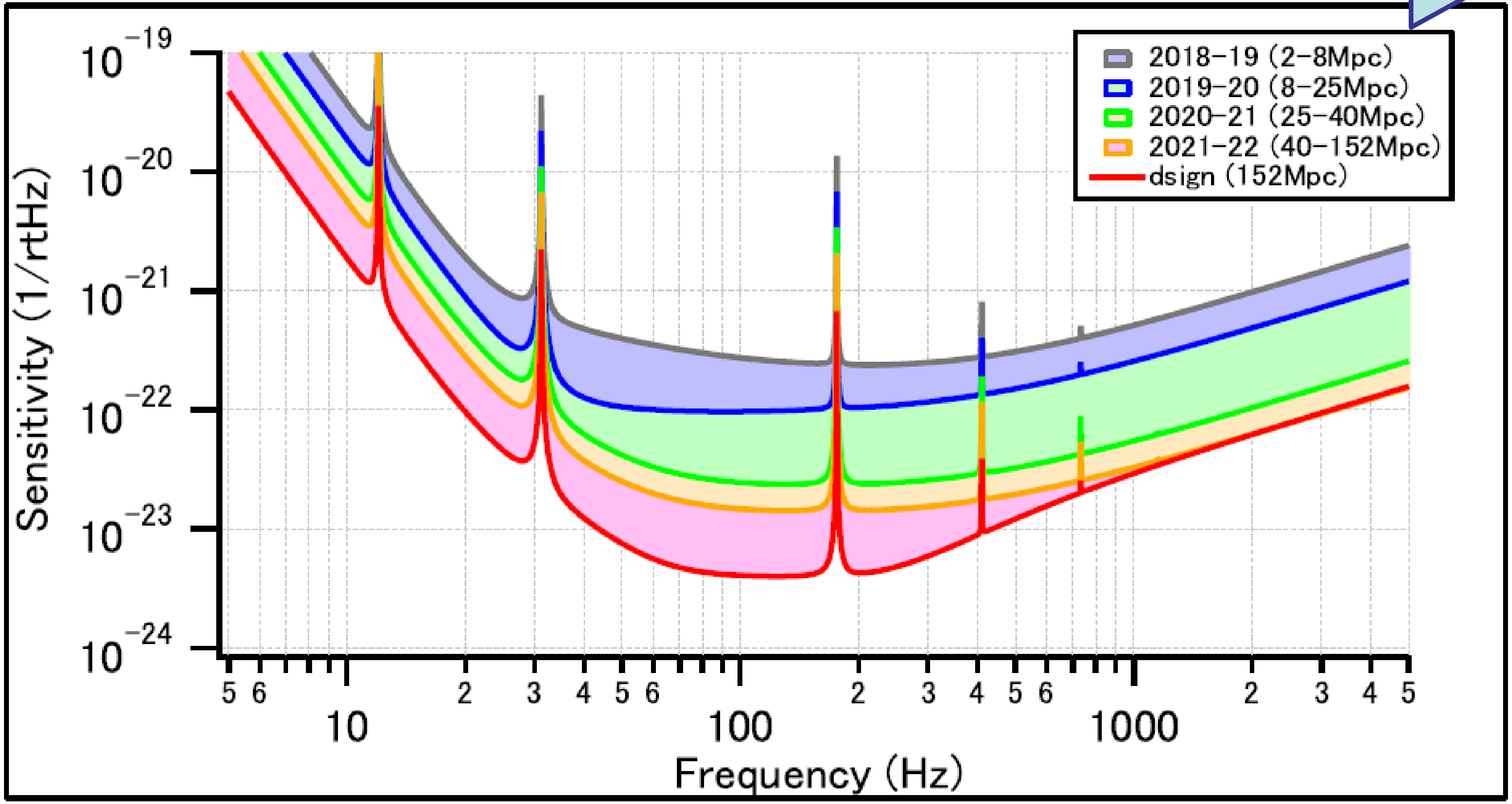
KAGRA



- **Japanese second generation GW detector**
- **Underground cryogenic interferometer**
- **To start the first cryogenic operation in 2018**

KAGRA observation scenario

preliminary



2018-19: low power cryogenic tuned RSE (x10)

2020-21: high power cryogenic tuned RSE (x5)

2021-22: high power cryogenic detuned RSE

KAGRA plan

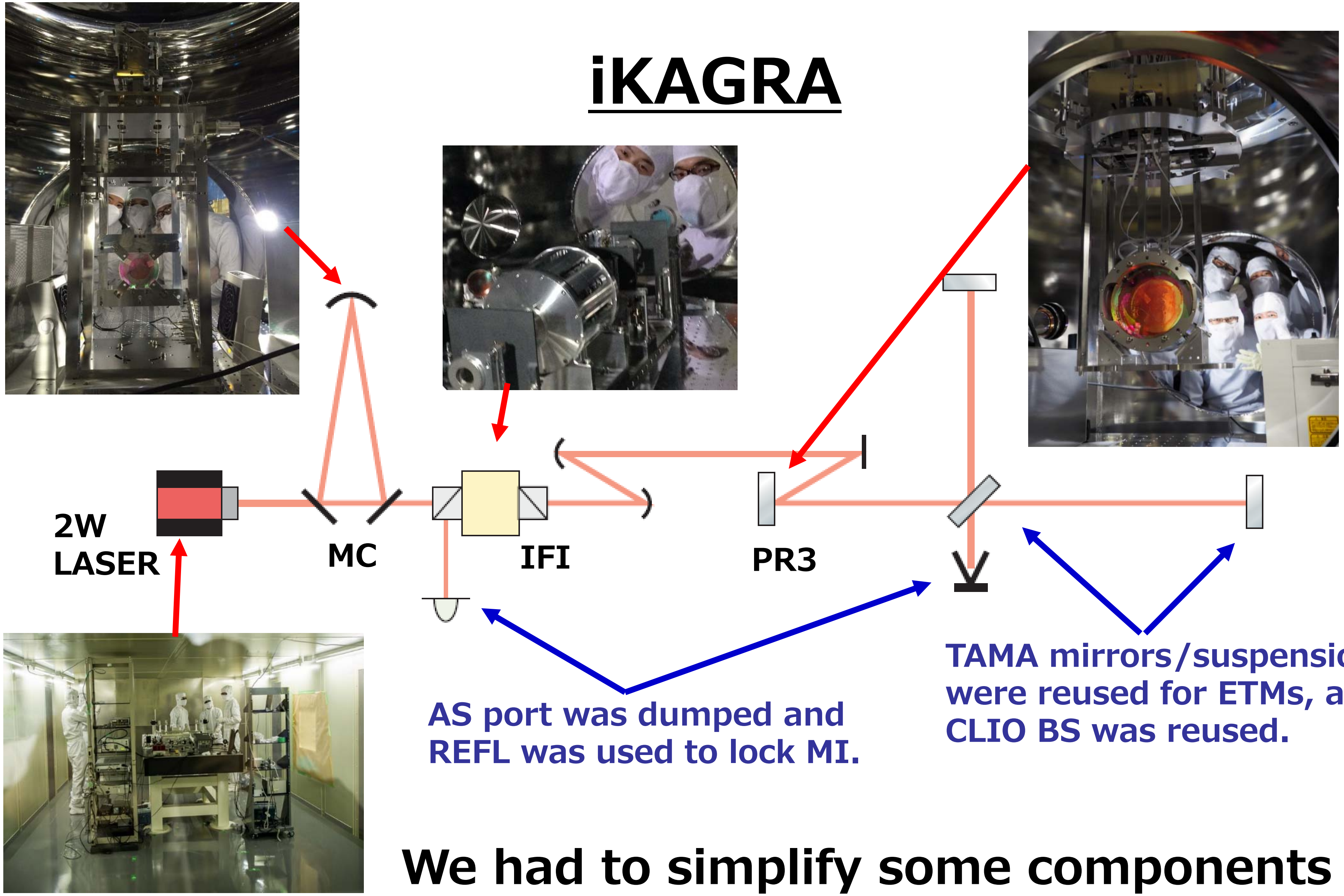
iKAGRA: room-temperature Michelson ifo
4-week test run in 2016 Mar-Apr

bKAGRA phase-1: cryogenic Michelson ifo
Type-A suspension + cryo-payload for ETMs
Type-B suspension for some recycling mirrors

bKAGRA phase-2: cryogenic RSE
short test runs at 300K ('18) and at 20K ('19)

bKAGRA phase-3: commissionings
final sensitivity at 2021~2022

iKAGRA

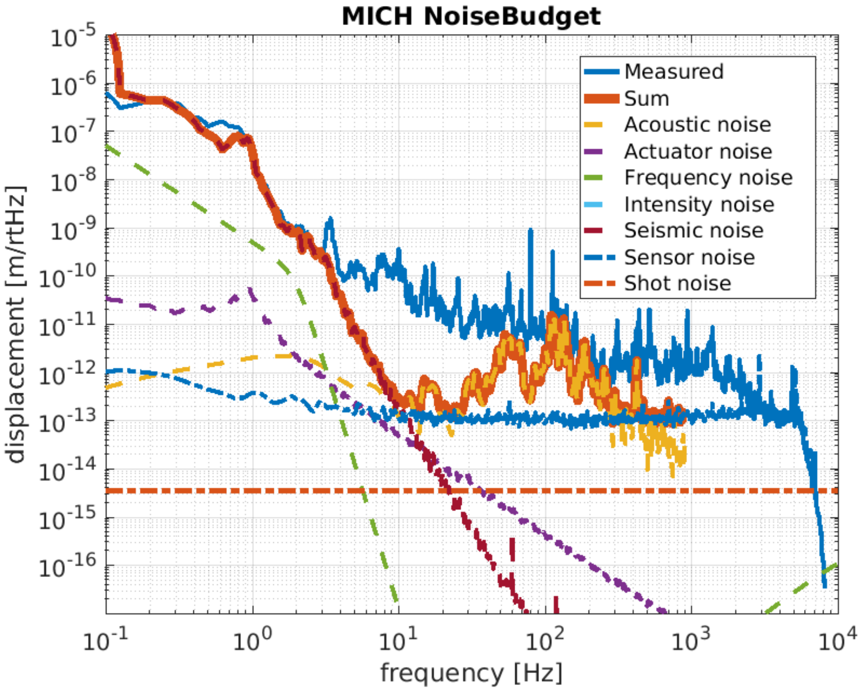


AS port was dumped and REFL was used to lock MI.

TAMA mirrors/suspensions were reused for ETMs, and CLIO BS was reused.

We had to simplify some components to catch up the delay of the installation.

iKAGRA test run



- **65 KAGRA members joined the shift for the 4 week operation**
- **Test of the integrated system (control, vacuum, data transfer, etc.)**
- **Our first experience to operate a km-scale ifo**

iKAGRA paper

What we learned from going underground to build a gravitational-wave detector

Authors list will be provided soon.*

Construction of the Japanese second-generation gravitational-wave detector KAGRA has been completed. The entire 3-km detector is buried underground in a mine to be isolated from seismic activities on the ground. Barebone equipment for the interferometer operation has been installed and the first test run was accomplished in March and April of 2016 with a considerably simple configuration. The initial-stage configuration of KAGRA is named *iKAGRA*. In this paper, we report the test run of iKAGRA and summarize what we learned from going underground to build a gravitational-wave detector.

1. INTRODUCTION

Gravitational waves (GWs) are ripples of spacetime radiated from dynamic motions of massive and compact objects, such as black holes and neutron stars, or from spacetime fluctuations in the early universe. With their strong transmissivity and nature of radiation sources, observation of GWs tells us various information that cannot be obtained by electromagnetic waves or other cosmic rays. The existence of GWs was theoretically predicted by Albert Einstein in 1916 and it had not been directly detected for about 100 years until the great first discovery by Advanced LIGO, the GW observatory in the US, in 2015 [1]. In the next few years, a European GW antenna Advanced Virgo [2] and a Japanese GW antenna KAGRA [3] will be in operational. The new era of GW astronomy will begin by network observations by these antennas; we can expect new astronomical knowledge with an increasing number of detected events, better parameter estimation accuracy for the sources (sky localization, mass, spin, distance, and orbital parameters), and detection of GWs from completely new type of sources. These antennas (Advanced LIGO, Advanced Virgo, and KAGRA) are called the "second-generation" detectors, which are upgraded from or constructed after the "first-generation" GW detectors [8–11].

While the scientists are making the intense efforts on the development of the second-generation detectors, design studies for the future antennas with better sensitivities, called third-generation GW detectors, have been started. One proposal is the European antenna named Einstein Telescope (ET) [4]. Another proposal of the third-generation antenna is the one in the US, which is called Cosmic Explorer (CE) [5]. Though both of them are designed based on a Michelson-type laser interferometer like the second-generation detectors, there are some differences in the design concepts. ET will be a triangle array of three interferometers with 10-km baseline length, and the entire system is planned to be buried under the ground. CE will be a conventional L-shape interferometer build on ground surface, with a 10-times longer baseline than the second-generation ones. One of the largest differences in these design concepts is the site selection: underground or ground surface. An underground site is advantageous in GW detectors; seismic motions are smaller than a surface site by a few orders in typical cases. This fact is critical for the sensitivity to low-frequency GW sources, and long-term stable operation of a sensitive interferometer. On the other hand, an underground site is disadvantageous in the point of construction cost, requiring excavation of long-baseline tunnels and caverns for an interferometer and the vacuum system to house it. In addition, operating a large-scale interferometer at an underground site requires new challenges from several realistic points of view.

KAGRA, one of the second-generation detectors, is the world-first large-scale GW antenna constructed underground. It is located in the Kamioka underground site at Gifu prefecture in Japan. At this site, a couple of prototype detectors, LISM (a 20-m scale interferometer, started in 1999 [6]) and CLIO (a 100-m scale interferometer, started in 2002 [7]), were constructed and operated to show advantages of an underground site. With these achievements and experiences, KAGRA was funded in 2010 and the excavation of the tunnel was started in May 2012. In October 2015, most of the installation activities for the initial KAGRA interferometer was completed, and after commissioning works, the interferometer was in operation for the first time in March 2016. Though the interferometer configuration at that time was simplified from the final KAGRA design, KAGRA was firstly operated as a full 3-km-scale interferometer connected to the data aquisition, transfer, and storage system. Then we carried out a three-weeks test run to check the overall performance as an interferometric GW antenna system.

In this paper, we report the results and lessons learned in this first operation of the large-scale underground GW antenna, and discuss the advantages and the challenges of going underground. In Sec. 2, we briefly explain our history of the site search and review the construction process. In Sec. 3 and Sec. 4, we list up advantages and challenges of building a gravitational-wave detector under the ground, which will serve as a useful reference in the consideration of next-generation gravitational-wave detectors. In Sec. 5, we show the operation results of our two underground detectors, which are namely a gravitational-

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FIG. 1: Map of the Kamioka mine. The blue thick lines are baselines of the KAGRA interferometer. The red points are the measurement points of the seismic motion (see Sec. 3.1).

FIG. 2: Some photos in the KAGRA facility. *Top Left*: spiral steps from the ground level to the upper level for the suspension tower. *Top Right*: installation of the granite stone for the geophysics interferometer. *Bottom*: transportation of the cryostat to the end room.

wave detector iKAGRA and a geophysics interferometer built next to the iKAGRA detector in the same tunnel. In Sec. 6, we summarize the work.

2. CONSTRUCTION OF KAGRA

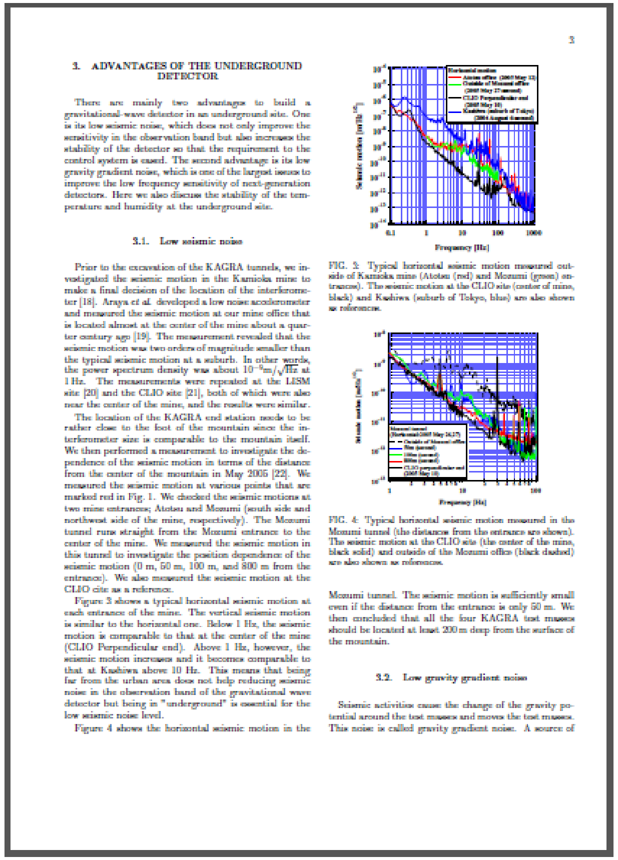
The site search of KAGRA was performed in the late 90's. We asked Sumitomo Corporation (Japan) to compare the geological and environmental conditions of 7 candidates in Japan. One of the candidates was Mt. Tsukuba in Ibaraki Pref. but the cost estimate was twice as high as the Kamioka mine. Another candidate was the Kamaishi mine in Iwate Pref. but there was a railroad tunnel near the site. The bedrock in Kamioka, Hida gneiss, was no doubt the best, the estimated cost was low, and we already started an optical experiment near the famous Super-Kamiokande that showed very low influence of the seismic motion. It was a natural choice to build KAGRA in the Kamioka mine.

The excavation of the KAGRA tunnels started in 2012. See Fig. 1. The geographical coordinates of the beamsplitter is 36.41 degrees North and 137.31 degrees East. The Y-arm is at the direction of 28.31 degrees from the north toward the west. Though the central station and the end stations are rather close to the foot of the 1300-m high mountain, they are still at least 200-m far from the ground surface. The X and Y arms are 3-km long and we have access tunnels to the central station and to the Y-arm end station. See Reference [12] for more details about the tunnel excavation of the KAGRA site.

Incredibly fast construction work performed by the Kajima Corporation (Japan) made it possible to complete the excavation within 2 years (May 2012 - March 2014). Installation of the facilities proceeded in parallel to the construction work. This includes electricity, air conditioning, water supply, anti-dust wall painting, floor treatment, crane setup, anchors, spiral steps, networks, PHS, laser clean room, etc. See Fig. 2 for some photos. Coping with leaking water in the mine took time but the water issues were finally settled. Soon after the tunnel and facility became almost ready in March 2014, installations of the vacuum system and interferometer components (the vibration-isolation systems, the laser source, the optics for the interferometer, the digital control system, and so on) were started.

The KAGRA project is split to two stages. In the first stage, the interferometer configuration is a simple Michelson interferometer that consists of two end test masses and a beamsplitter. The detector in this stage is called the *initial-stage KAGRA*, or *iKAGRA*. In the second stage, the interferometer configuration is a Michelson interferometer with Fabry-Perot optical resonators in two arms and also with power- and signal-recycling cavities. The detector in this stage is called the *baseline-design KAGRA*, or *bKAGRA*.

While the goal of bKAGRA is frequent observations of gravitational waves from various sources, the main goal of iKAGRA is to integrate basic subsystems and to operate the detector. It is the most important milestone in the KAGRA project to realize the world first large-scale underground gravitational-wave detector.



3. ADVANTAGES OF THE UNDERGROUND DETECTOR

There are mainly two advantages to build a gravitational-wave detector in an underground site. One is its low seismic noise, which does not only improve the sensitivity in the observation band but also increases the stability of the detector so that the requirement to the control system is eased. The second advantage is its low gravity gradient noise, which is one of the largest issues to improve the low frequency sensitivity of next-generation detectors. Here we also discuss the stability of the temperature and humidity at the underground site.

3.1. Low seismic noise

Prior to the excavation of the KAGRA tunnels, we investigated the seismic motion in the Kamioka mine to make a final decision of the location of the interferometer [18]. Araya et al. developed a low noise accelerometer and measured the seismic motion at our mine office that is located almost at the center of the mine about a quarter century ago [19]. The measurement revealed that the seismic motion was two orders of magnitude smaller than the typical seismic motion at a suburb. In other words, the power spectrum density was about $10^{-9}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 1 Hz. The measurements were repeated at the LISM site [20] and the CLIO site [21], both of which were also near the center of the mine, and the results were similar.

The location of the KAGRA end station needs to be rather close to the foot of the mountain since the interferometer size is comparable to the mountain itself. We then performed a measurement to investigate the dependence of the seismic motion in terms of the distance from the center of the mountain in May 2005 [22]. We measured the seismic motion at various points that are marked red in Fig. 1. We checked the seismic motions at two mine entrances; Atotsu and Mozumi (south side and northwest side of the mine, respectively). The Mozumi tunnel runs straight from the Mozumi entrance to the center of the mine. We measured the seismic motion in this tunnel to investigate the position dependence of the seismic motion (0 m, 50 m, 100 m, and 800 m from the entrance). We also measured the seismic motion at the CLIO site as a reference.

Figure 3 shows a typical horizontal seismic motion at each entrance of the mine. The vertical seismic motion is similar to the horizontal one. Below 1 Hz, the seismic motion is comparable to that at the center of the mine (CLIO Perpendicular end). Above 1 Hz, however, the seismic motion increases and it becomes comparable to that at Kashiwa above 10 Hz. This means that being far from the urban area does not help reducing seismic noise in the observation band of the gravitational wave detector but being in "underground" is essential for the low seismic noise level.

Figure 4 shows the horizontal seismic motion in the Mozumi tunnel. The seismic motion is sufficiently small even if the distance from the entrance is only 50 m. We then concluded that all the four KAGRA test masses should be located at least 200 m deep from the surface of the mountain.

FIG. 3: Typical horizontal seismic motion measured outside of Kamioka mine (Atotsu (red) and Mozumi (green) entrances). The seismic motion at the CLIO site (center of mine, black) and Kashiwa (suburb of Tokyo, blue) are also shown as references.

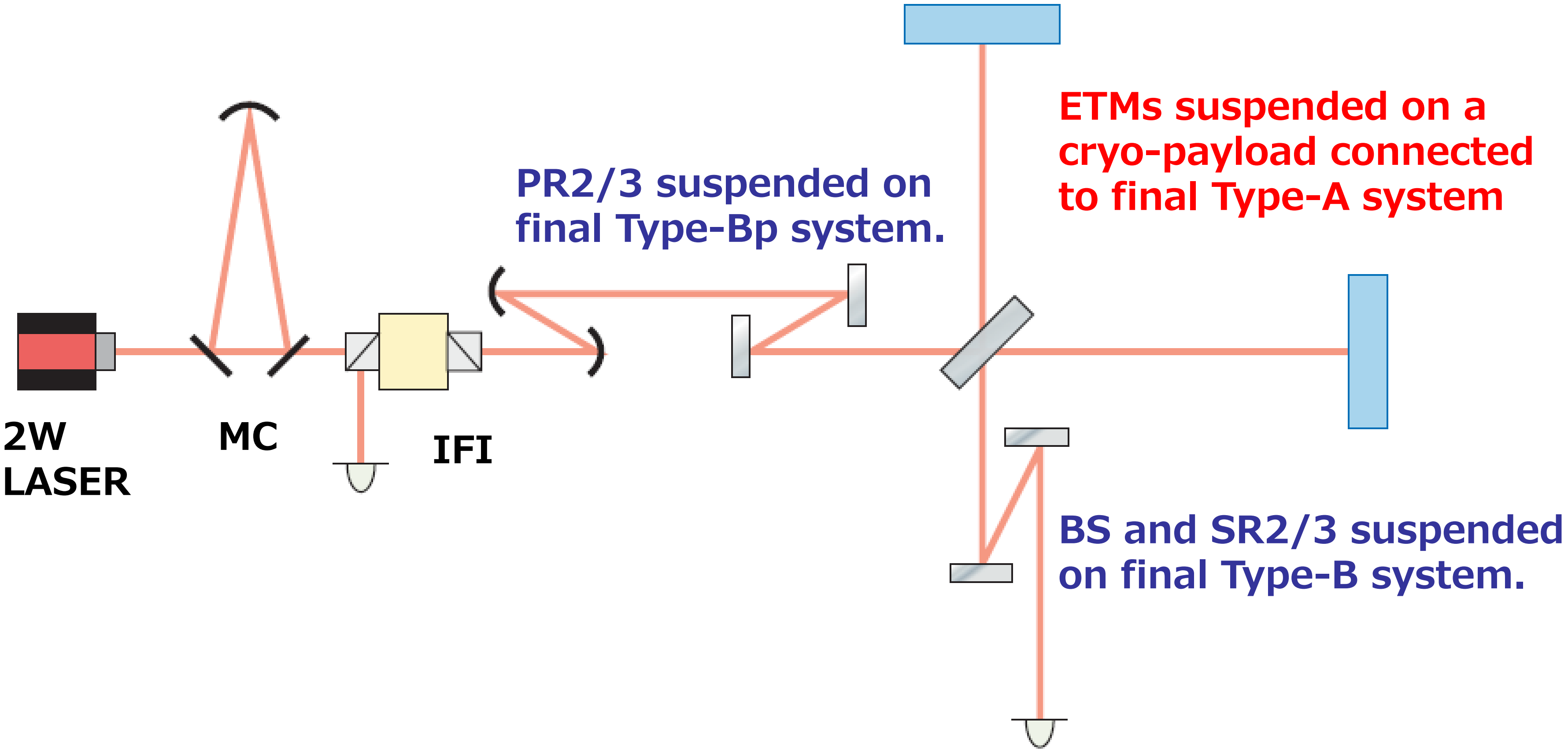
FIG. 4: Typical horizontal seismic motion measured in the Mozumi tunnel (the distances from the entrance are shown). The seismic motion at the CLIO site (the center of the mine, black solid) and outside of the Mozumi office (black dashed) are also shown as references.

3.2. Low gravity gradient noise

Seismic activities cause the change of the gravity potential around the test masses and moves the test masses. This noise is called gravity gradient noise. A source of

- **A 12-page paper to summarize the construction of the km-scale underground detector**
- **KAGRA's first all-author paper**

bKAGRA phase-1



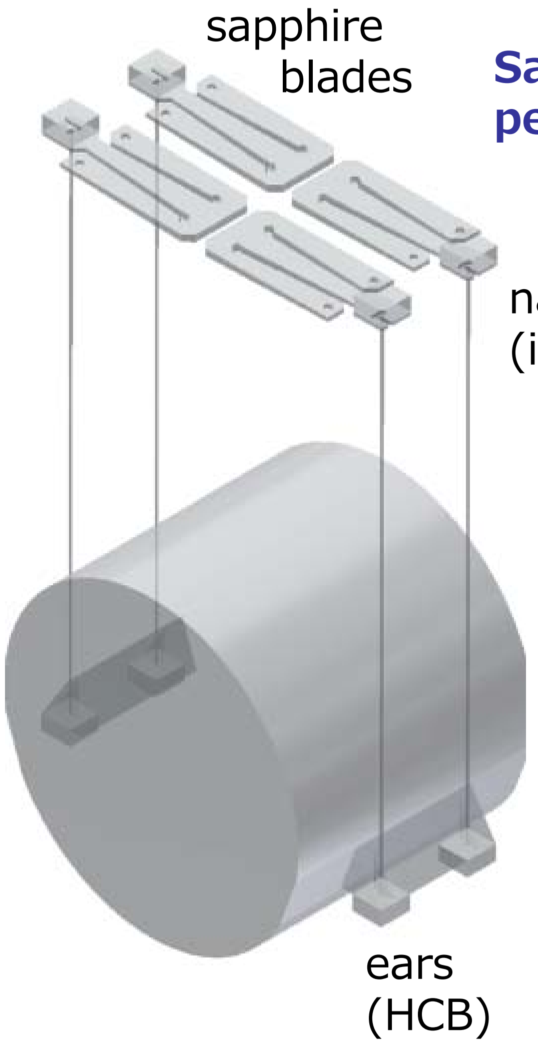
PR2/3 suspended on final Type-Bp system.

ETMs suspended on a cryo-payload connected to final Type-A system

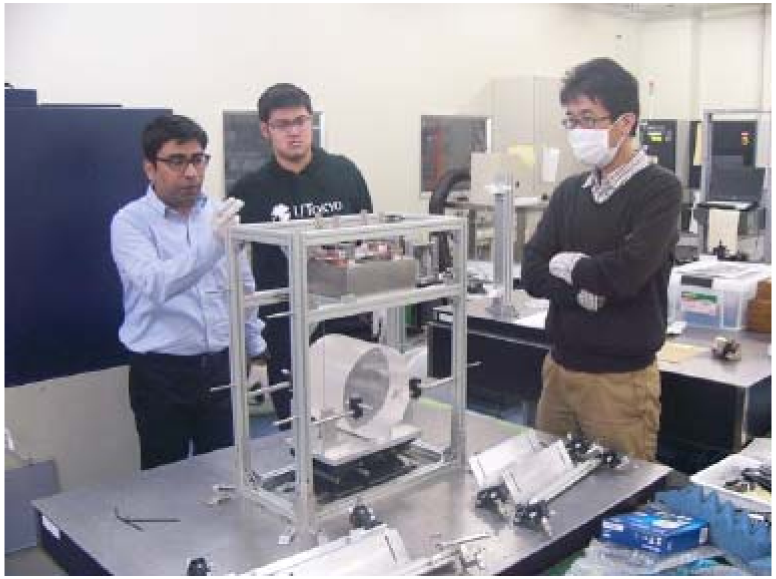
BS and SR2/3 suspended on final Type-B system.

- The goal is to operate a cryogenic interferometer by Mar 2018
- CRY/VIS people are working hard to make it in time to install the cryogenic mirrors

Development of cryo-payload



Sapphire prototype to perform test hanging.



HCB training using a metal mass with glass inserts.

An issue of the indium bonding

Gallium can be heated using
a supersonic soldering iron.

Melting temperature of indium is as high as 150 C.

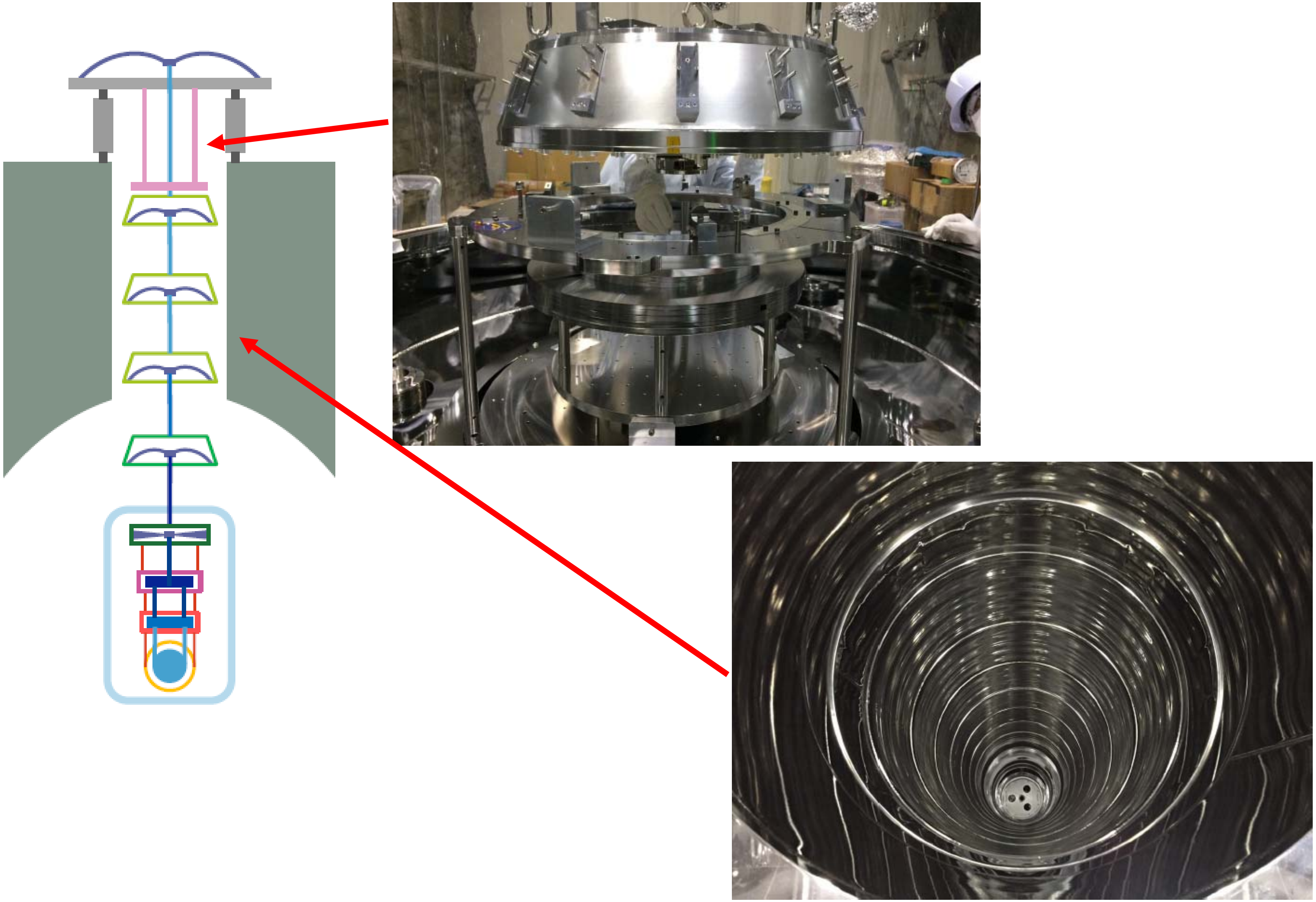
⬇

The heating process may damage the sapphire fiber (and mirrors).

A possible solution

Use gallium instead of indium.
The melting temperature is 30 C.
A concern is that it may be too low.

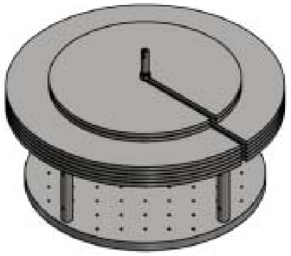
Development of Type-A



Installation schedule

ETMY

2017.4-5: Installation of Type-A with a dummy metal payload
2017.6: Replace the dummy metal by a cryo-payload
(a dummy sapphire is used)
2017.7-8: Full hanging test
2017.7 : A real sapphire mirror delivered
2017.8-9: HCB on the sapphire mirror
2017.10-11: ETMY installation
(to be cooled in 2017.12)



200kg
dummy payload

ETMX

2017.6-7: Installation of Type-A with a dummy metal payload
2017.8-9: Some measurements of Type-A
2017.12-2018.1: ETMX installation
(to be cooled in 2018.1)

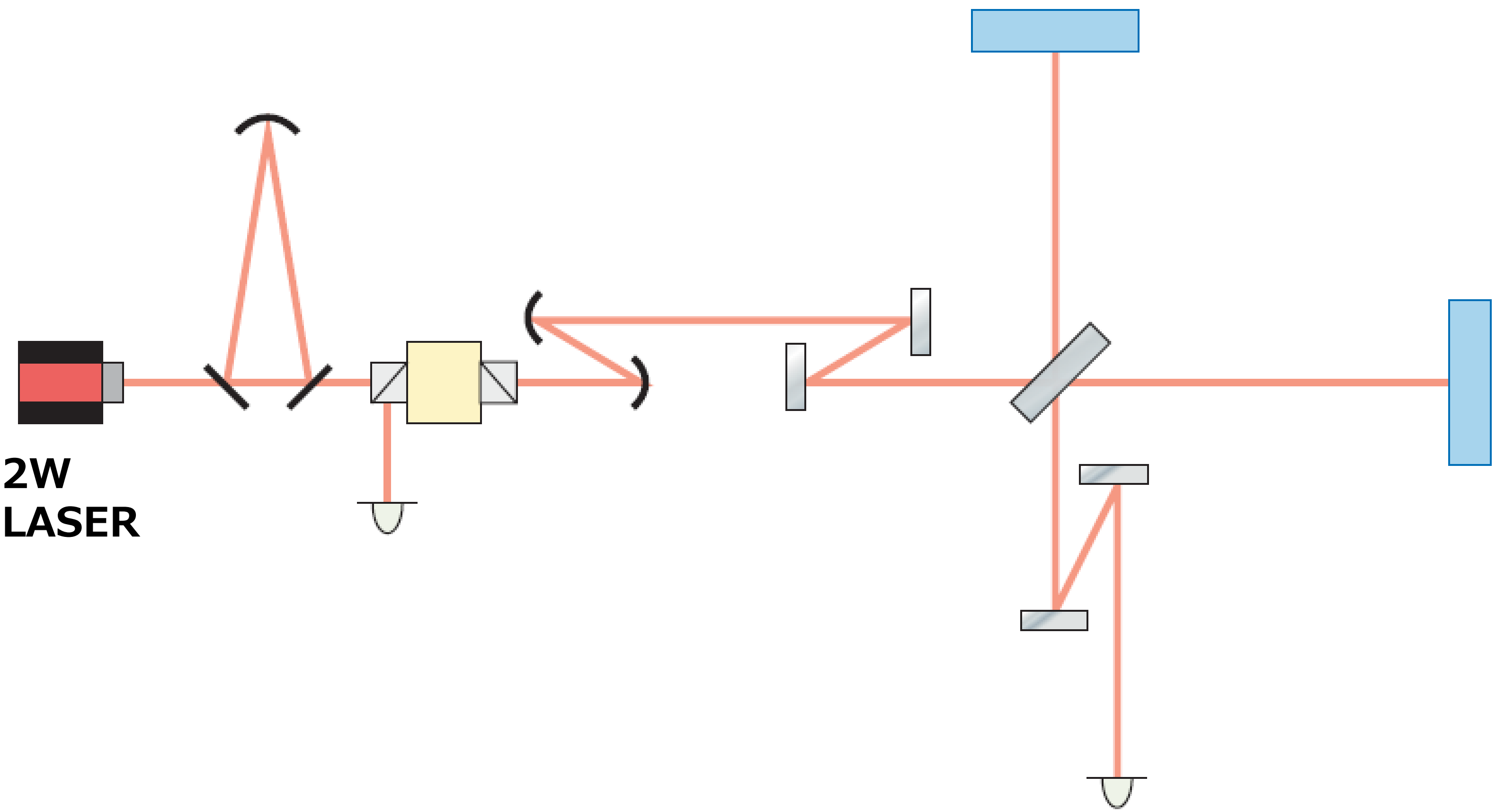
Spare mirrors

We have various sapphire mirrors.

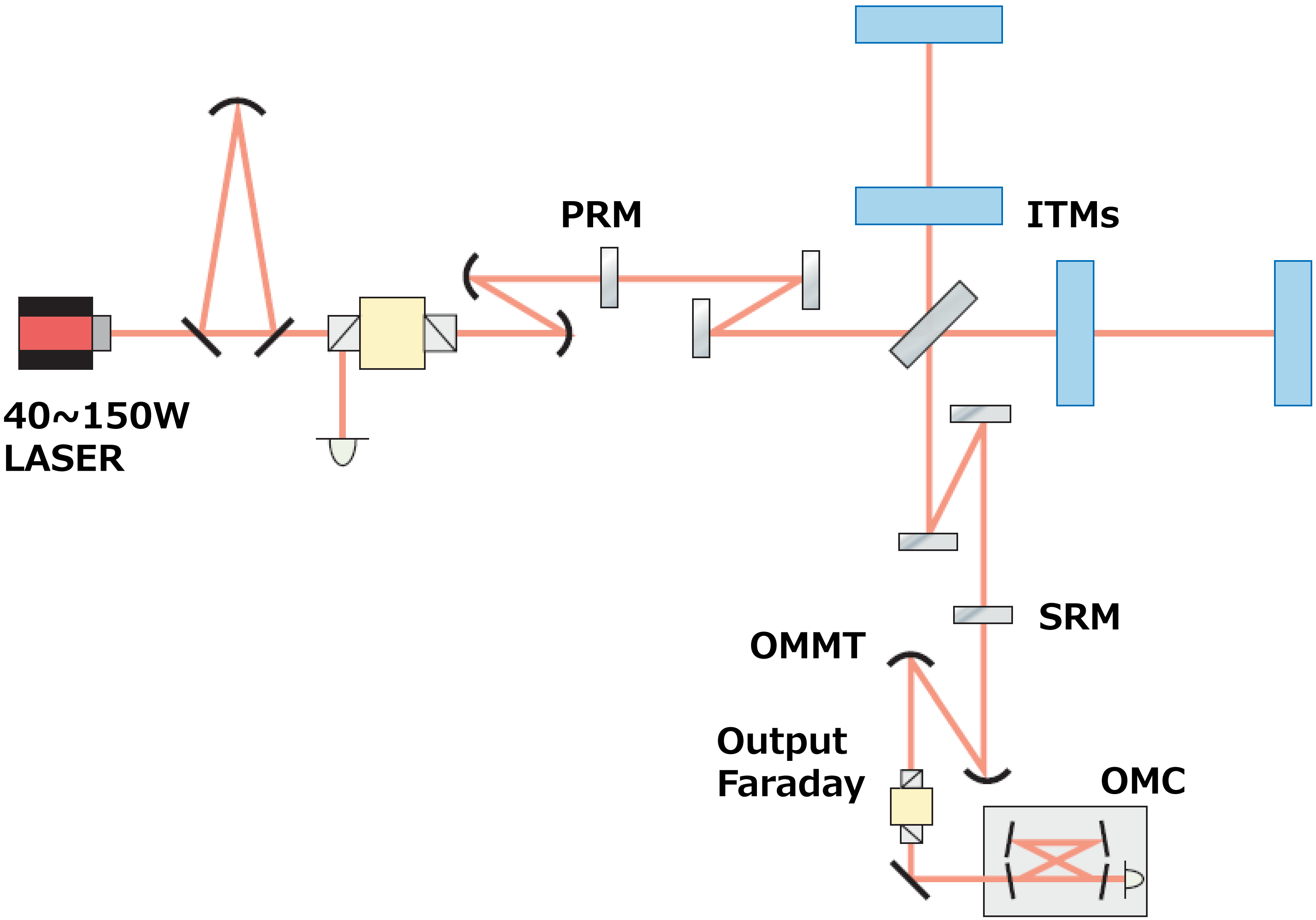
- ***original*: 2 expensive mirrors to be delivered in 2017.7**
- ***spare*: 2 cheaper mirrors to be delivered in 2017.10-11**
- ***for hanging test*: unpolished, also used for HCB training (x2)**
- ***for coating test*: no side-cut, flat (x2)**
- ***prototype*: ϕ205 mirror (x1)**

We discussed if we should use the spare mirrors first to reduce a risk to break original mirrors, but it turned out the spares cannot meet the schedule.

bKAGRA phase-1

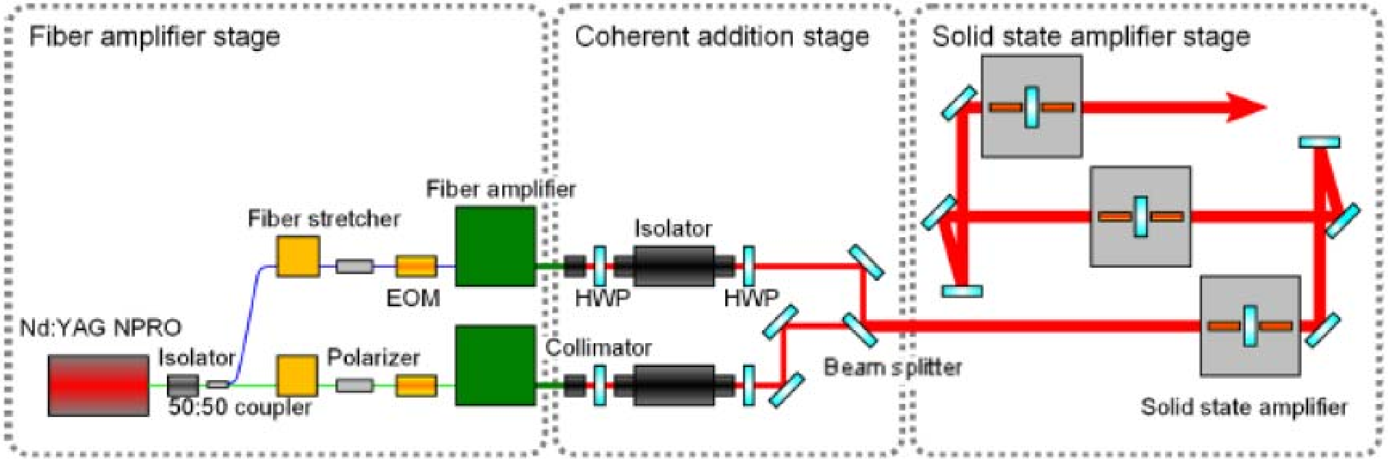


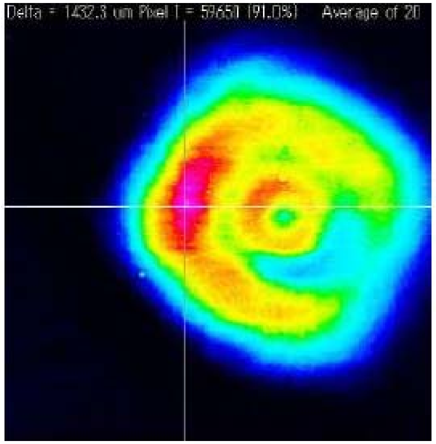
bKAGRA phase-2



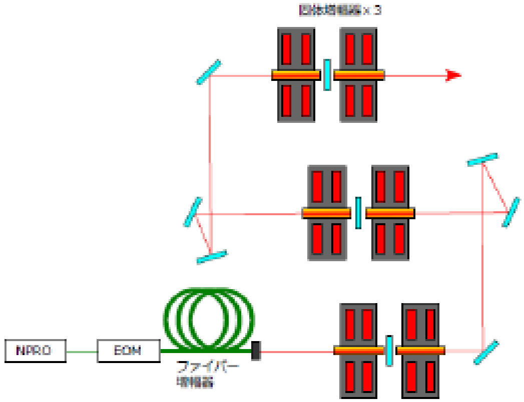
Development of a high-power laser

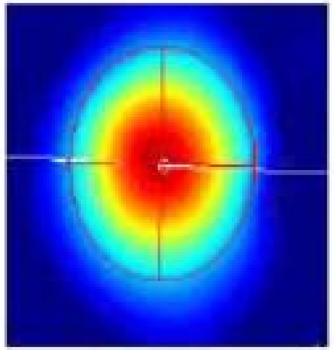
2014: 200W was created but the beam looks dirty.





2015: A fiber amp got broken but a clean 110W was created.





φ 1.0 mm

How much power do we need?

Three suggestions by our LASER group

Suggestion (1): almost no training needed

Generate 40W using a single fiber amplifier

Suggestion (2): some training needed

Generate 80W using two fiber amplifiers

Suggestion (3): very hard

Generate 150W using two fiber amps and a solid-state amplifier

How much power do we need?

It turned out that we cannot cool the mirrors if we inject the full power.

(1) Measured fiber thermal conductivity is 6580W/m/K
while the requirement is 7000W/m/K
(2) Fiber length has been changed from 30cm to 35cm
(3) 0.5K loss for the blade and bonds

TM coating	ITM subst.
0.5ppm	50ppm/cm
	80ppm/cm

input power	temperature
80W	23.0K
55W	21.6K
33W	20K
80W	24.9K
55W	23.1K
23W	20K

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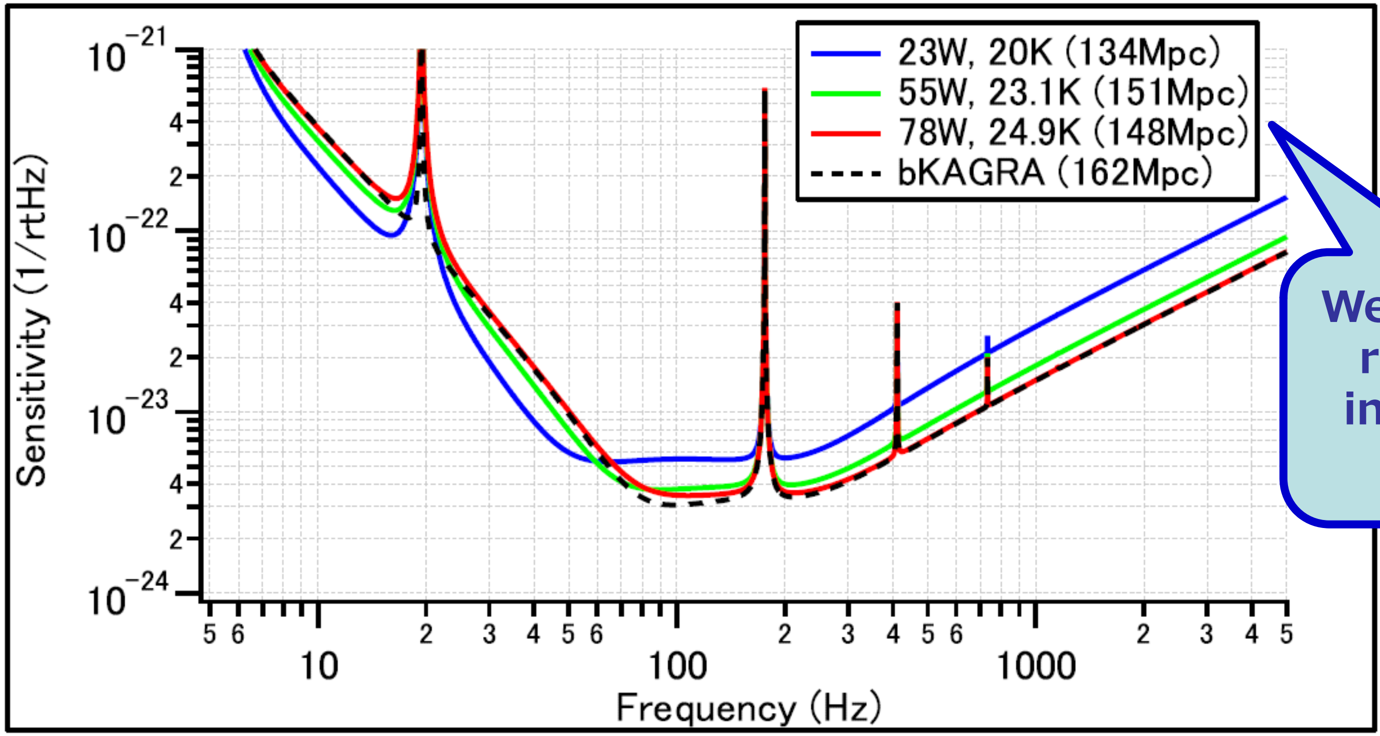


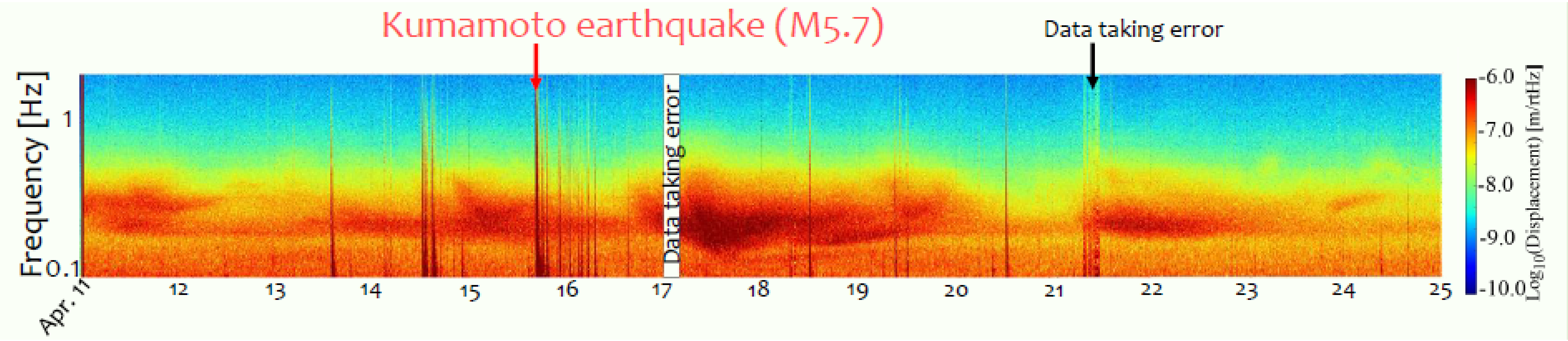
We decided to reduce the input power to 55W.

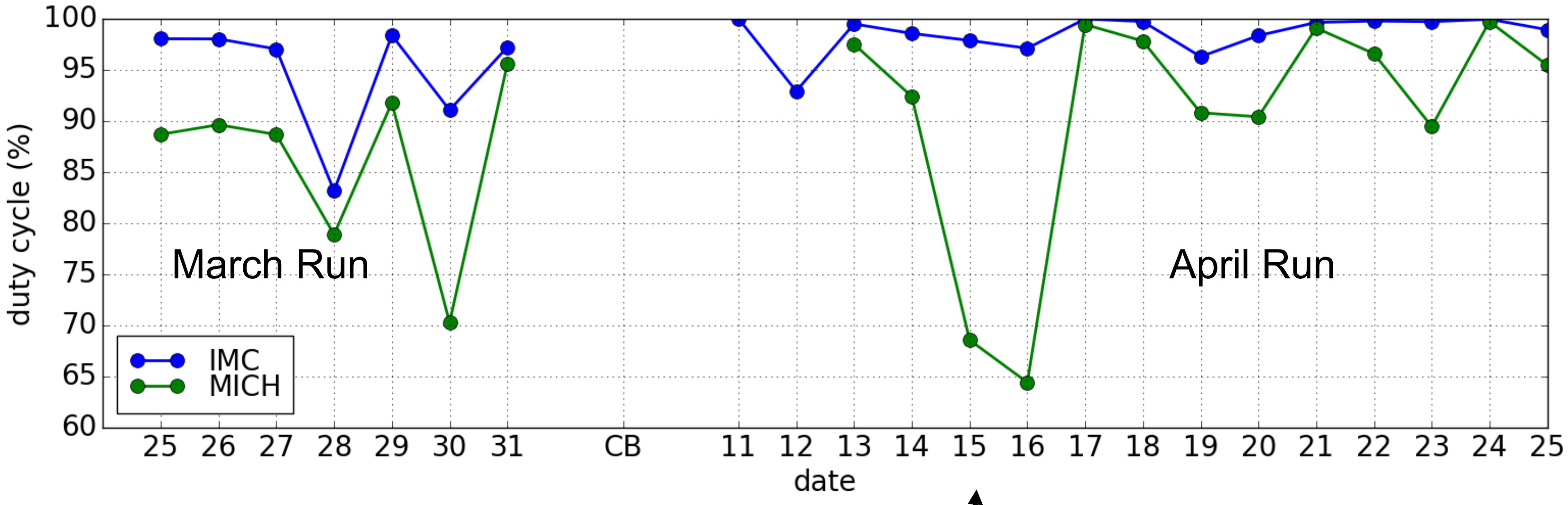
Summary

- bKAGRA development has been started
- Type-A + cryo-payload hanging test starts in July 2017
- Indium bonding is to be replaced by Gallium that does not require much heating
- Laser development is on-going

Supplementary slides

Seismic noise in the test run





Kumamoto Earthquake; BS went wrong