LIMMA2019 @ The Dukes Retreat, Khandala, India

January 17, 2019

Status of KAGRA: Recent Progress towards O3 and Future Plans

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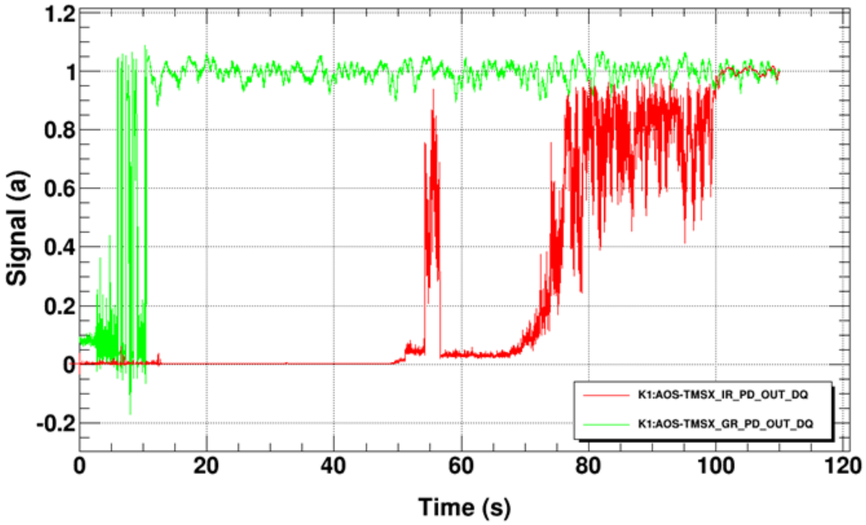
on behalf of the KAGRA Collaboration

Current Status of KAGRA

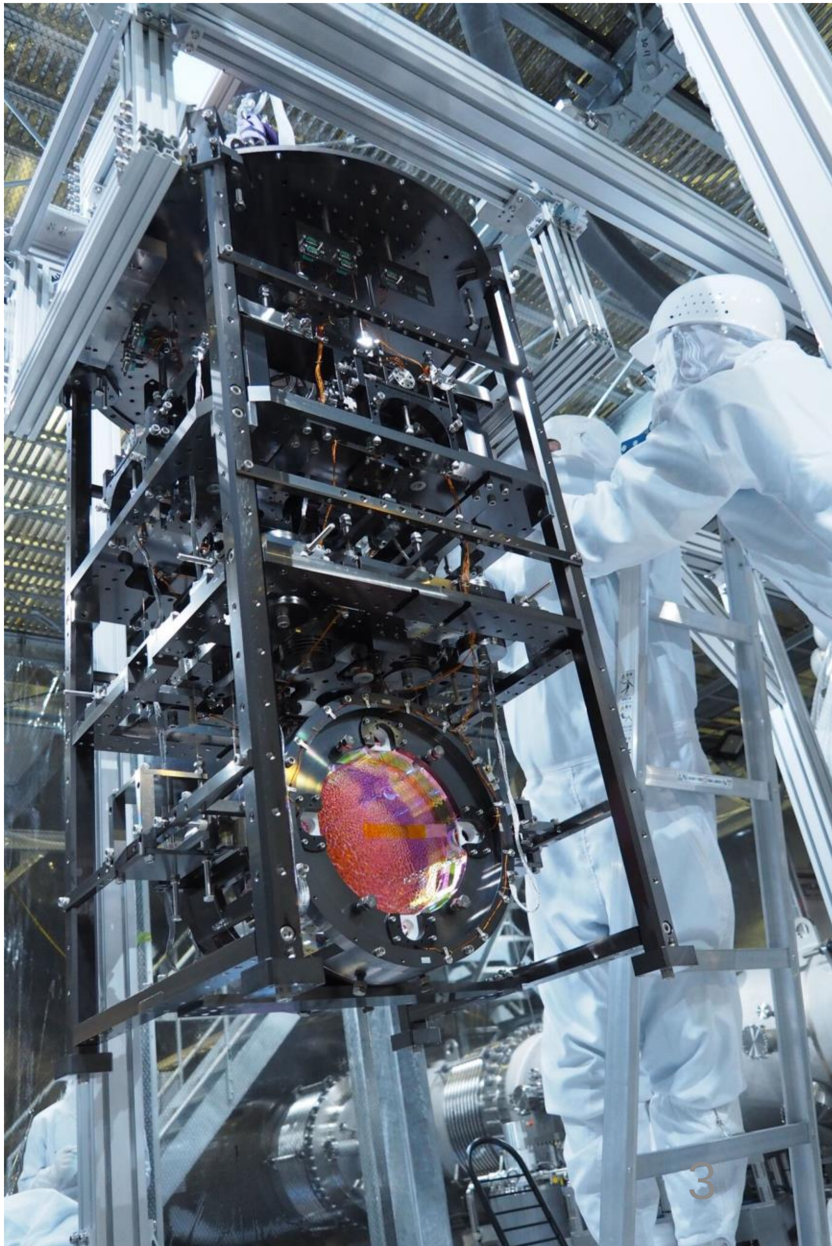
- First cryogenic test run with 3-km Michelson interferometer successfully done in May 2018
- Almost all the optics installed in vacuum
  - Cryogenic sapphire test masses
  - Signal recycling mirrors
  - Output faraday and output mode cleaner
- Successful completion of X-arm commissioning last week



- Y-arm and dual recycled Michelson commissioning starts this month
- Working hard to join O3

Outline

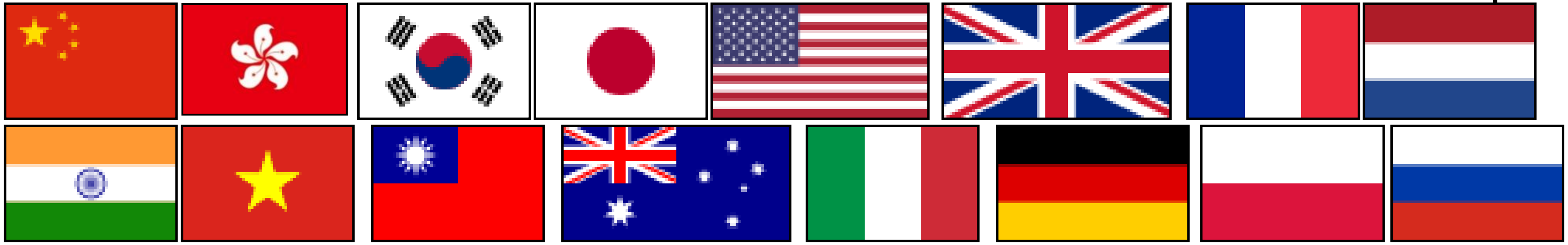
- Introduction
  - KAGRA project
  - KAGRA detector
  - Timeline
- Current status
  - Installation and test runs
  - X arm commissioning
- Future plans
  - KAGRA upgrade plans
- Summary



KAGRA Project

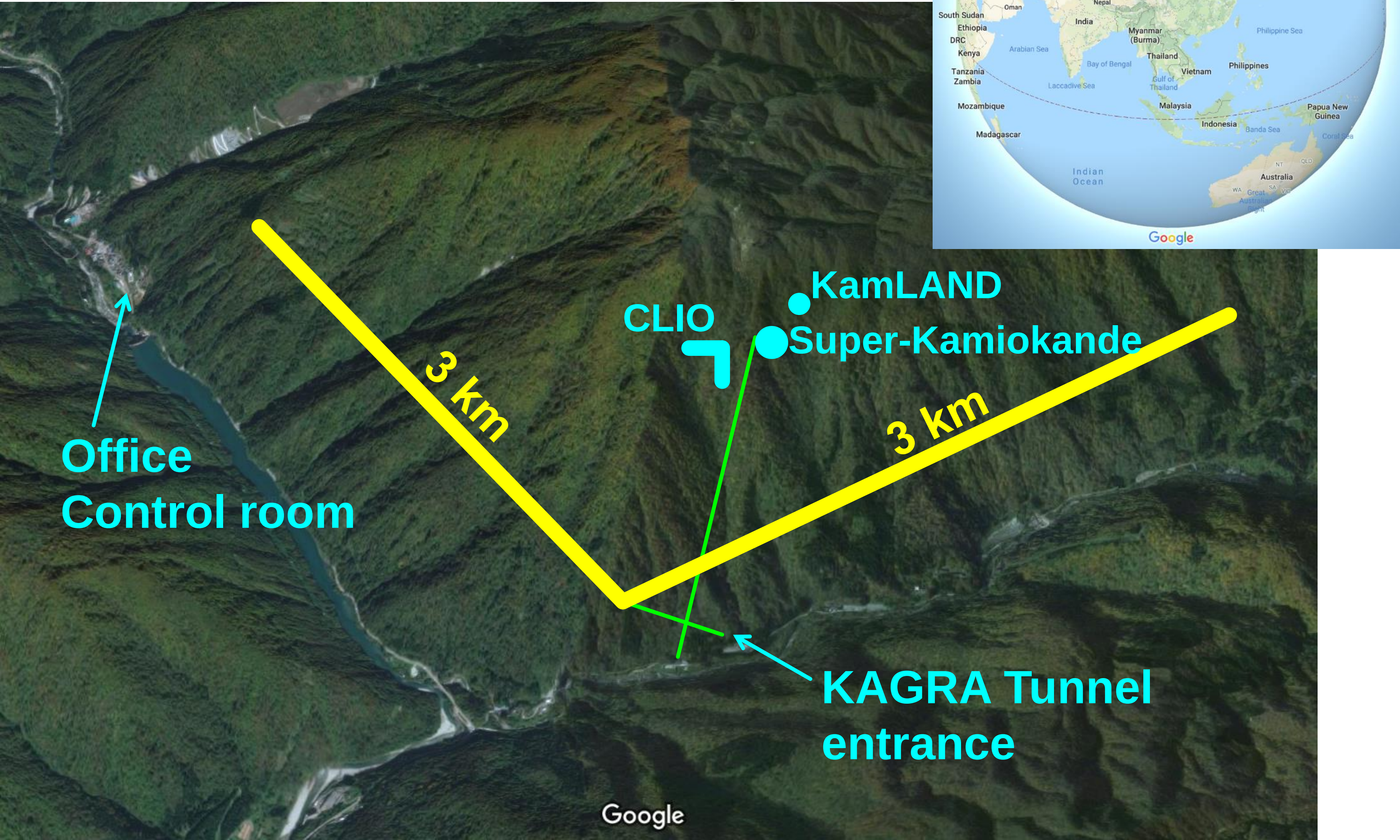
- Underground cryogenic interferometer in Japan
- Funded in 2010
- 97 institutes, 460 collaborators (162 authors)

as of Sept 2018



KAGRA Site

- Located inside Mt. Ikenoyama



KAGRA Site

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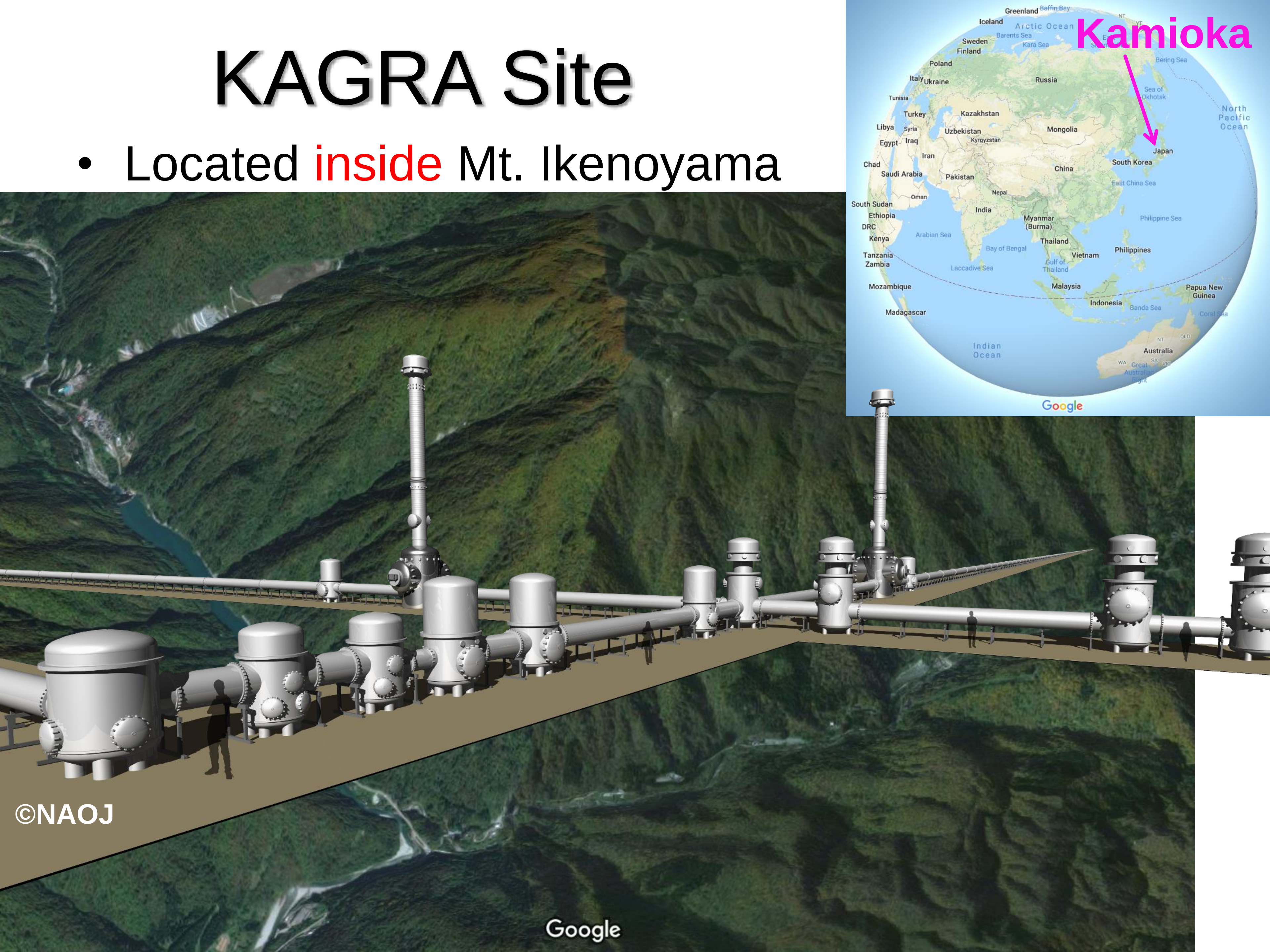
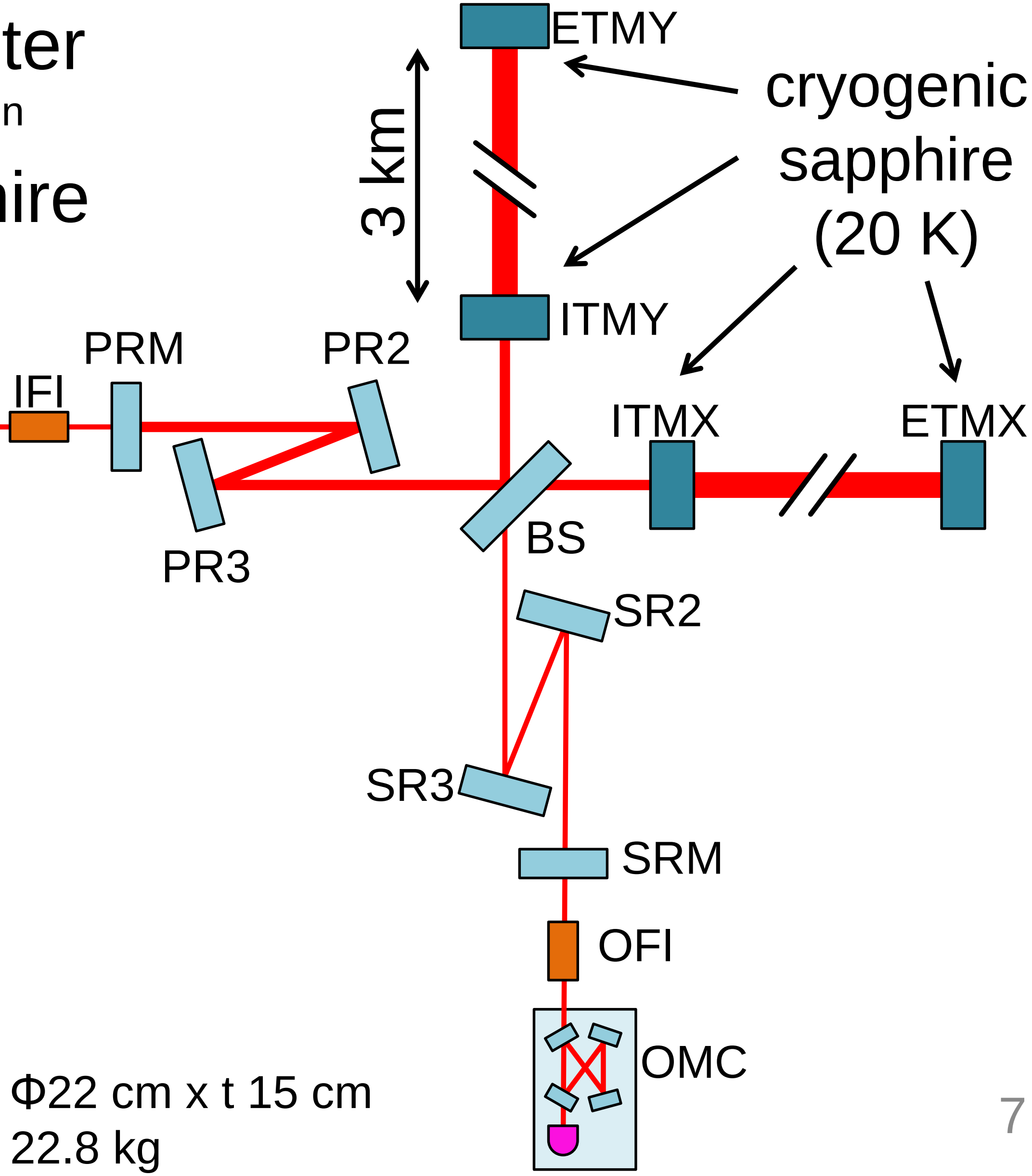
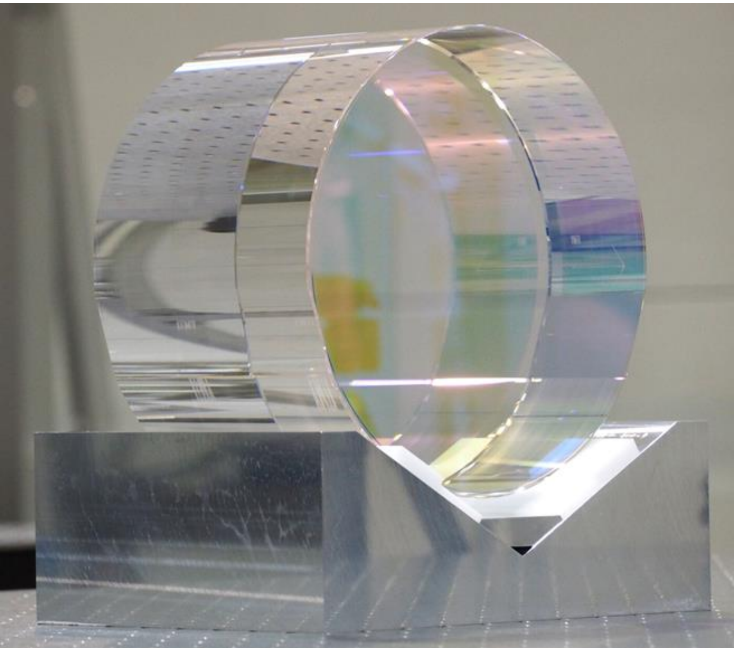


Interferometer Configuration

- RSE interferometer
  Resonant Sideband Extraction
- Cryogenic sapphire test masses

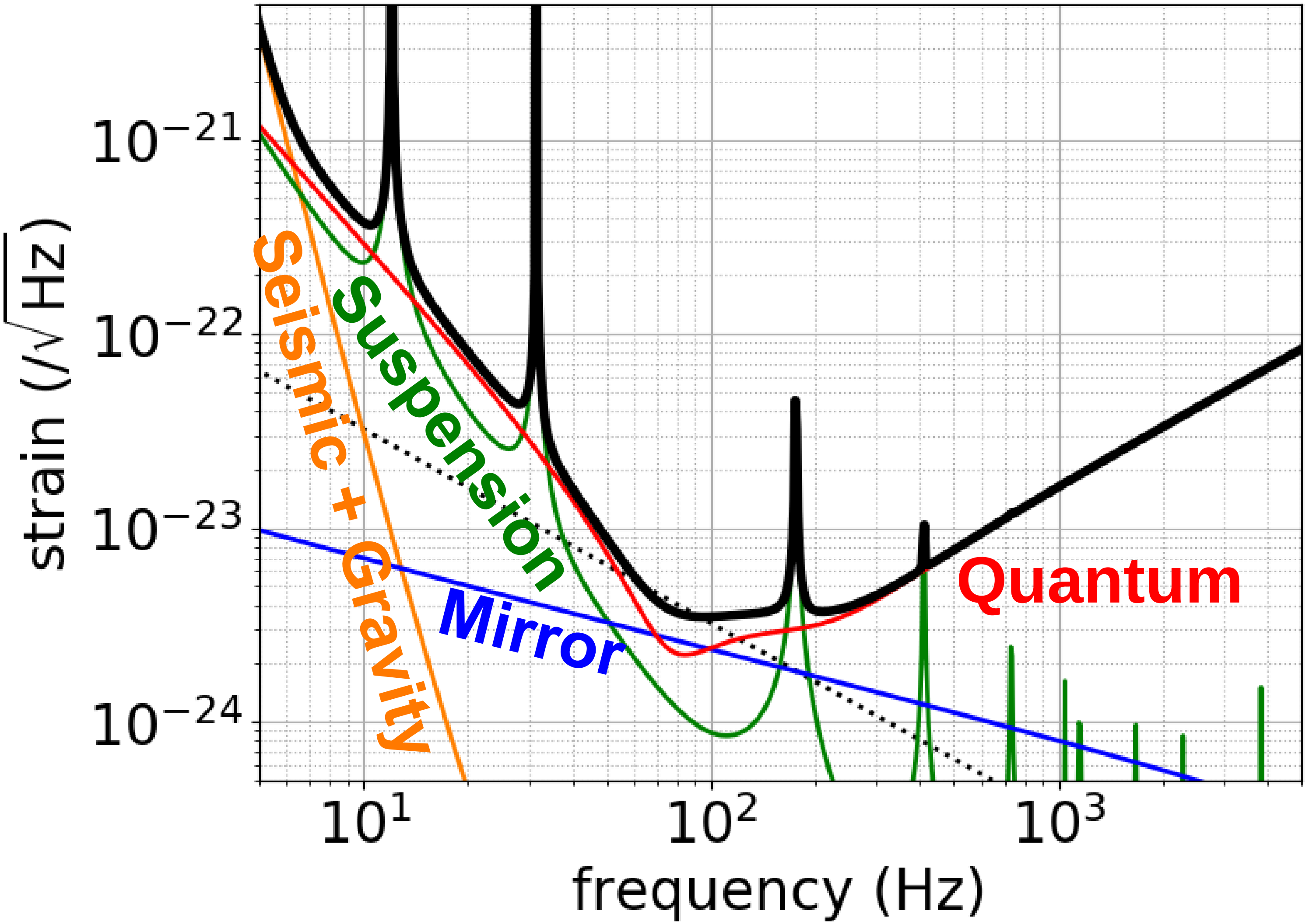




Φ22 cm x t 15 cm
22.8 kg

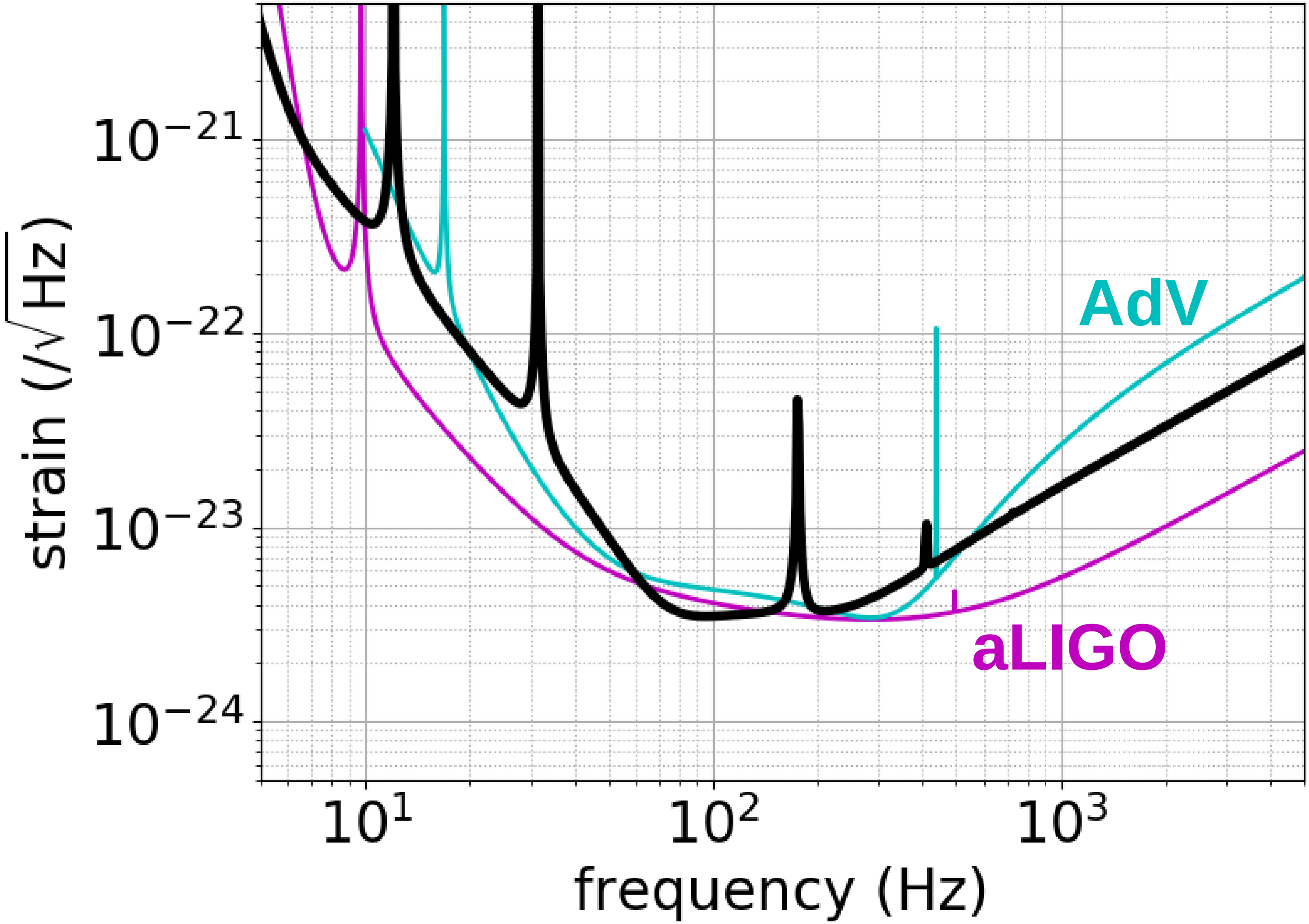
Design Sensitivity

- Binary neutron star (BNS) range 153 Mpc

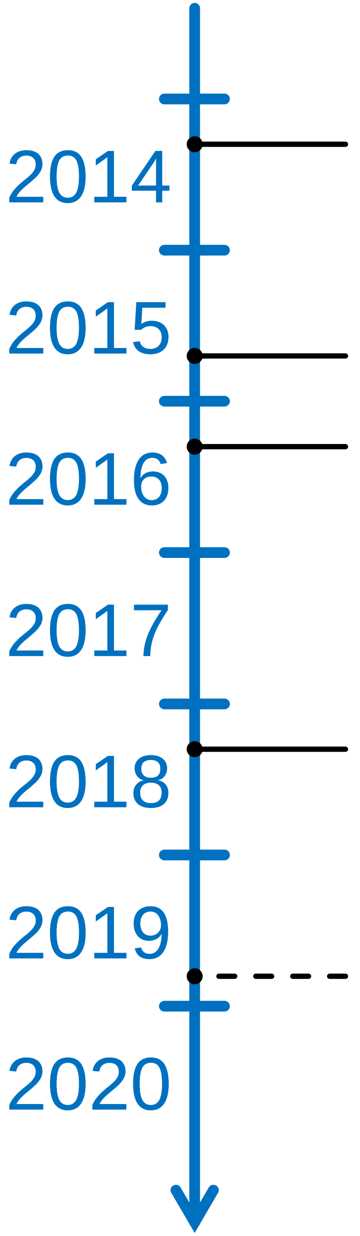


Comparison with aLIGO and AdV

- Comparable to aLIGO and AdV



KAGRA Timeline



Tunnel excavation done

Inauguration of initial-phase facility

First test run at room temp. (iKAGRA)

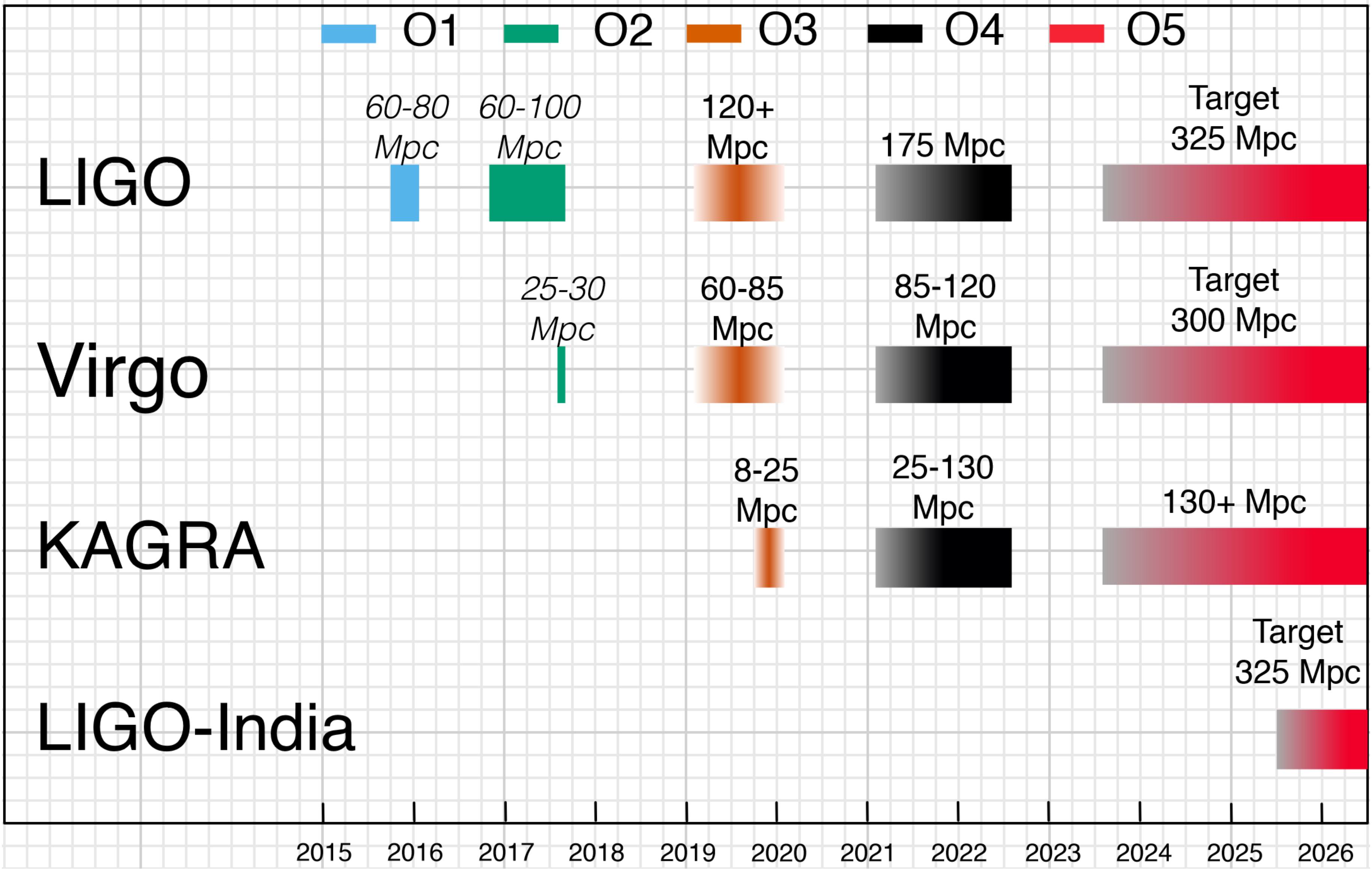
KAGRA Collaboration, [PTEP 2018, 013F01 (2018)]

First cryogenic test run (Phase 1)

KAGRA Collaboration, [arXiv:1901.03569]

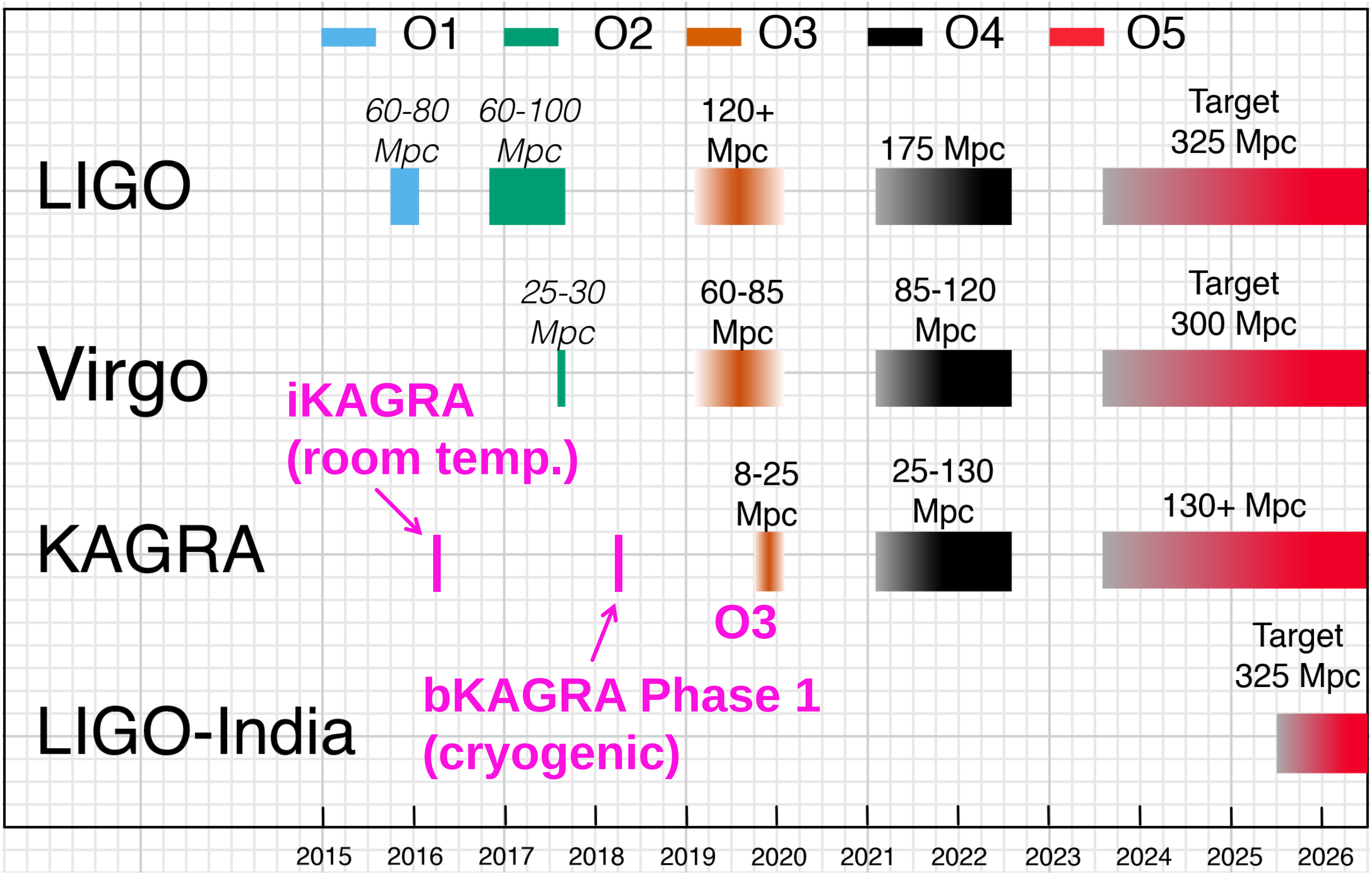
Expect to join observing run O3

Observation Scenario



Living Reviews in Relativity 21, 3 (2018); updated version available from https://git.ligo.org/publications/detectors/obs-scenarios-2018/blob/master/Figures/ObsScen_fig2_v12.pdf

Observation Scenario



iKAGRA (room temp.)

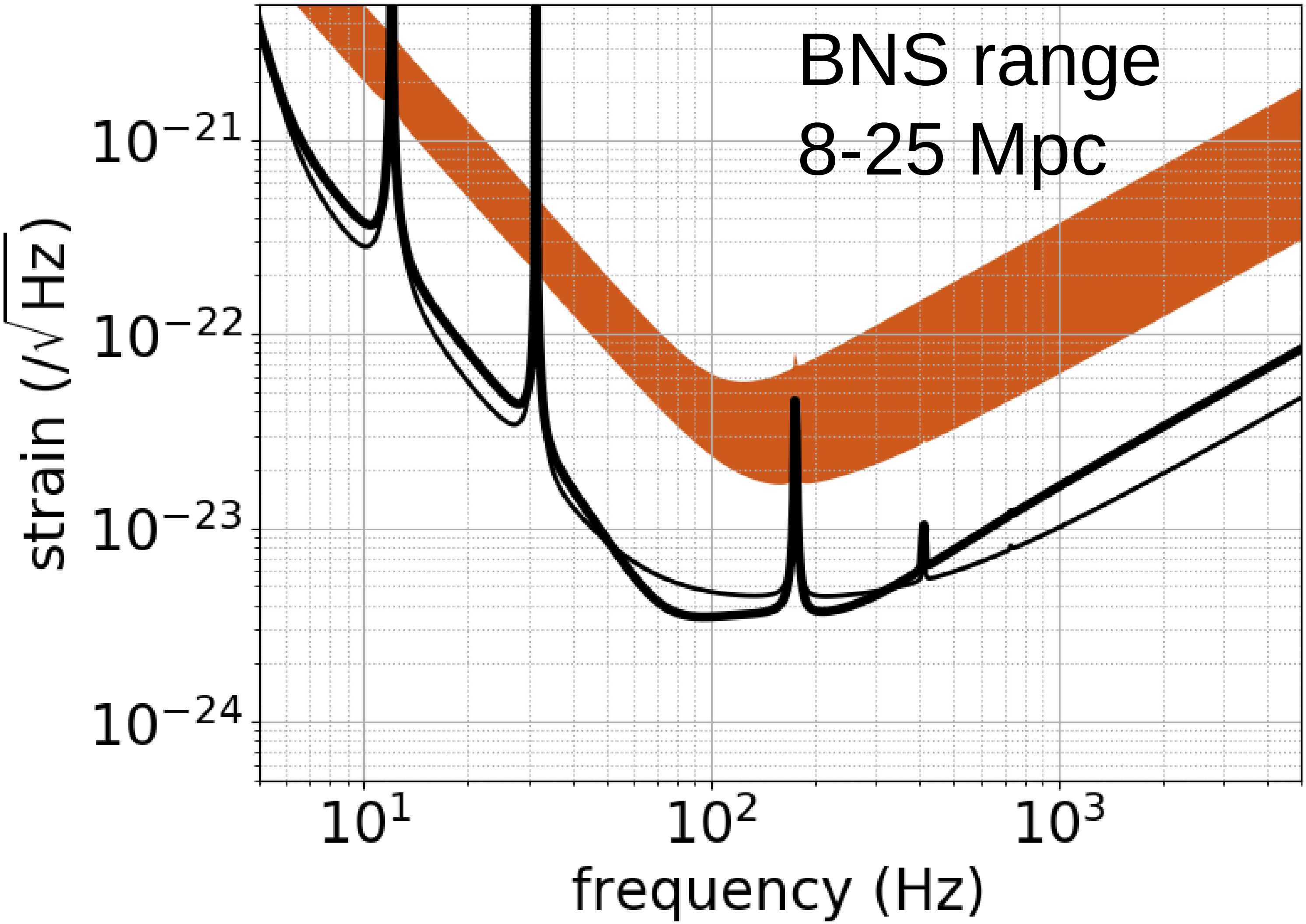
O3

bKAGRA Phase 1 (cryogenic)

Living Reviews in Relativity 21, 3 (2018); updated version available from https://git.ligo.org/publications/detectors/obs-scenarios-2018/blob/master/Figures/ObsScen_fig2_v12.pdf

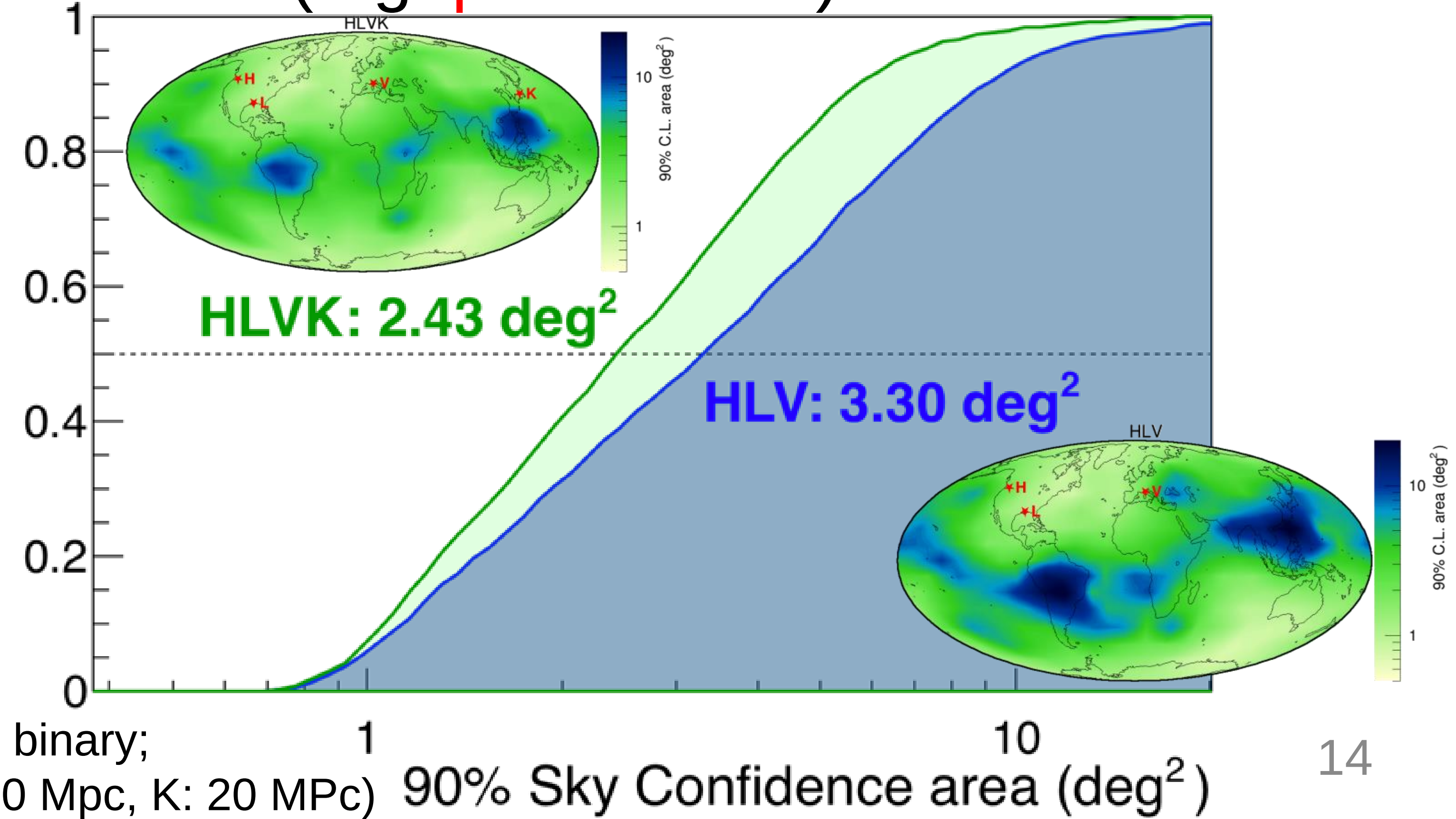
Target Sensitivity for O3

- Aims for 10-30 W input, BRSE with R_SRM = 70%



If KAGRA Joins O3

- Improves sky coverage, network duty factor, source parameter estimation
- Some parameter degeneracy can be resolved with four detectors (e.g. polarization)



JGW-G1808212
Calculation
by S. Haino
(GW170817-like binary;
L: 120 Mpc, V: 80 Mpc, K: 20 MPc)

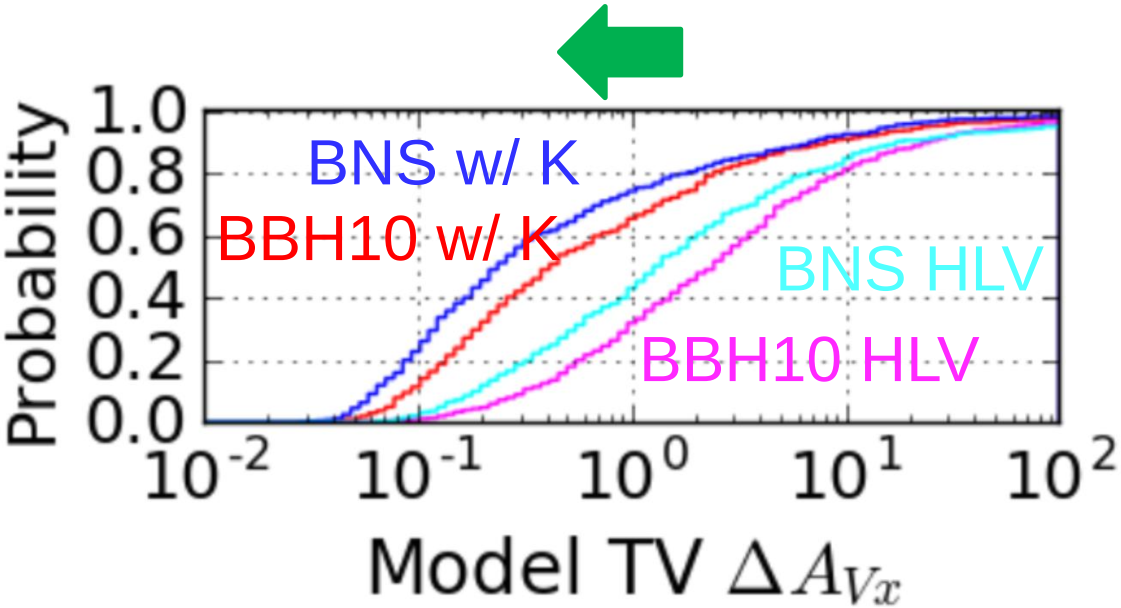
Test of GR with CBC Polarization

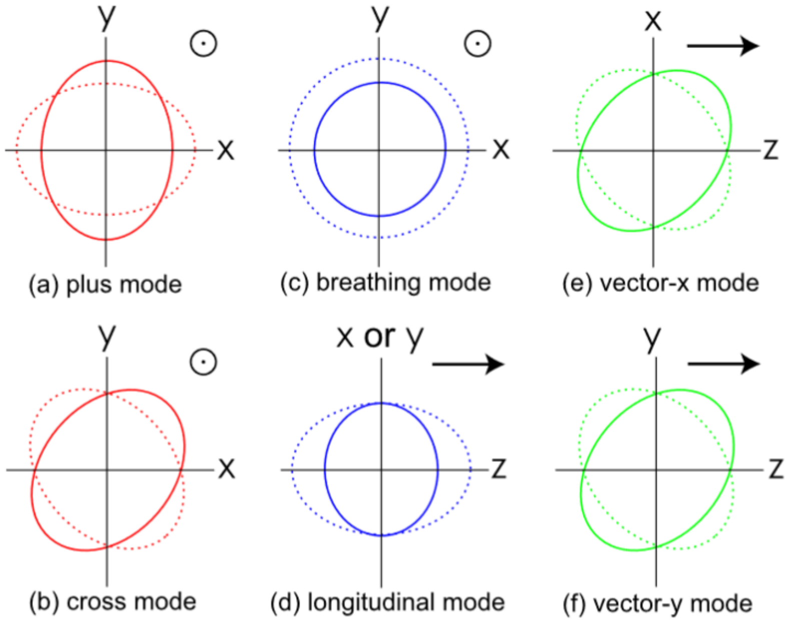
- Fourth detector necessary to distinguish four polarizations

H. Takeda+, PRD 98, 022008 (2018)

- Number of detector matters!

error reduces to < 1 with KAGRA

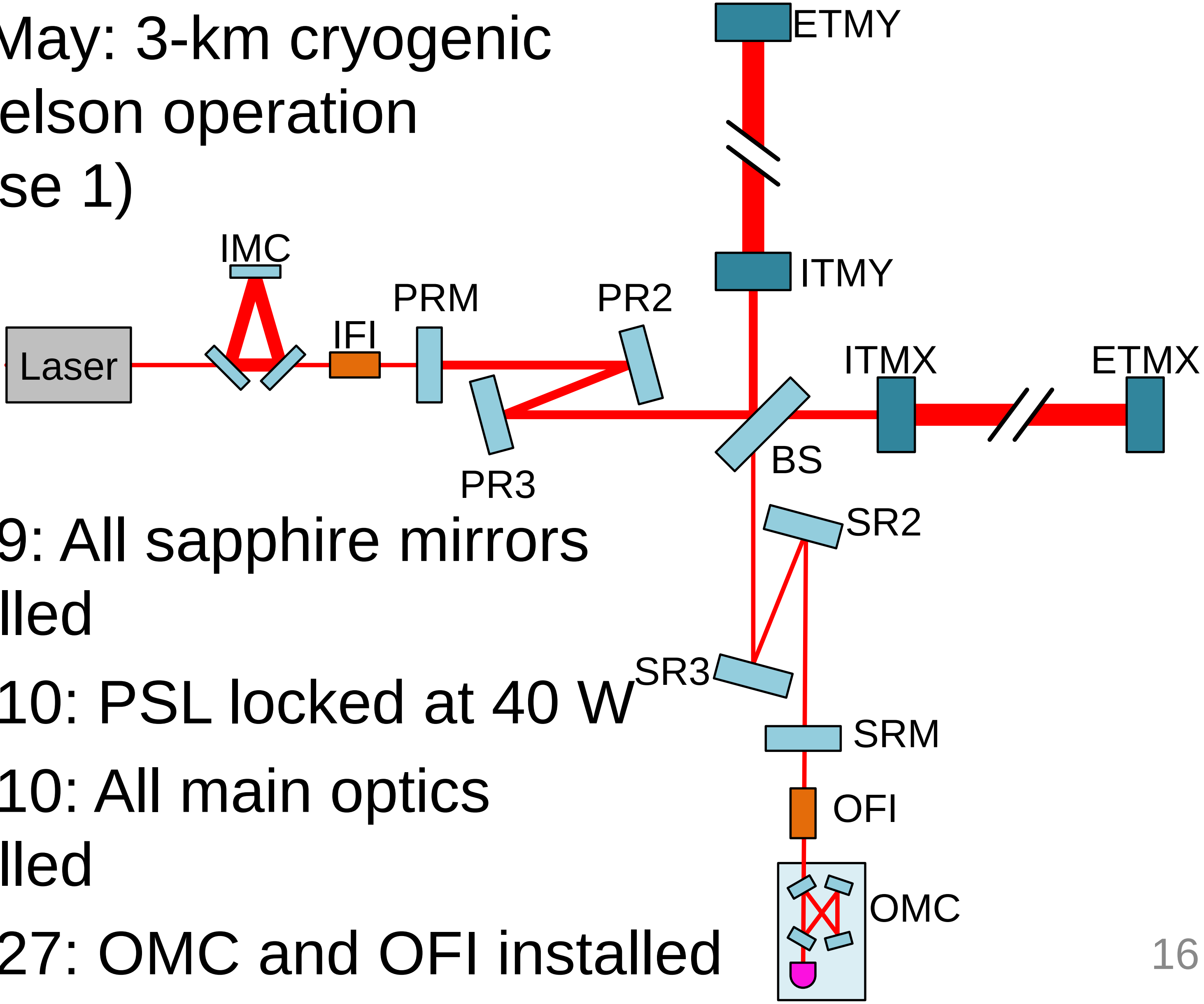




Error in vector-x mode amplitude

A Lot of Progress in 2018

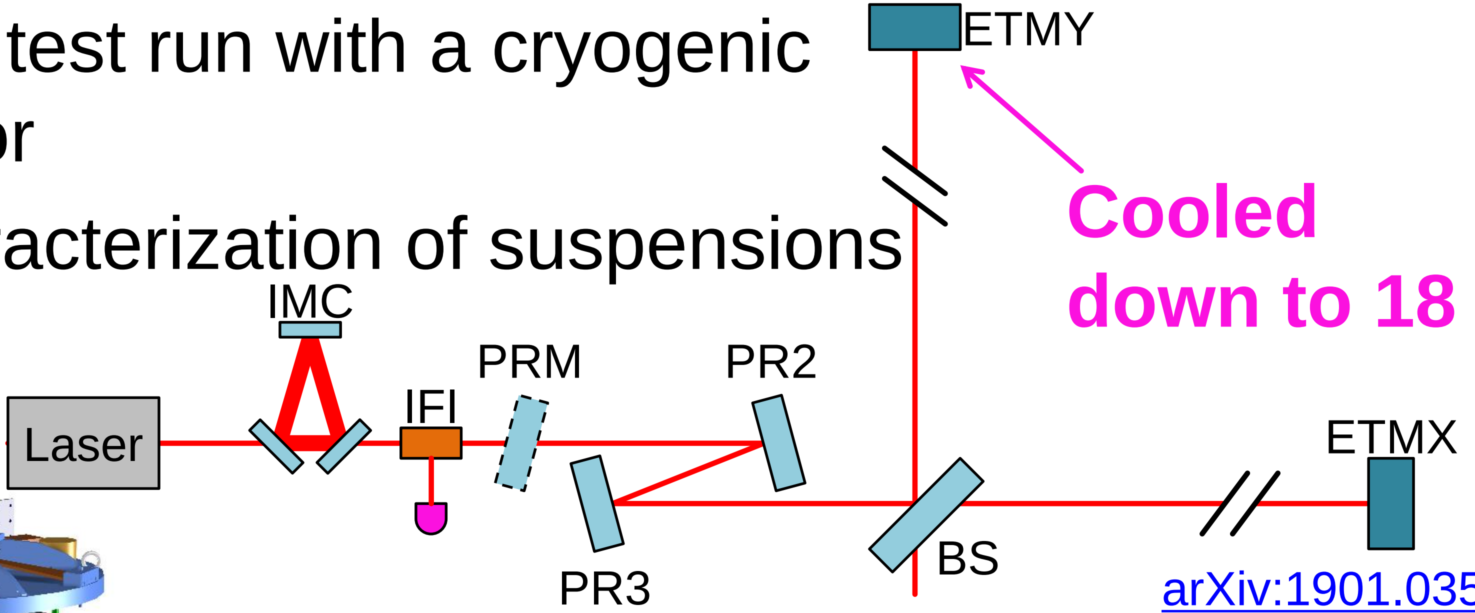
- Apr-May: 3-km cryogenic Michelson operation (Phase 1)



- Nov 9: All sapphire mirrors installed
- Nov 10: PSL locked at 40 W
- Dec 10: All main optics installed
- Dec 27: OMC and OFI installed

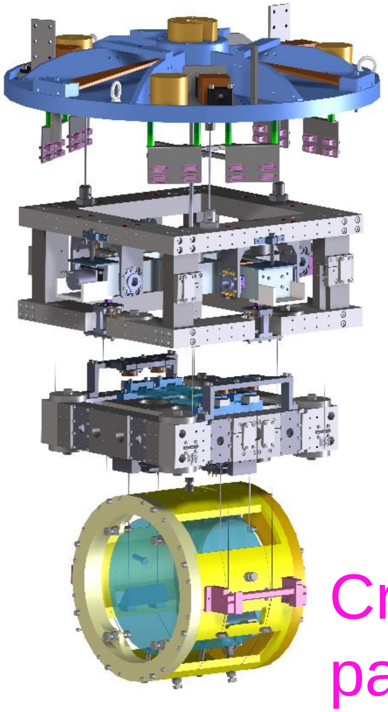
Phase 1 Operation

- First test run with a cryogenic mirror
- Characterization of suspensions

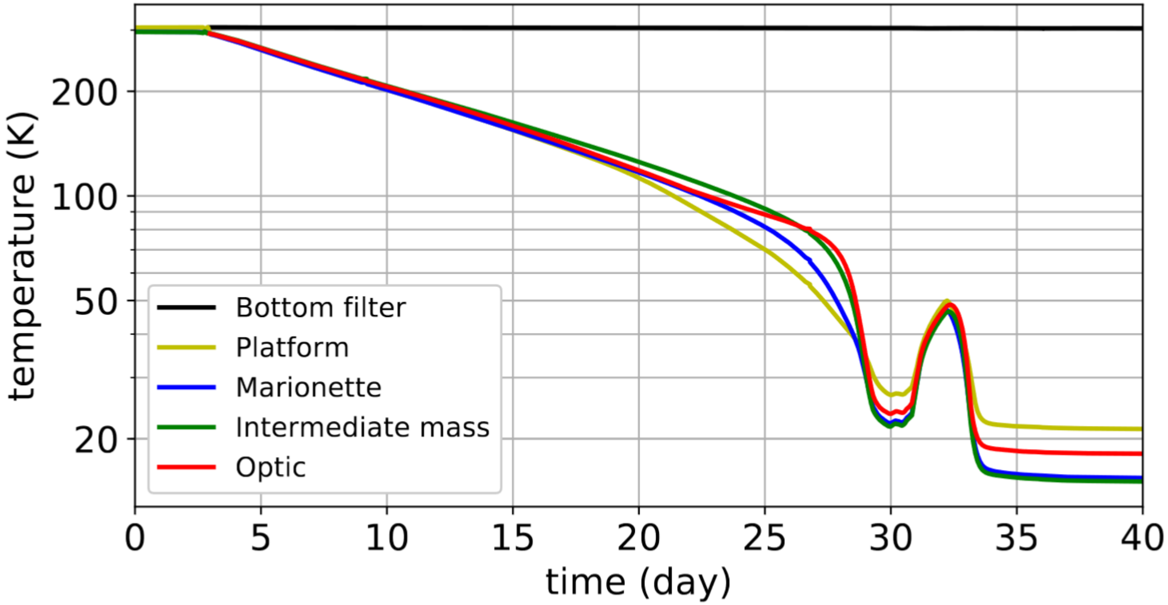


Cooled down to 18 K

arXiv:1901.03569

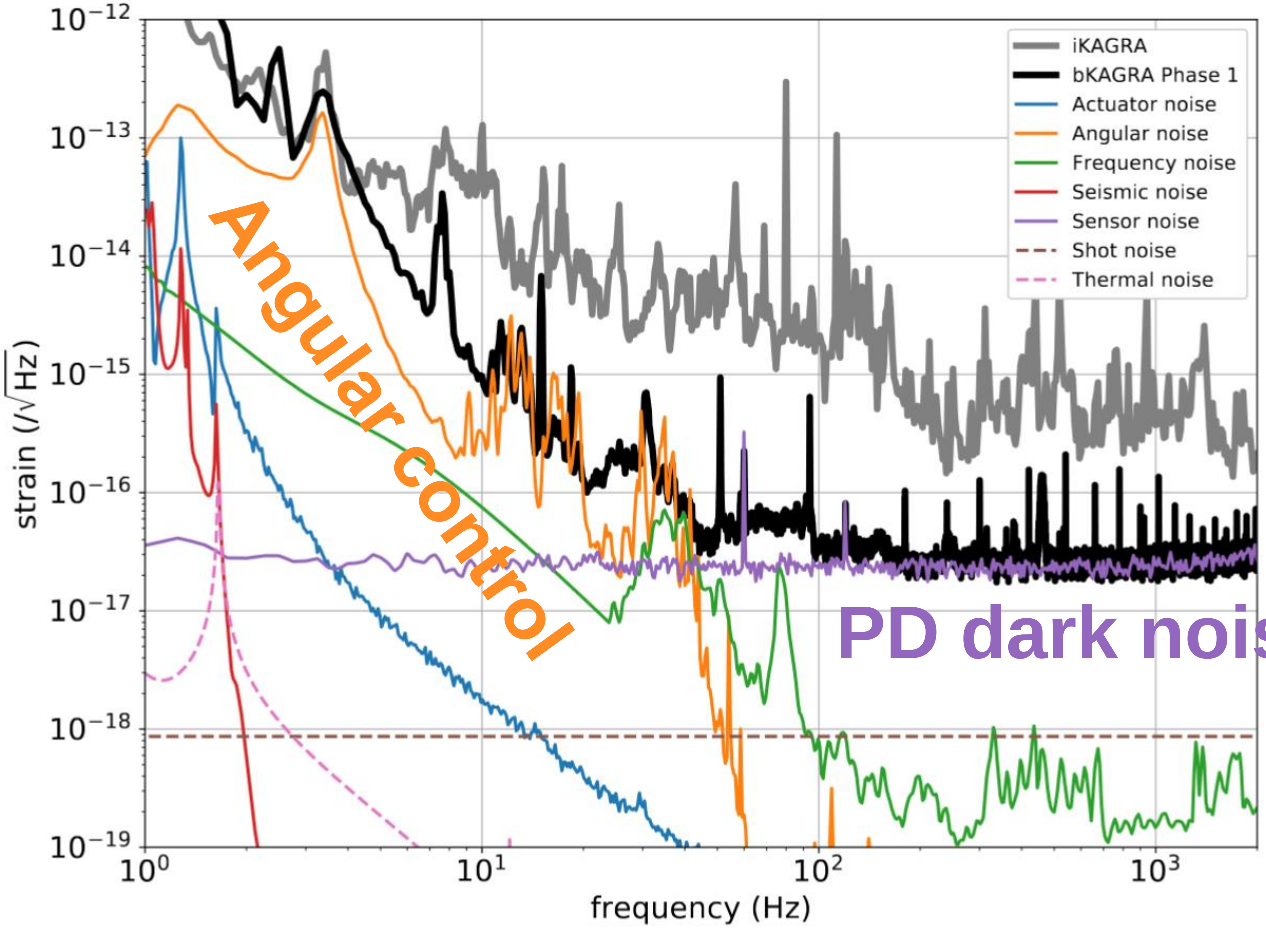


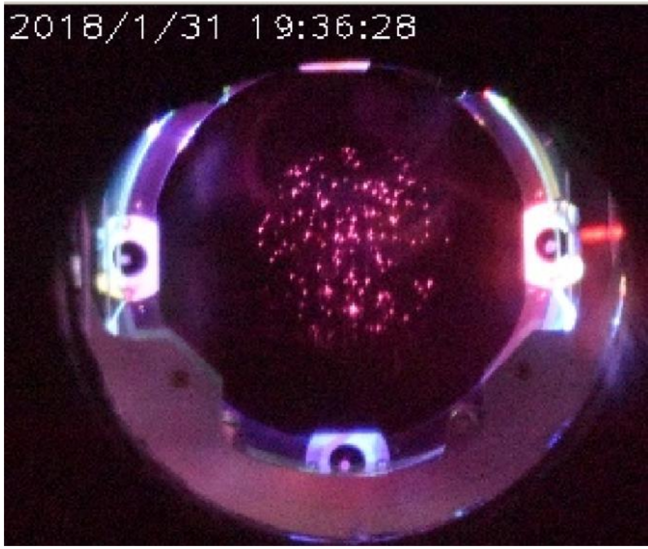
Cryogenic payload



Phase 1 Operation

- Sensitivity at 3e-17 /rtHz @ 100 Hz
- Gained experience in aligning and operating cryogenic interferometer





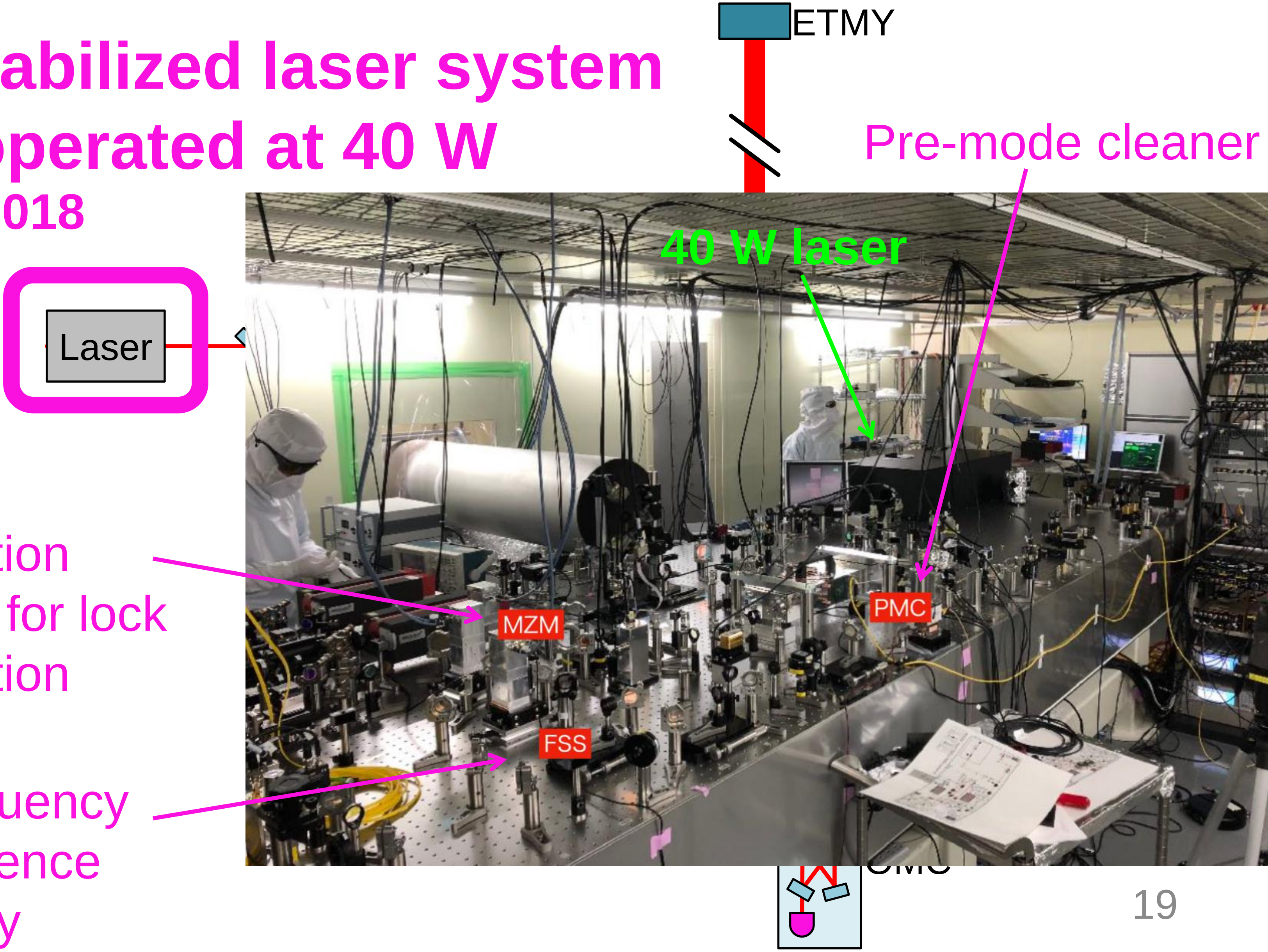
ETMY taken by telephoto camera

arXiv:1901.03569

Installation Progress: PSL

Pre-stabilized laser system fully operated at 40 W

Nov 9, 2018



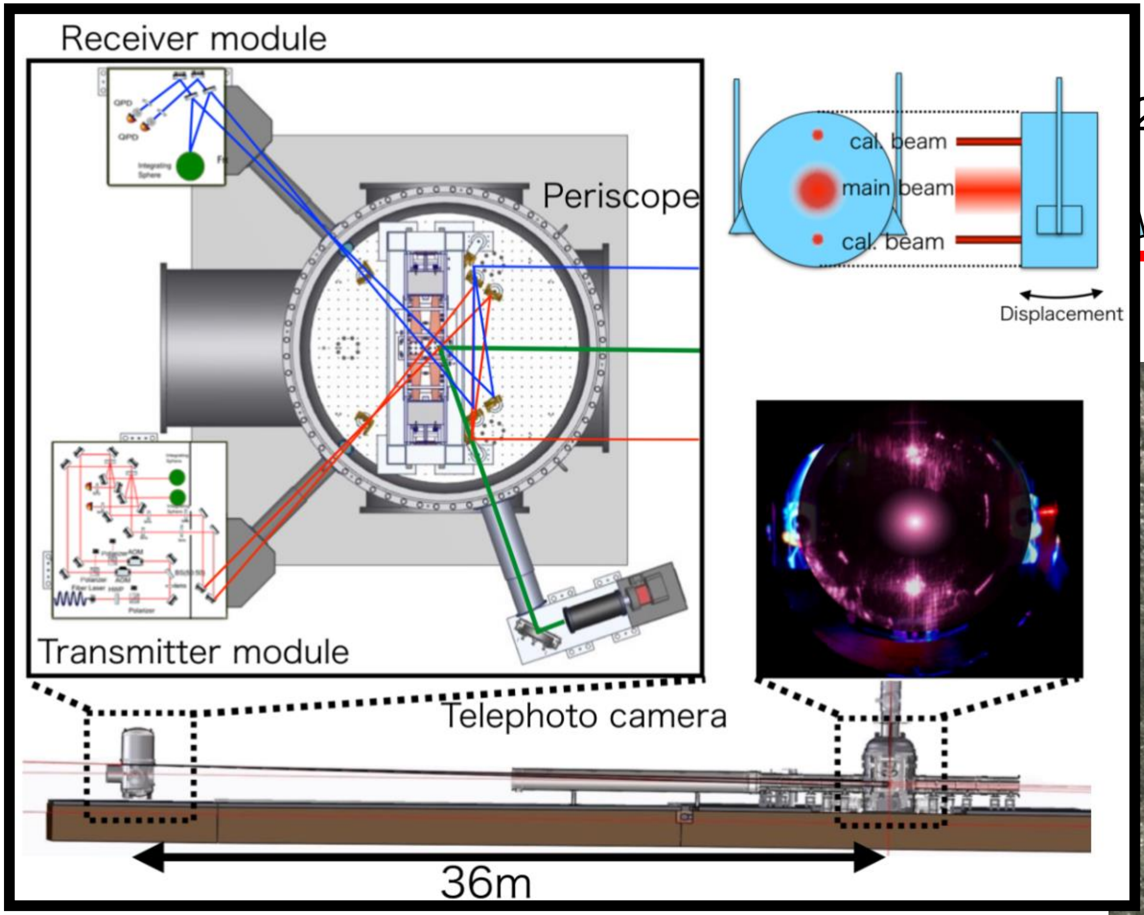
Pre-mode cleaner

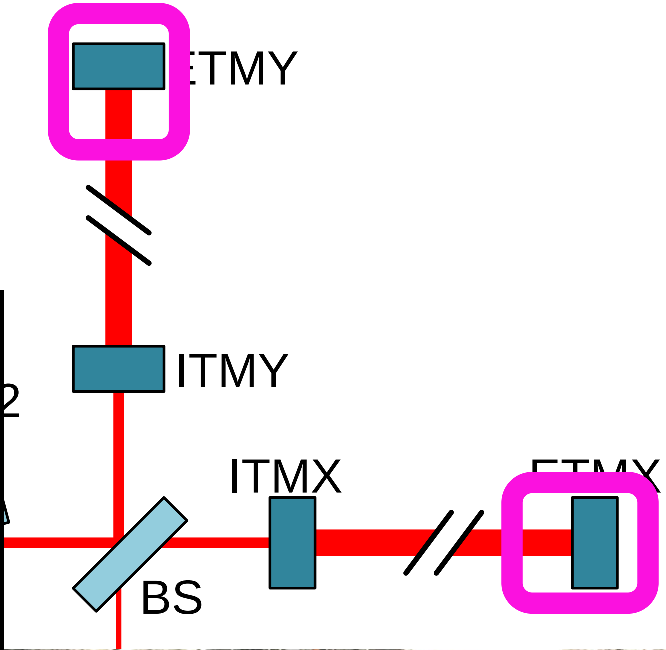
RF AM generation system for lock acquisition

Frequency teference cavity

Installation Progress: PCal

Photon calibrator installed to both ends

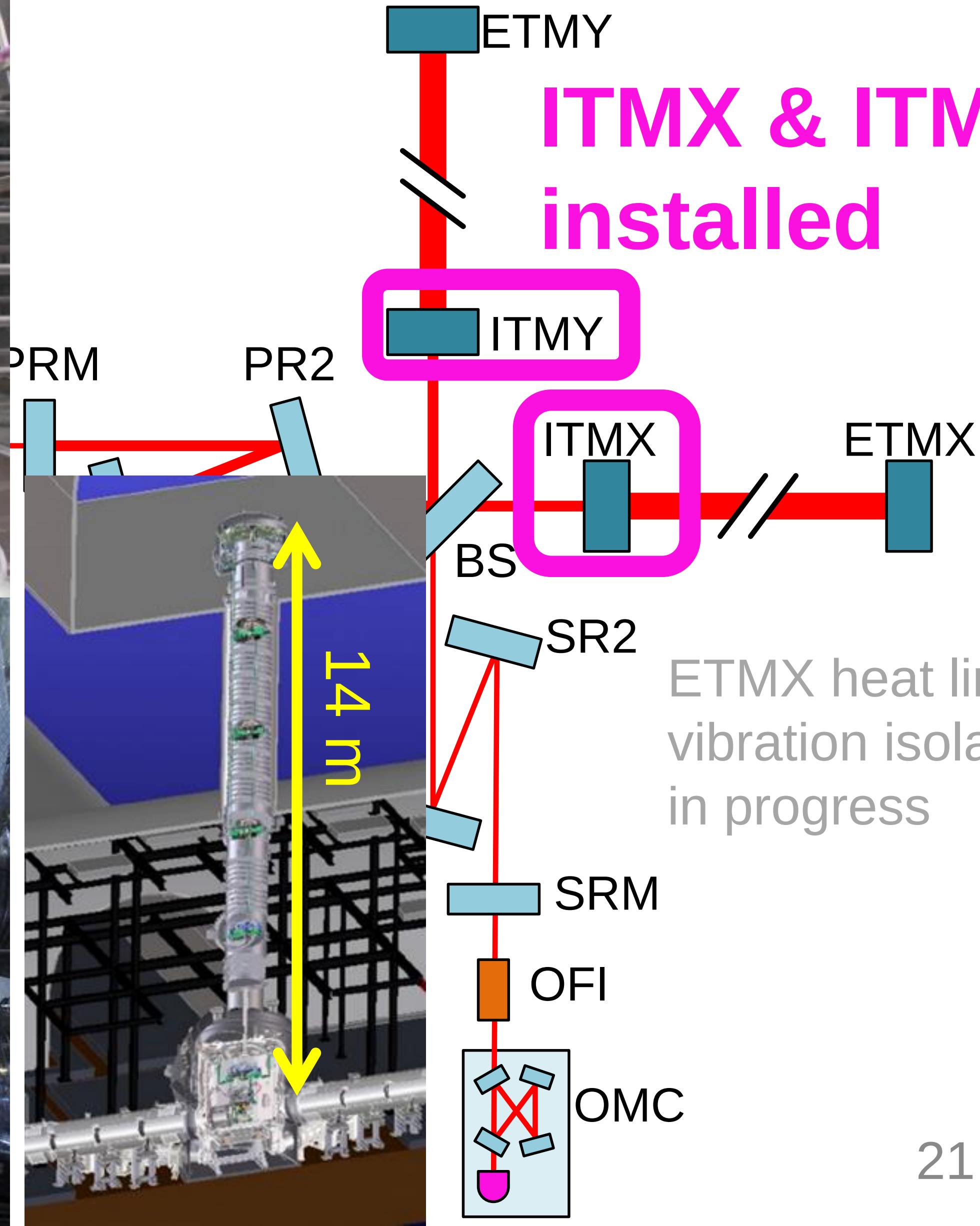




July 24, 2018

Installation Progress: Cryopayload

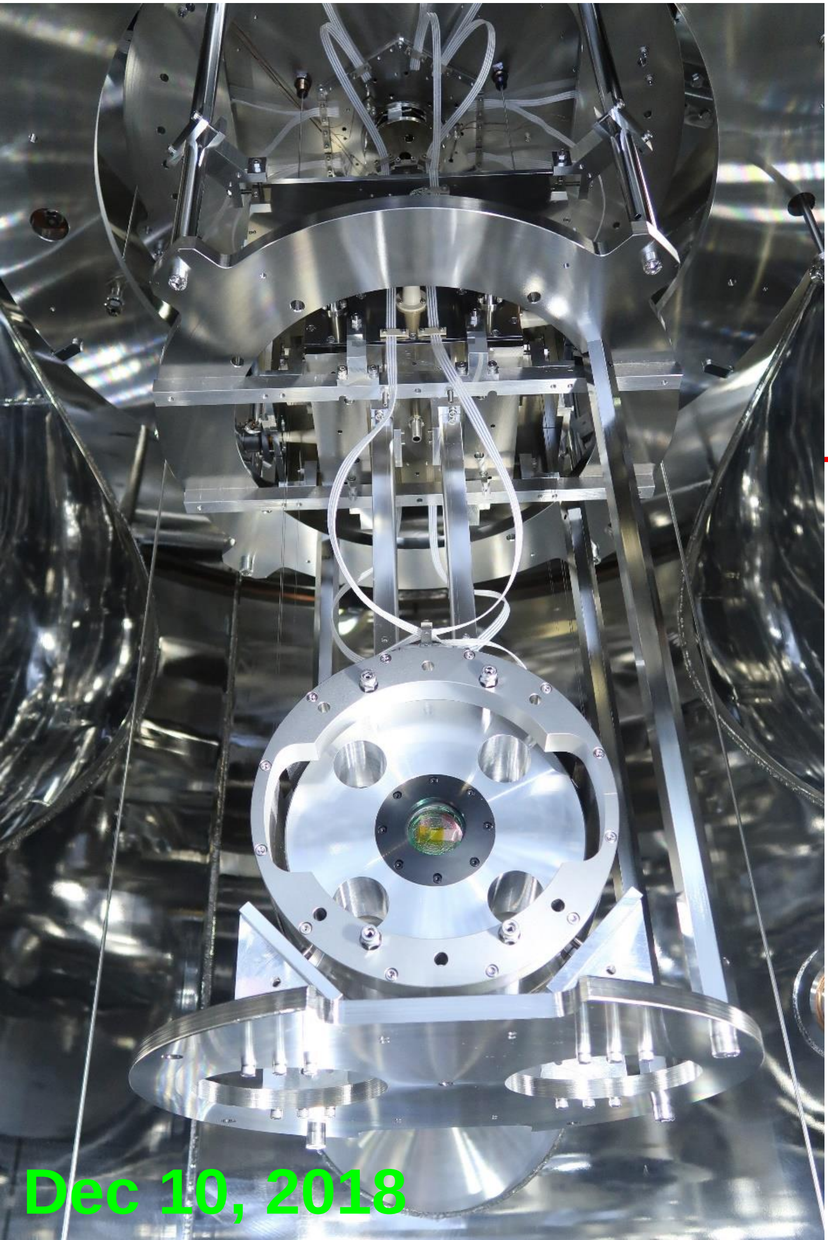
Nov 9, 2018



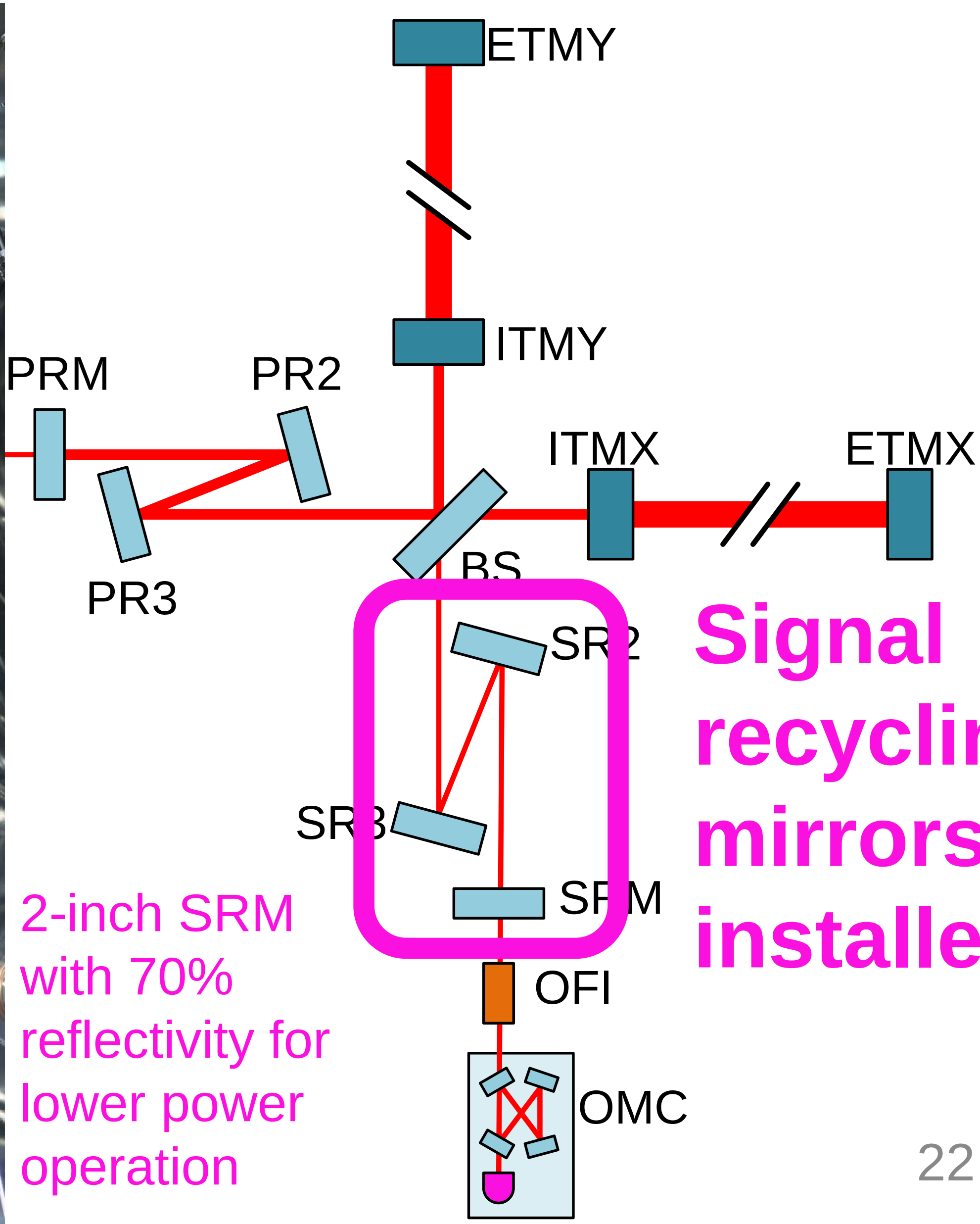
ITMX & ITMY installed

ETMX heat link vibration isolation in progress

Installation Progress: SR Mirrors



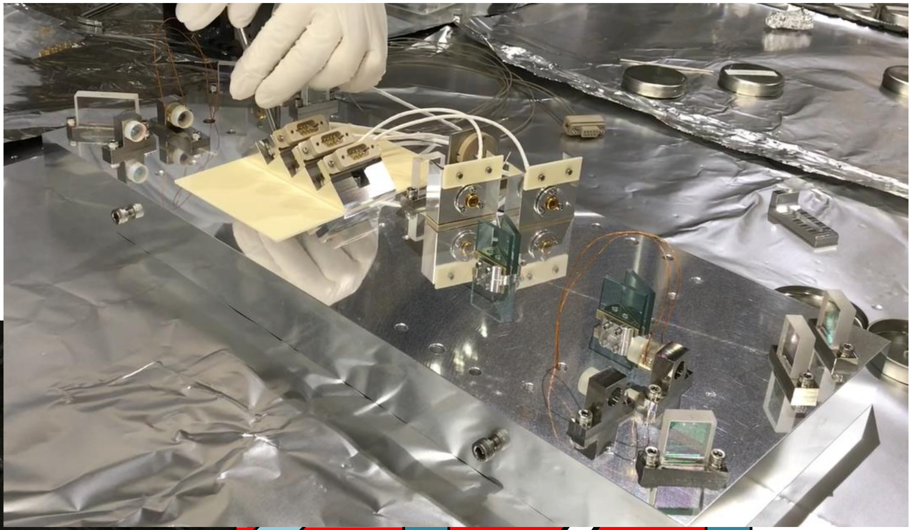
Dec 10, 2018

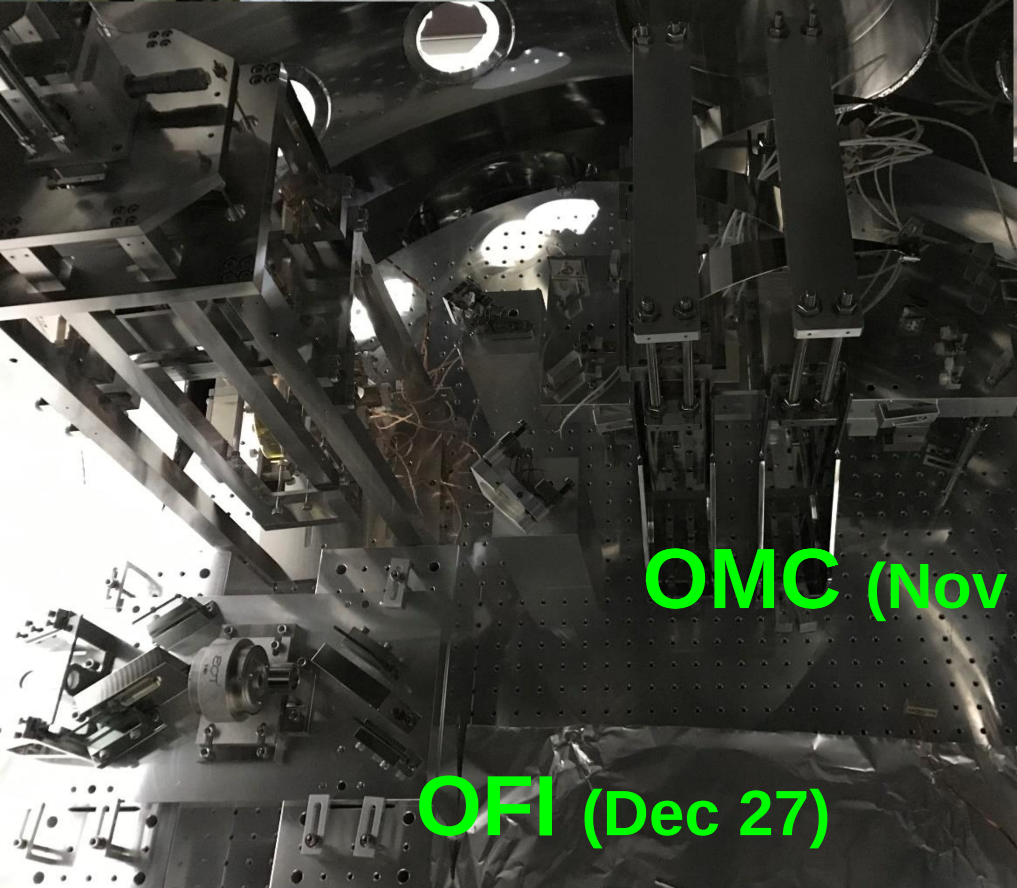


Signal recycling mirrors installed

2-inch SRM with 70% reflectivity for lower power operation

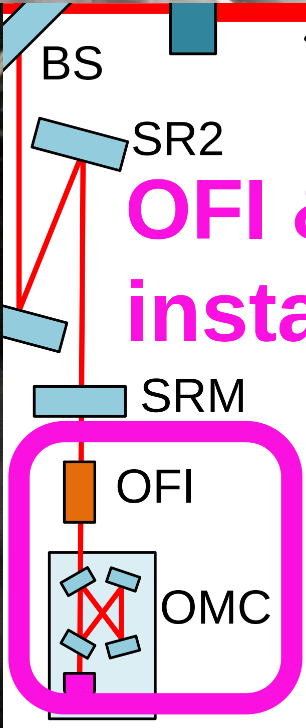
Installation Progress: Output Optics





OMC (Nov 9)

OFI (Dec 27)



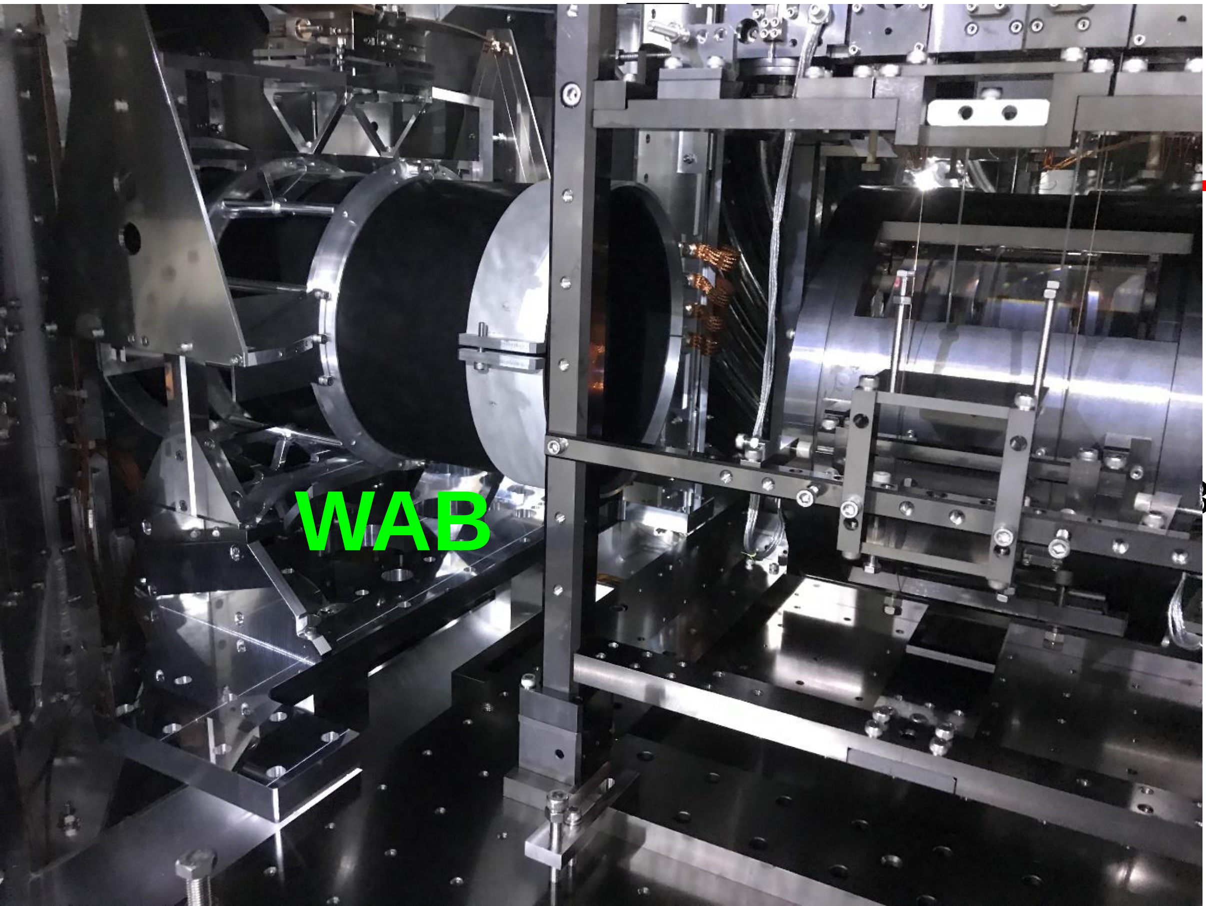
OFI & OMC installed

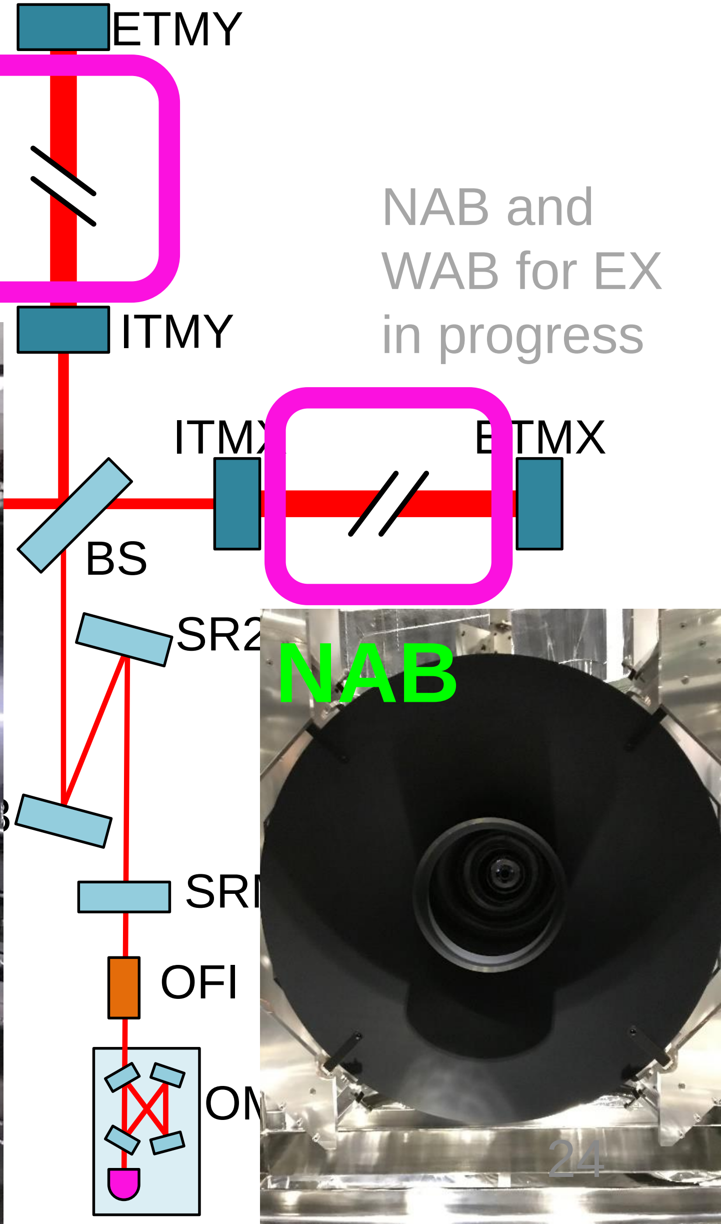
OSTM
in progress

Installation Progress: Baffles

Narrow angle baffles,
Wide angle baffles
3 of 4 installed

IMC



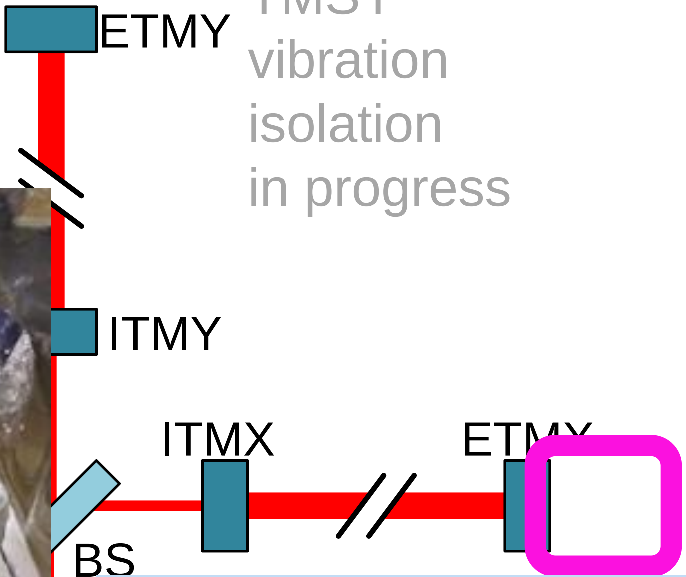


NAB and
WAB for EX
in progress

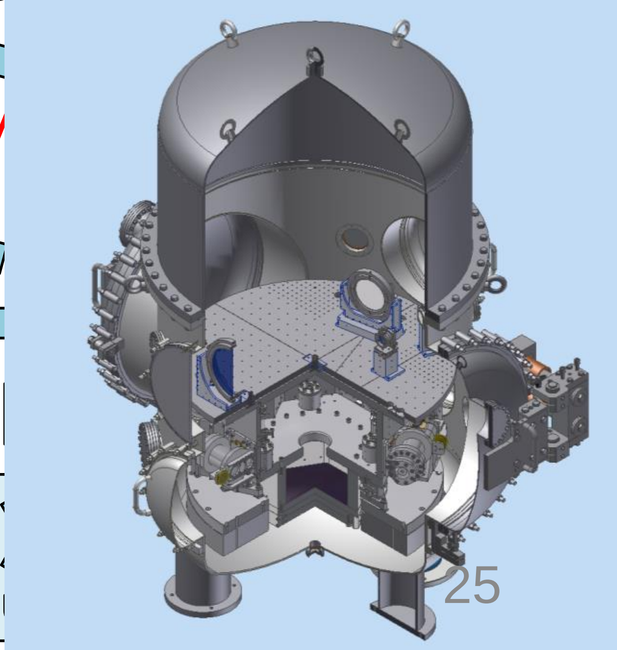
Installation Progress: Trans Mons

Both transmission monitor system installed

Oct 1, 2018

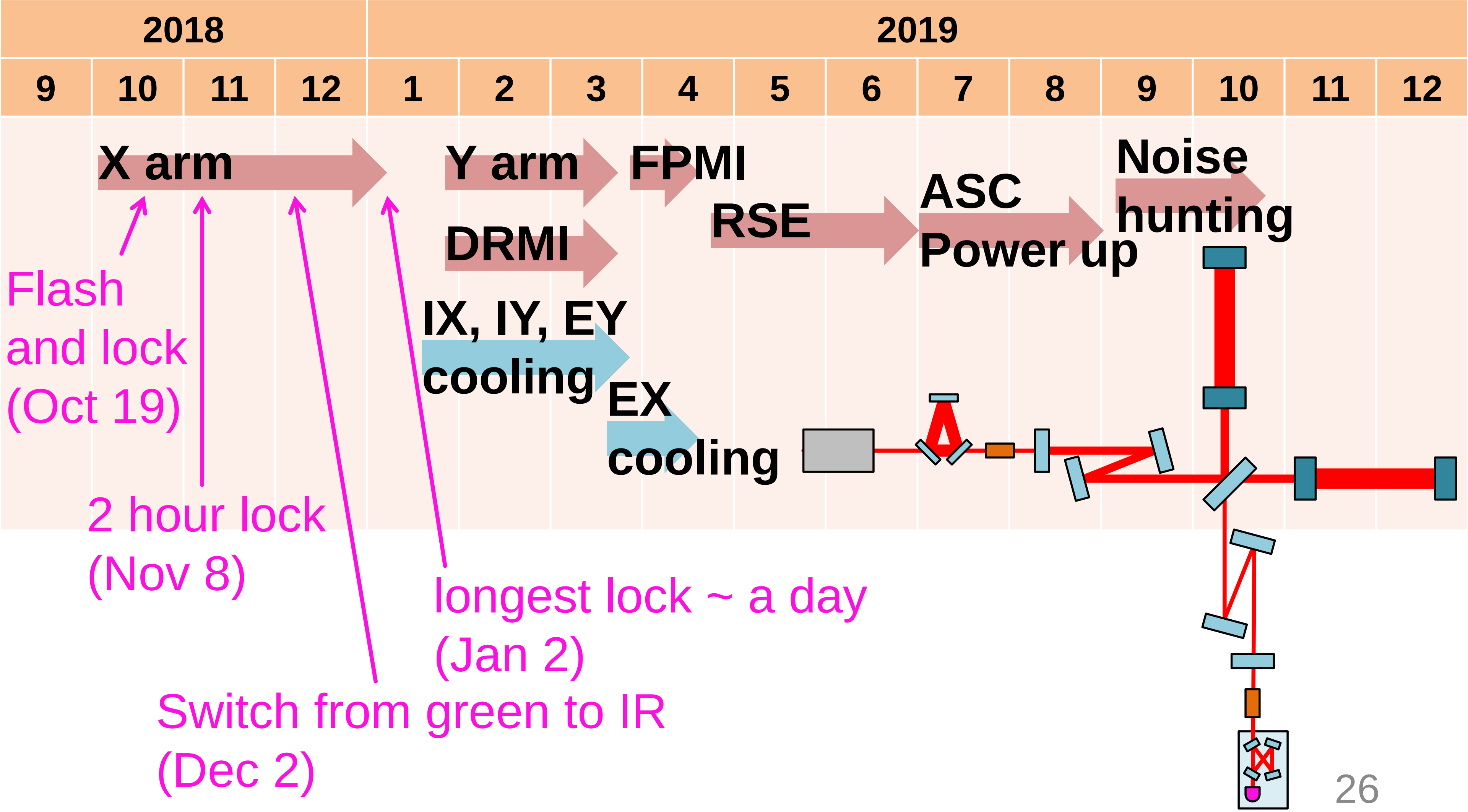


TMSY vibration isolation in progress



Commissioning Schedule

- X-arm commissioning completed



2018				2019											
9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12

Flash and lock (Oct 19)

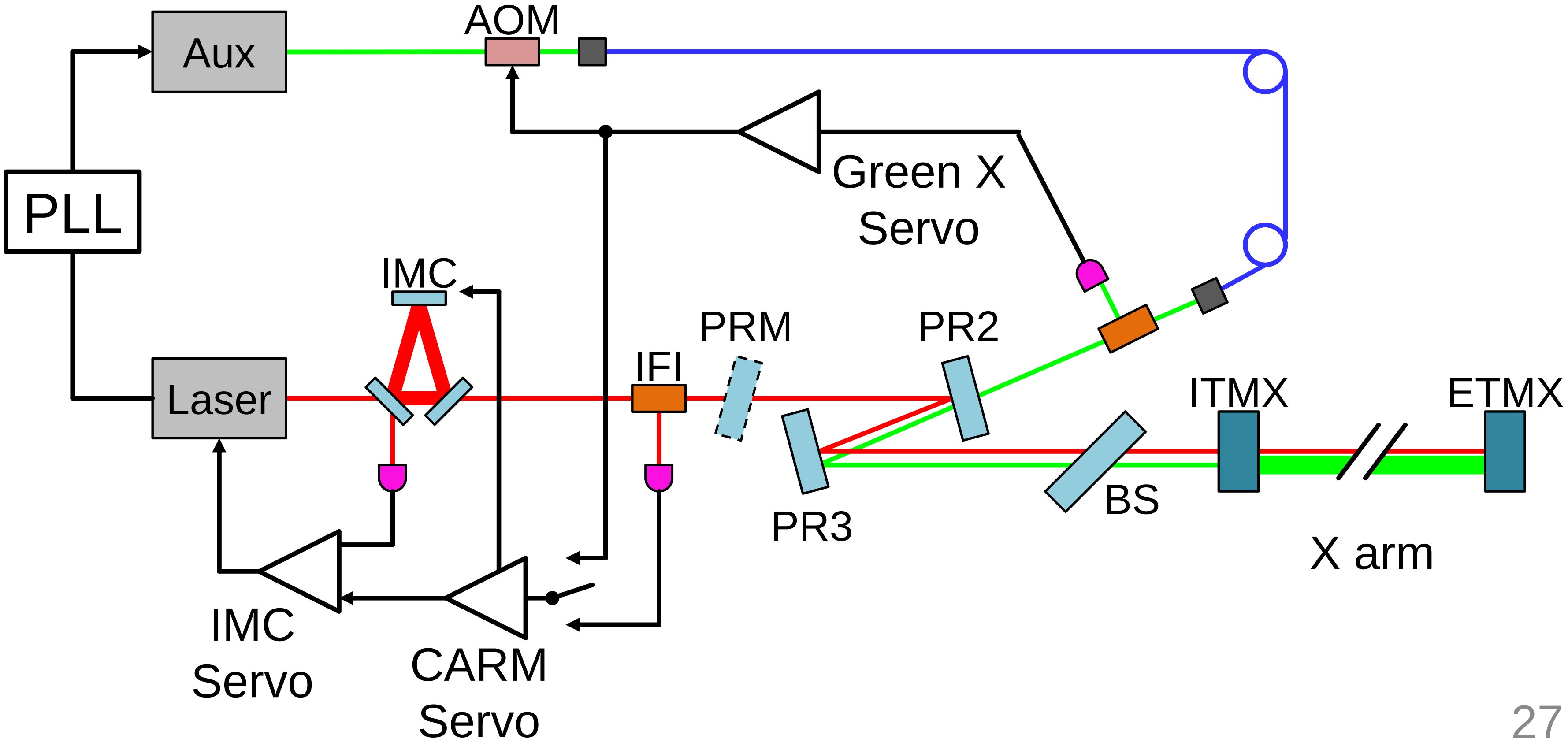
2 hour lock (Nov 8)

Switch from green to IR (Dec 2)

longest lock ~ a day (Jan 2)

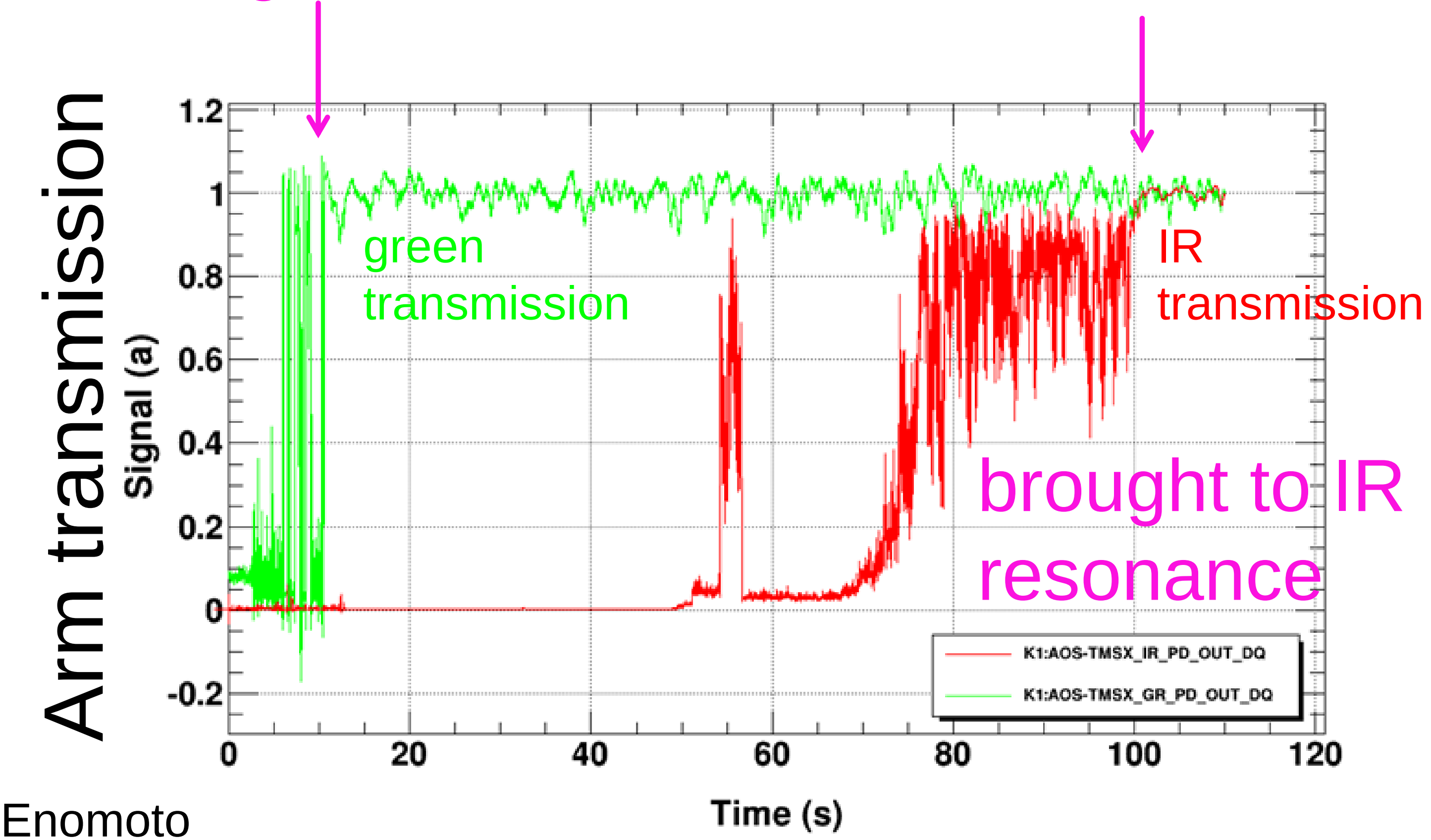
X-arm Commissioning

- First test of arm length stabilization system using green beam
- Simpler configuration than aLIGO



X-arm Commissioning

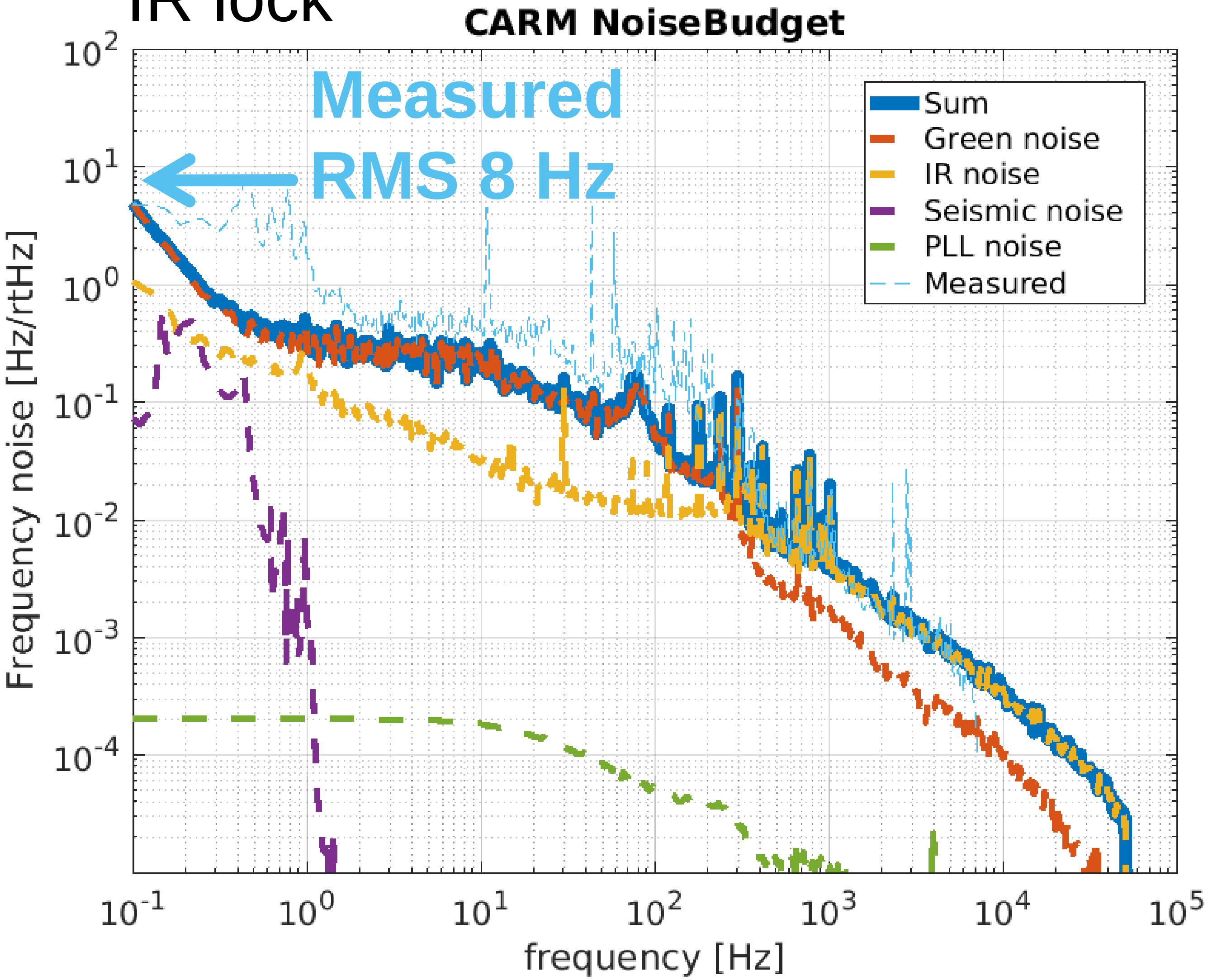
- Successfully switched directly from green lock to IR lock



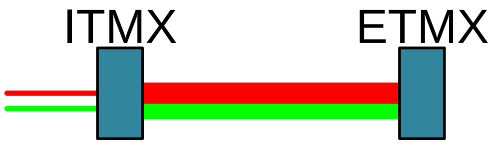
Plot by Y. Enomoto

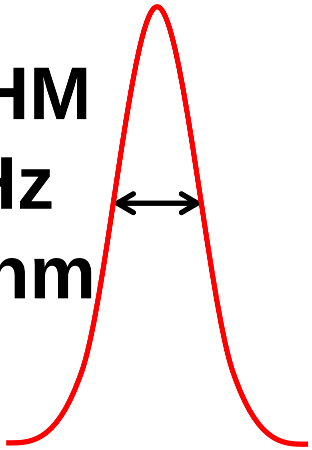
X-arm Commissioning

- Successfully switched directly from green lock to IR lock



Measured RMS 8 Hz





FWHM 33 Hz 0.3 nm

Plot by Y. Enomoto

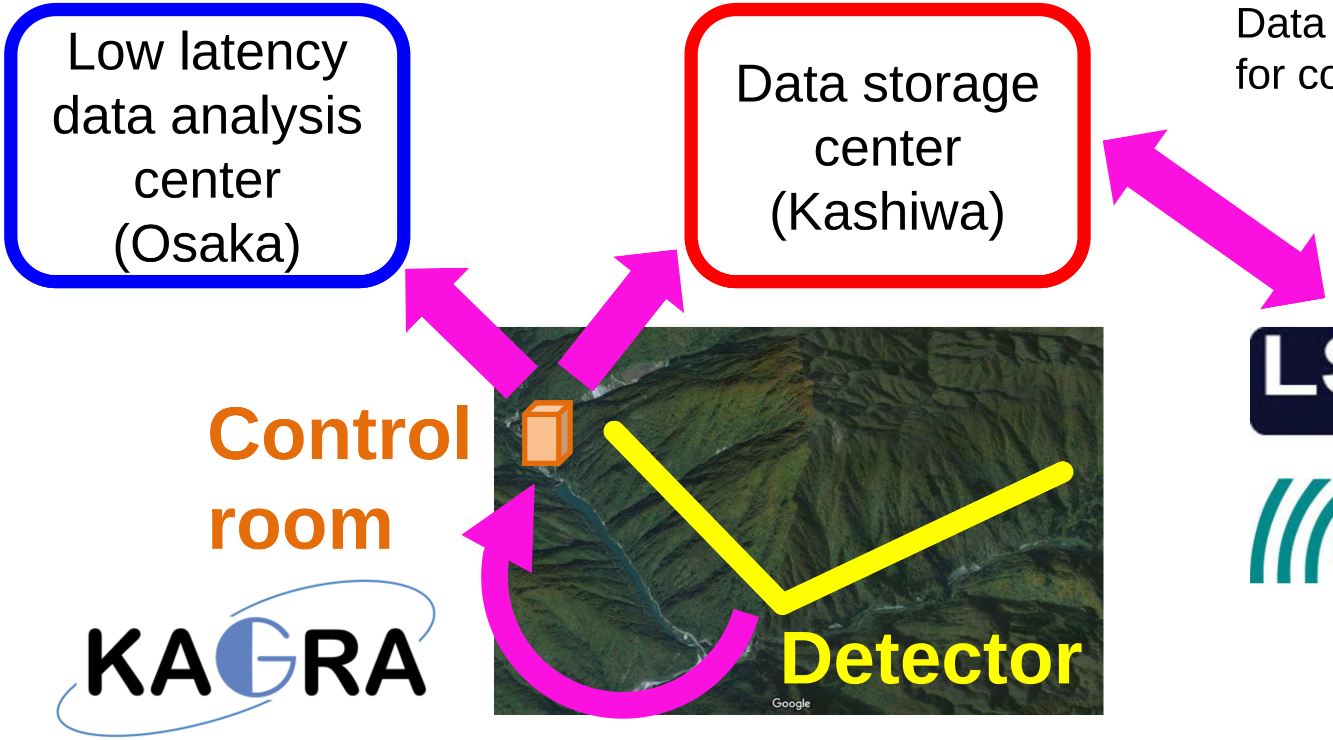
X-arm Characterization

- As expected, less than 100 ppm roundtrip loss

	Design	**Measured**
Finesse	1530	1411±2±30
ITMX transmission	0.4 %(+0.1 %)	0.44 %
Mode matching		91±1 %
Roundtrip loss	< 100 ppm	86±3 ppm
Arm length	3000 m	2999.990(2) m
Transverse mode spacing	34.80 kHz	34.79(5) kHz
Finesse (Green)	52	41.0±0.3
Mode matching (Green)		~70 %

Data Sharing and Analysis

- Low latency h(t) sharing with LIGO and Virgo
  - data transfer test in June 2018
  - 4 sec h(t) transfer to be done in ~Feb 2019
- Data analysis tools, detector characterization tools also under development with great help from LV



Low latency data analysis center (Osaka)

Data storage center (Kashiwa)

Control room

Detector

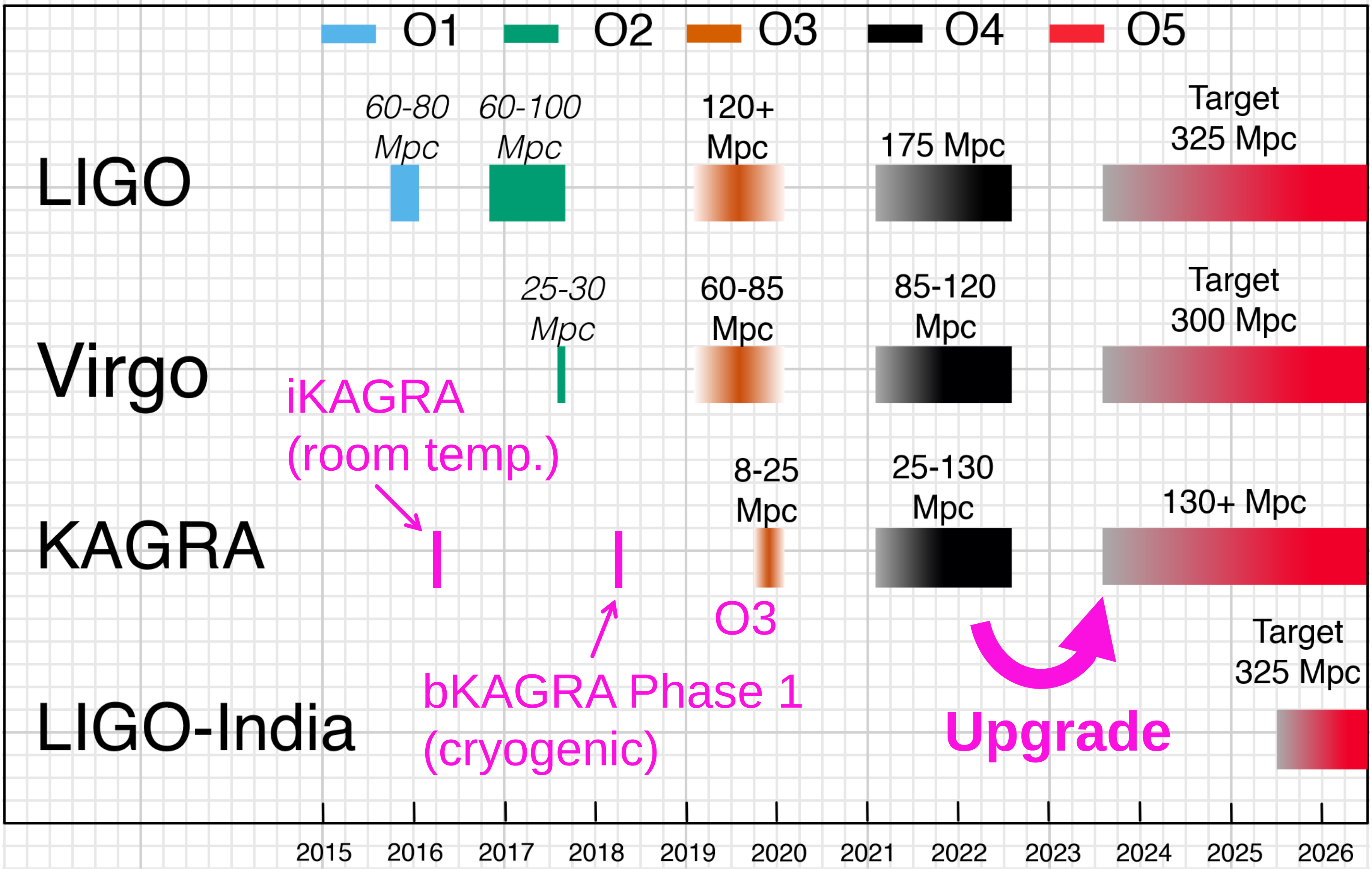
Data analysis groups re-organized for collaboration with LV

KAGRA

LSC LIGO Scientific Collaboration

VIRGO

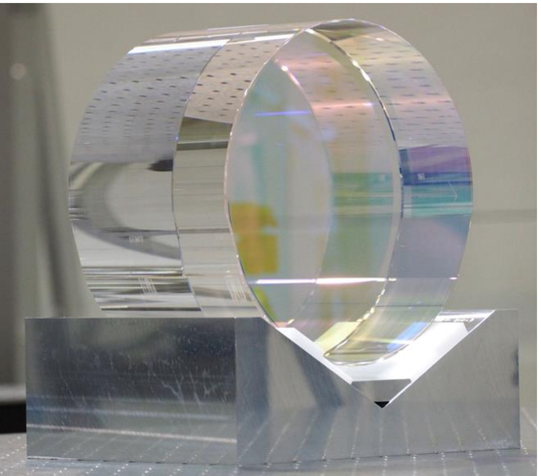
Observation Scenario



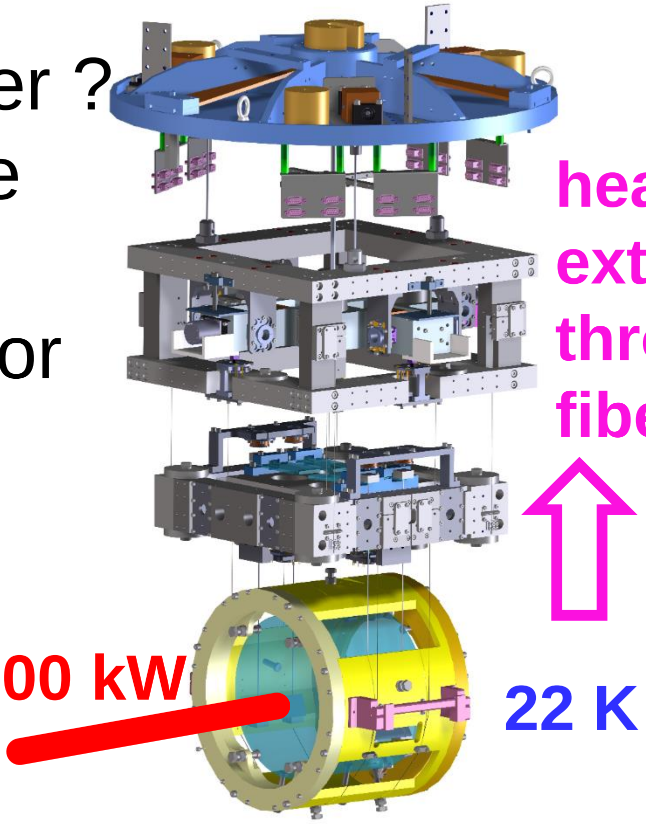
Updated version of Living Reviews in Relativity 21, 3 (2018); available from https://git.ligo.org/publications/detectors/obs-scenarios-2018/blob/master/Figures/ObsScen_fig2_v12.pdf

KAGRA Upgrade Study

- Upgrade study *formally* started in December 2018
- Future Planning Committee formulated
- Science case study and technical feasibility study on going
  - High power or low power ?
  - Sapphire test mass size
  - Squeezing
  - KAGRA as a 4th detector

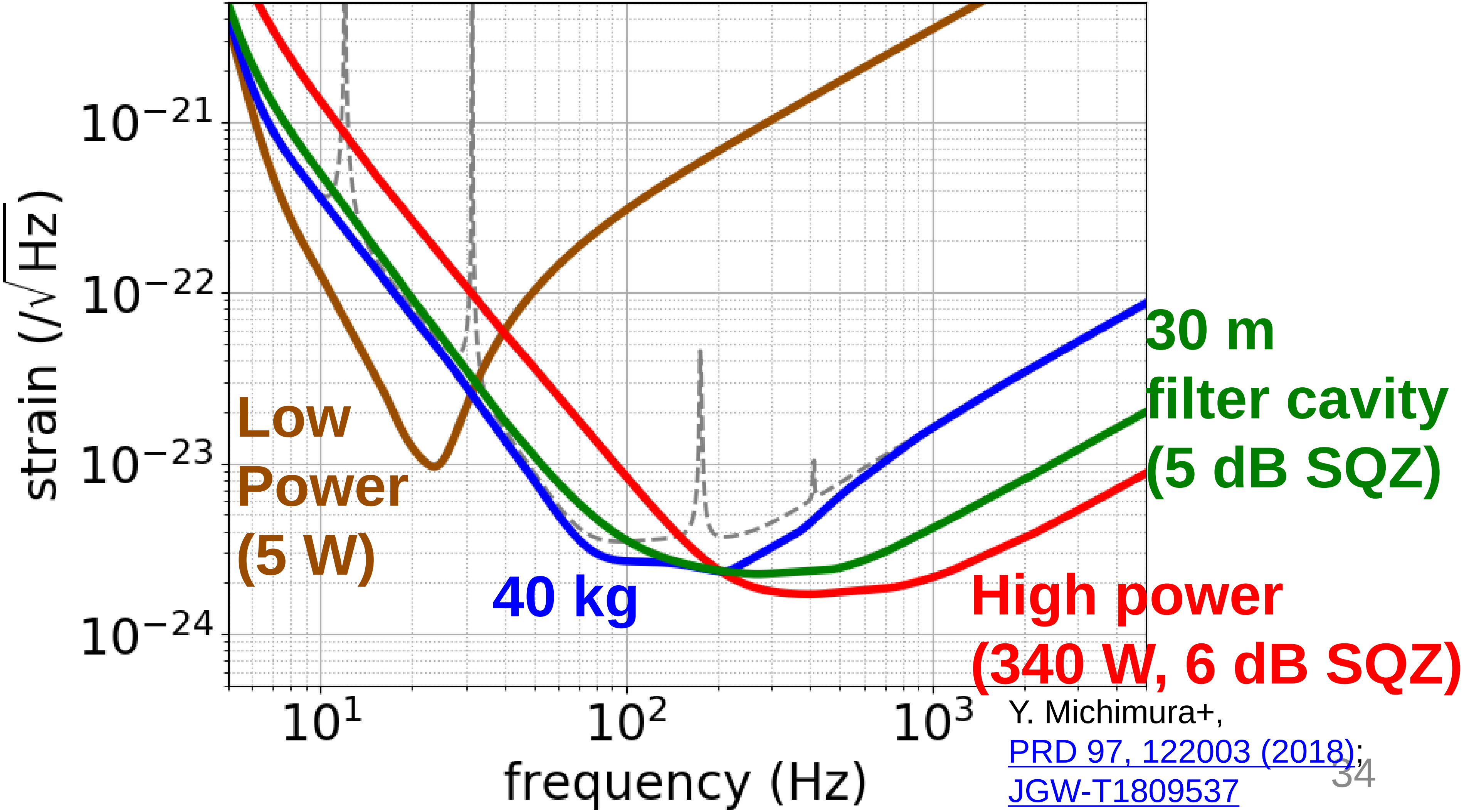


Φ22 cm x t 15 cm
22.8 kg



Possible Near Term Upgrade Plans

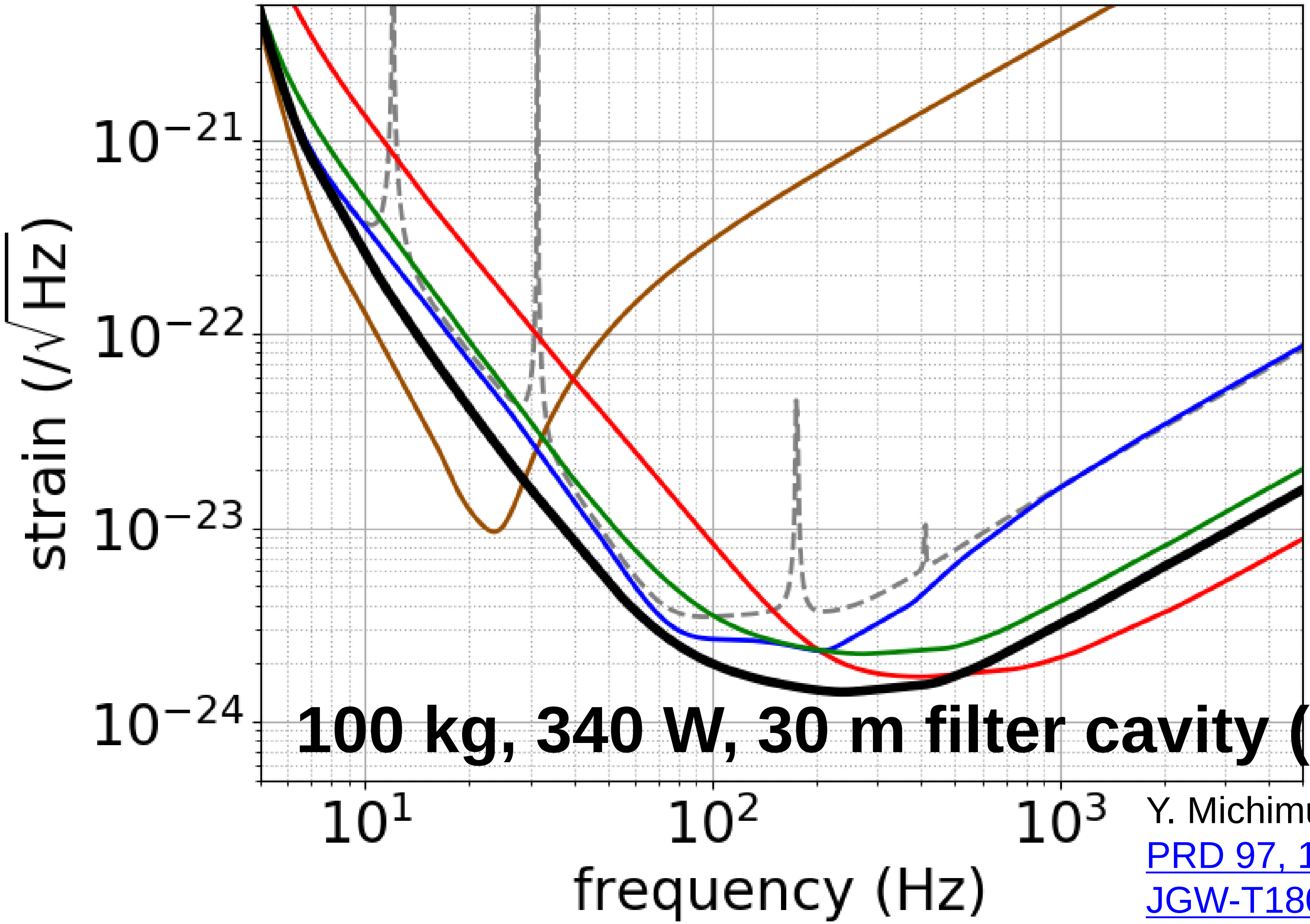
- Based on technical feasibility, facility and budget constraints



Y. Michimura+, PRD 97, 122003 (2018); JGW-T1809537

Possible Longer Term Upgrade

- Reaches BNS range of 300 Mpc by combining technologies (twofold improvement)



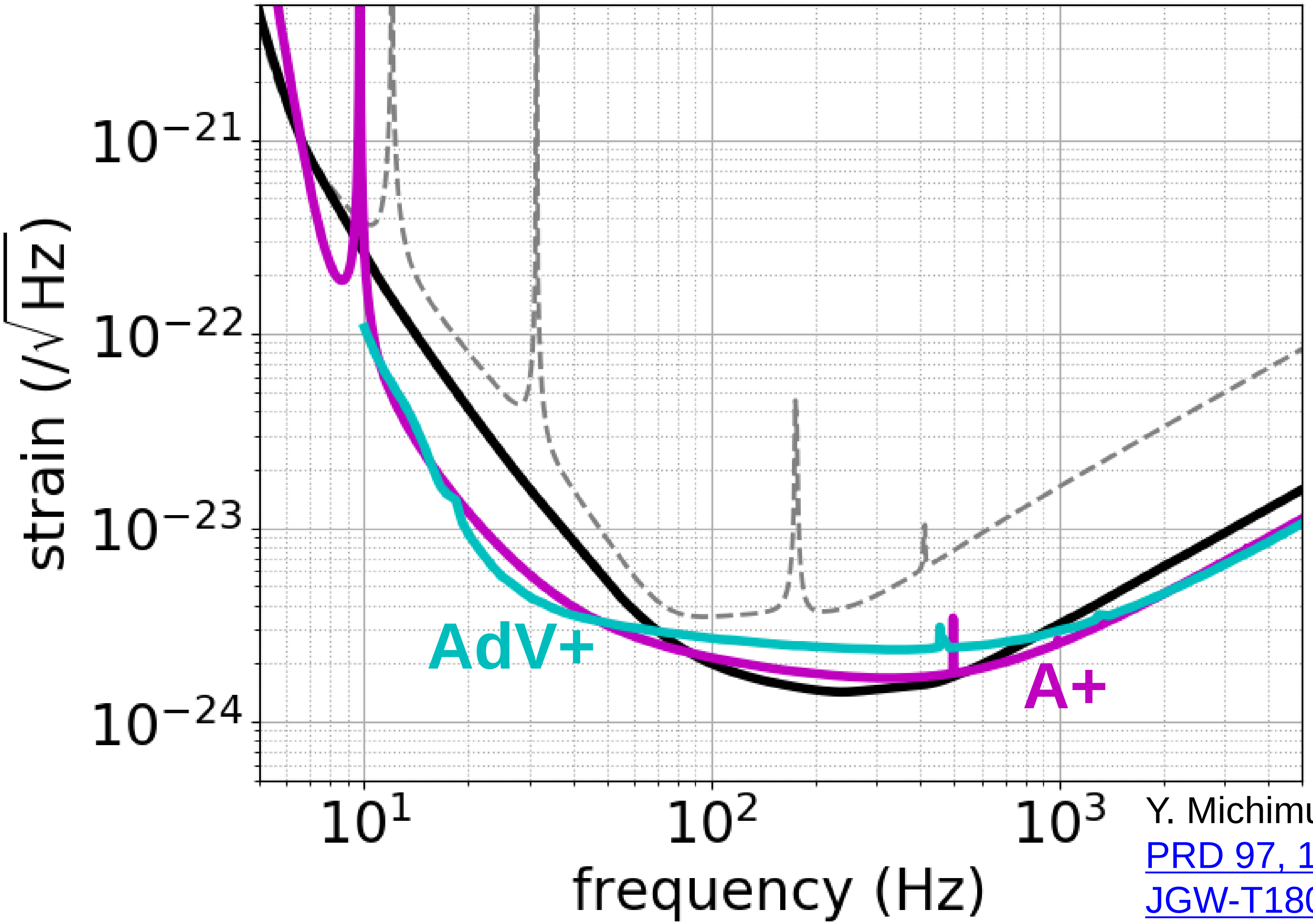
100 kg, 340 W, 30 m filter cavity (5 dB SQZ)

NOTE:
No coating improvements assumed

Y. Michimura+,
[PRD 97, 122003 (2018)](); [JGW-T1809537]()

Possible Longer Term Upgrade

- Comparable to A+ and AdV+



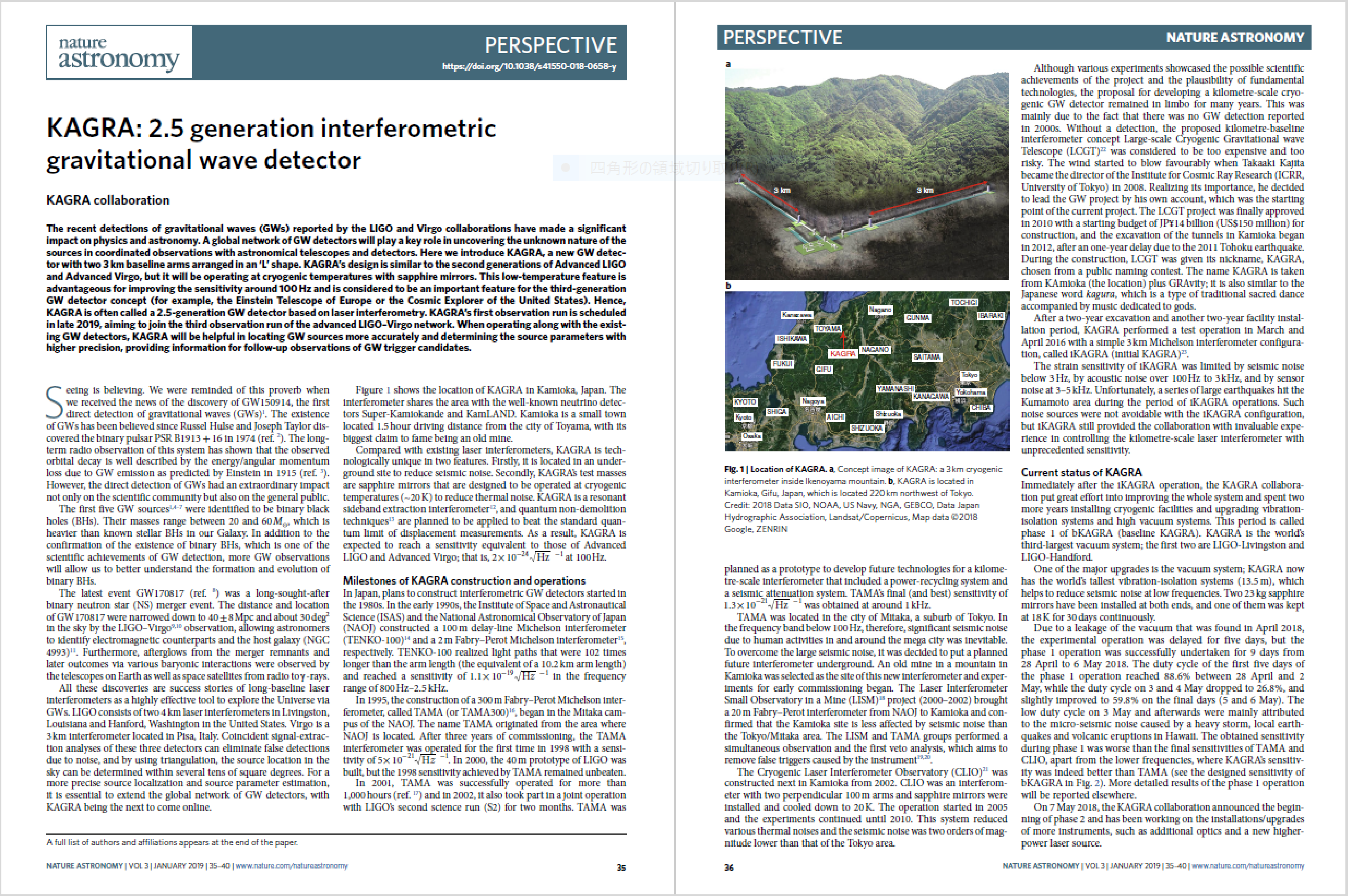
Y. Michimura+,
[PRD 97, 122003 (2018)](https://doi.org/10.1103/PhysRevD.97.122003);
JGW-T1809537

Summary

- KAGRA is an underground cryogenic GW detector
- First cryogenic test operation done in May 2018
- Almost all the installation works completed
- X-arm commissioning successfully done
- So far so good for O3

- KAGRA upgrade study formally started
- Different approach for the upgrade might be required for KAGRA

KAGRA collaboration, Nature Astronomy **3**, 35 (2019)



nature astronomy
PERSPECTIVE
https://doi.org/10.1038/s41550-018-0658-y

KAGRA: 2.5 generation interferometric gravitational wave detector

KAGRA collaboration

The recent detections of gravitational waves (GWs) reported by the LIGO and Virgo collaborations have made a significant impact on physics and astronomy. A global network of GW detectors will play a key role in uncovering the unknown nature of the sources in coordinated observations with astronomical telescopes and detectors. Here we introduce KAGRA, a new GW detector with two 3 km baseline arms arranged in an 'L' shape. KAGRA's design is similar to the second generations of Advanced LIGO and Advanced Virgo, but it will be operating at cryogenic temperatures with sapphire mirrors. This low-temperature feature is advantageous for improving the sensitivity around 100 Hz and is considered to be an important feature for the third-generation GW detector concept (for example, the Einstein Telescope of Europe or the Cosmic Explorer of the United States). Hence, KAGRA is often called a 2.5-generation GW detector based on laser interferometry. KAGRA's first observation run is scheduled in late 2019, aiming to join the third observation run of the advanced LIGO–Virgo network. When operating along with the existing GW detectors, KAGRA will be helpful in locating GW sources more accurately and determining the source parameters with higher precision, providing information for follow-up observations of GW trigger candidates.

Seeing is believing. We were reminded of this proverb when we received the news of the discovery of GW150914, the first direct detection of gravitational waves (GWs)[1]. The existence of GWs has been believed since Russel Hulse and Joseph Taylor discovered the binary pulsar PSR B1913 + 16 in 1974 (ref. [2]). The long-term radio observation of this system has shown that the observed orbital decay is well described by the energy/angular momentum loss due to GW emission as predicted by Einstein in 1915 (ref. [3]). However, the direct detection of GWs had an extraordinary impact not only on the scientific community but also on the general public.

The first five GW sources[1,4–7] were identified to be binary black holes (BHs). Their masses range between 20 and $60\,M_{\odot}$, which is heavier than known stellar BHs in our Galaxy. In addition to the confirmation of the existence of binary BHs, which is one of the scientific achievements of GW detection, more GW observations will allow us to better understand the formation and evolution of binary BHs.

The latest event GW170817 (ref. [8]) was a long-sought-after binary neutron star (NS) merger event. The distance and location of GW170817 were narrowed down to 40 ± 8 Mpc and about 30 deg^2 in the sky by the LIGO–Virgo[9,10] observation, allowing astronomers to identify electromagnetic counterparts and the host galaxy (NGC 4993)[11]. Furthermore, afterglows from the merger remnants and later outcomes via various baryonic interactions were observed by the telescopes on Earth as well as space satellites from radio to γ-rays.

All these discoveries are success stories of long-baseline laser interferometers as a highly effective tool to explore the Universe via GWs. LIGO consists of two 4 km laser interferometers in Livingston, Louisiana and Hanford, Washington in the United States. Virgo is a 3 km interferometer located in Pisa, Italy. Coincident signal-extraction analyses of these three detectors can eliminate false detections due to noise, and by using triangulation, the source location in the sky can be determined within several tens of square degrees. For a more precise source localization and source parameter estimation, it is essential to extend the global network of GW detectors, with KAGRA being the next to come online.

Figure 1 shows the location of KAGRA in Kamioka, Japan. The interferometer shares the area with the well-known neutrino detectors Super-Kamiokande and KamLAND. Kamioka is a small town located 1.5 hour driving distance from the city of Toyama, with its biggest claim to fame being an old mine.

Compared with existing laser interferometers, KAGRA is technologically unique in two features. Firstly, it is located in an underground site to reduce seismic noise. Secondly, KAGRA's test masses are sapphire mirrors that are designed to be operated at cryogenic temperatures (~20 K) to reduce thermal noise. KAGRA is a resonant sideband extraction interferometer[12], and quantum non-demolition techniques[13] are planned to be applied to beat the standard quantum limit of displacement measurements. As a result, KAGRA is expected to reach a sensitivity equivalent to those of Advanced LIGO and Advanced Virgo; that is, $2\times10^{-24}\sqrt{\mathrm{Hz}}^{\,-1}$ at 100 Hz.

Milestones of KAGRA construction and operations

In Japan, plans to construct interferometric GW detectors started in the 1980s. In the early 1990s, the Institute of Space and Astronautical Science (ISAS) and the National Astronomical Observatory of Japan (NAOJ) constructed a 100 m delay-line Michelson interferometer (TENKO-100)[14] and a 2 m Fabry–Perot Michelson interferometer[15], respectively. TENKO-100 realized light paths that were 102 times longer than the arm length (the equivalent of a 10.2 km arm length) and reached a sensitivity of $1.1\times10^{-19}\sqrt{\mathrm{Hz}}^{\,-1}$ in the frequency range of 800 Hz–2.5 kHz.

In 1995, the construction of a 300 m Fabry–Perot Michelson interferometer, called TAMA (or TAMA300)[16], began in the Mitaka campus of the NAOJ. The name TAMA originated from the area where NAOJ is located. After three years of commissioning, the TAMA interferometer was operated for the first time in 1998 with a sensitivity of $5\times10^{-21}\sqrt{\mathrm{Hz}}^{\,-1}$. In 2000, the 40 m prototype of LIGO was built, but the 1998 sensitivity achieved by TAMA remained unbeaten.

In 2001, TAMA was successfully operated for more than 1,000 hours (ref. [17]) and in 2002, it also took part in a joint operation with LIGO's second science run (S2) for two months. TAMA was planned as a prototype to develop future technologies for a kilometre-scale interferometer that included a power-recycling system and a seismic attenuation system. TAMA's final (and best) sensitivity of $1.3\times10^{-21}\sqrt{\mathrm{Hz}}^{\,-1}$ was obtained at around 1 kHz.

A full list of authors and affiliations appears at the end of the paper.

Fig. 1 | Location of KAGRA. a, Concept image of KAGRA: a 3 km cryogenic interferometer inside Ikenoyama mountain. **b**, KAGRA is located in Kamioka, Gifu, Japan, which is located 220 km northwest of Tokyo. Credit: 2018 Data SIO, NOAA, US Navy, NGA, GEBCO, Data Japan Hydrographic Association, Landsat/Copernicus, Map data ©2018 Google, ZENRIN

TAMA was located in the city of Mitaka, a suburb of Tokyo. In the frequency band below 100 Hz, therefore, significant seismic noise due to human activities in and around the mega city was inevitable. To overcome the large seismic noise, it was decided to put a planned future interferometer underground. An old mine in a mountain in Kamioka was selected as the site of this new interferometer and experiments for early commissioning began. The Laser Interferometer Small Observatory in a Mine (LISM)[18] project (2000–2002) brought a 20 m Fabry–Perot interferometer from NAOJ to Kamioka and confirmed that the Kamioka site is less affected by seismic noise than the Tokyo/Mitaka area. The LISM and TAMA groups performed a simultaneous observation and the first veto analysis, which aims to remove false triggers caused by the instrument[19,20].

The Cryogenic Laser Interferometer Observatory (CLIO)[21] was constructed next in Kamioka from 2002. CLIO was an interferometer with two perpendicular 100 m arms and sapphire mirrors were installed and cooled down to 20 K. The operation started in 2005 and the experiments continued until 2010. This system reduced various thermal noises and the seismic noise was two orders of magnitude lower than that of the Tokyo area.

Although various experiments showcased the possible scientific achievements of the project and the plausibility of fundamental technologies, the proposal for developing a kilometre-scale cryogenic GW detector remained in limbo for many years. This was mainly due to the fact that there was no GW detection reported in 2000s. Without a detection, the proposed kilometre-baseline interferometer concept Large-scale Cryogenic Gravitational wave Telescope (LCGT)[22] was considered to be too expensive and too risky. The wind started to blow favourably when Takaaki Kajita became the director of the Institute for Cosmic Ray Research (ICRR, University of Tokyo) in 2008. Realizing its importance, he decided to lead the GW project by his own account, which was the starting point of the current project. The LCGT project was finally approved in 2010 with a starting budget of JP¥14 billion (US$150 million) for construction, and the excavation of the tunnels in Kamioka began in 2012, after an one-year delay due to the 2011 Tohoku earthquake. During the construction, LCGT was given its nickname, KAGRA, chosen from a public naming contest. The name KAGRA is taken from KAmioka (the location) plus GRAvity; it is also similar to the Japanese word *kagura*, which is a type of traditional sacred dance accompanied by music dedicated to gods.

After a two-year excavation and another two-year facility installation period, KAGRA performed a test operation in March and April 2016 with a simple 3 km Michelson interferometer configuration, called iKAGRA (initial KAGRA)[23].

The strain sensitivity of iKAGRA was limited by seismic noise below 3 Hz, by acoustic noise over 100 Hz to 3 kHz, and by sensor noise at 3–5 kHz. Unfortunately, a series of large earthquakes hit the Kumamoto area during the period of iKAGRA operations. Such noise sources were not avoidable with the iKAGRA configuration, but iKAGRA still provided the collaboration with invaluable experience in controlling the kilometre-scale laser interferometer with unprecedented sensitivity.

Current status of KAGRA

Immediately after the iKAGRA operation, the KAGRA collaboration put great effort into improving the whole system and spent two more years installing cryogenic facilities and upgrading vibration-isolation systems and high vacuum systems. This period is called phase 1 of bKAGRA (baseline KAGRA). KAGRA is the world's third-largest vacuum system; the first two are LIGO-Livingston and LIGO-Handford.

One of the major upgrades is the vacuum system; KAGRA now has the world's tallest vibration-isolation systems (13.5 m), which helps to reduce seismic noise at low frequencies. Two 23 kg sapphire mirrors have been installed at both ends, and one of them was kept at 18 K for 30 days continuously.

Due to a leakage of the vacuum that was found in April 2018, the experimental operation was delayed for five days, but the phase 1 operation was successfully undertaken for 9 days from 28 April to 6 May 2018. The duty cycle of the first five days of the phase 1 operation reached 88.6% between 28 April and 2 May, while the duty cycle on 3 and 4 May dropped to 26.8%, and slightly improved to 59.8% on the final days (5 and 6 May). The low duty cycle on 3 May and afterwards were mainly attributed to the micro-seismic noise caused by a heavy storm, local earthquakes and volcanic eruptions in Hawaii. The obtained sensitivity during phase 1 was worse than the final sensitivities of TAMA and CLIO, apart from the lower frequencies, where KAGRA's sensitivity was indeed better than TAMA (see the designed sensitivity of bKAGRA in Fig. 2). More detailed results of the phase 1 operation will be reported elsewhere.

On 7 May 2018, the KAGRA collaboration announced the beginning of phase 2 and has been working on the installations/upgrades of more instruments, such as additional optics and a new higher-power laser source.

KAGRA collaboration, Nature Astronomy **3**, 35 (2019)

Supplementary Slides

2G/2G+ Parameter Comparison

	KAGRA	**AdVirgo**	**aLIGO**	**A+**	**Voyager**
Arm length [km]	3	3	4	4	4
Mirror mass [kg]	23	42	40	80	200
Mirror material	Sapphire	Silica	Silica	Silica	Silicon
Mirror temp [K]	22	295	295	295	123
Sus fiber	35cm Sap.	70cm SiO_2	60cm SiO_2	60cm SiO_2	60cm Si
Fiber type	Fiber	Fiber	Fiber	Fiber	Ribbon
Input power [W]	67	125	125	125	140
Arm power [kW]	340	700	710	1150	3000
Wavelength [nm]	1064	1064	1064	1064	2000
Beam size [cm]	3.5 / 3.5	4.9 / 5.8	5.5 / 6.2	5.5 / 6.2	5.8 / 6.2
SQZ factor	0	0	0	6	8
F. C. length [m]	none	none	none	16	300

LIGO parameters from LIGO-T1600119, AdVirgo parameters from JPCS 610, 01201 (2015)

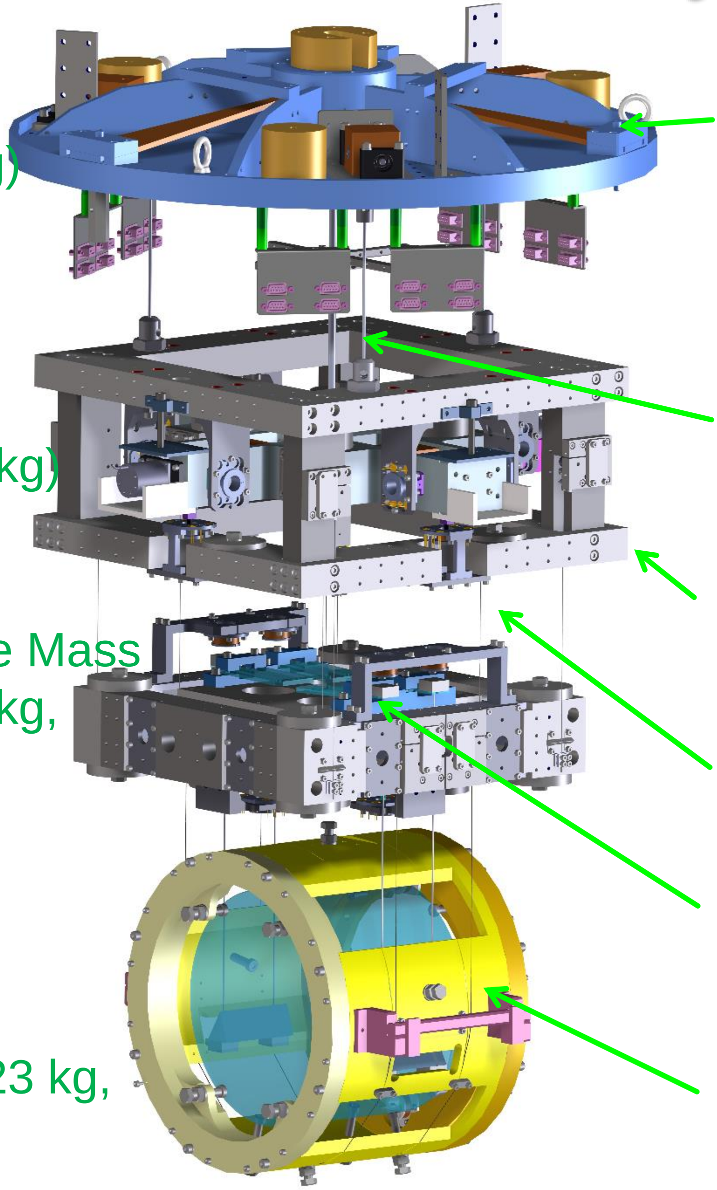
KAGRA Detailed Parameters

K. Komori *et al.*, JGW-T1707038

- **Optical parameters**
  - Mirror transmission: 0.4 % for ITM, 10 % for PRM, 15.36 % for SRM
  - Power at BS: 674 W
  - Detune phase: 3.5 deg (DRSE case)
  - Homodyne phase: 135.1 deg (DRSE case)
- **Sapphire mirror parameters**
  - TM size: 220 mm dia., 150 mm thick
  - TM mass: 22.8 kg
  - TM temperature: 22 K
  - Beam radius at ITM: 3.5 cm
  - Beam radius at ETM: 3.5 cm
  - Q of mirror substrate: 1e8
  - Coating: tantala/silica
  - Coating loss angle: 3e-4 for silica, 5e-4 for tantala
  - Number of layers: 22 for ITM, 40 for ETM
  - Coating absorption: 0.5 ppm
  - Substrate absorption: 50 ppm/cm
- **Suspension parameters**
  - TM-IM fiber: 35 cm long, 1.6 mm dia.
  - IM temperature: 16 K
  - Heat extraction: 5800 W/m/K at 20 K
  - Loss angle: 5e-6/2e-7/7e-7 for CuBe fiber/sapphire fiber/sapphire blade
- **Inspiral range calculation**
  - SNR=8, fmin=10 Hz, sky average constant 0.442478
- Seismic noise curve includes vertical coupling, vibration from heatlinks and Newtonian noise from surface and bulk

KAGRA Cryopayload

Figure by T. Ushiba and A. Hagiwara



Platform
(SUS, 65 kg)

Marionette
(SUS, 22.5 kg)

Intermediate Mass
(SUS, 20.1 kg,
16 K)

Test Mass
(Sapphire, 23 kg,
22 K)

3 CuBe blade springs

MN suspended by 1 Maraging steel fiber
(35 cm long, 2-7mm dia.)
MRM suspended by 3 CuBe fibers

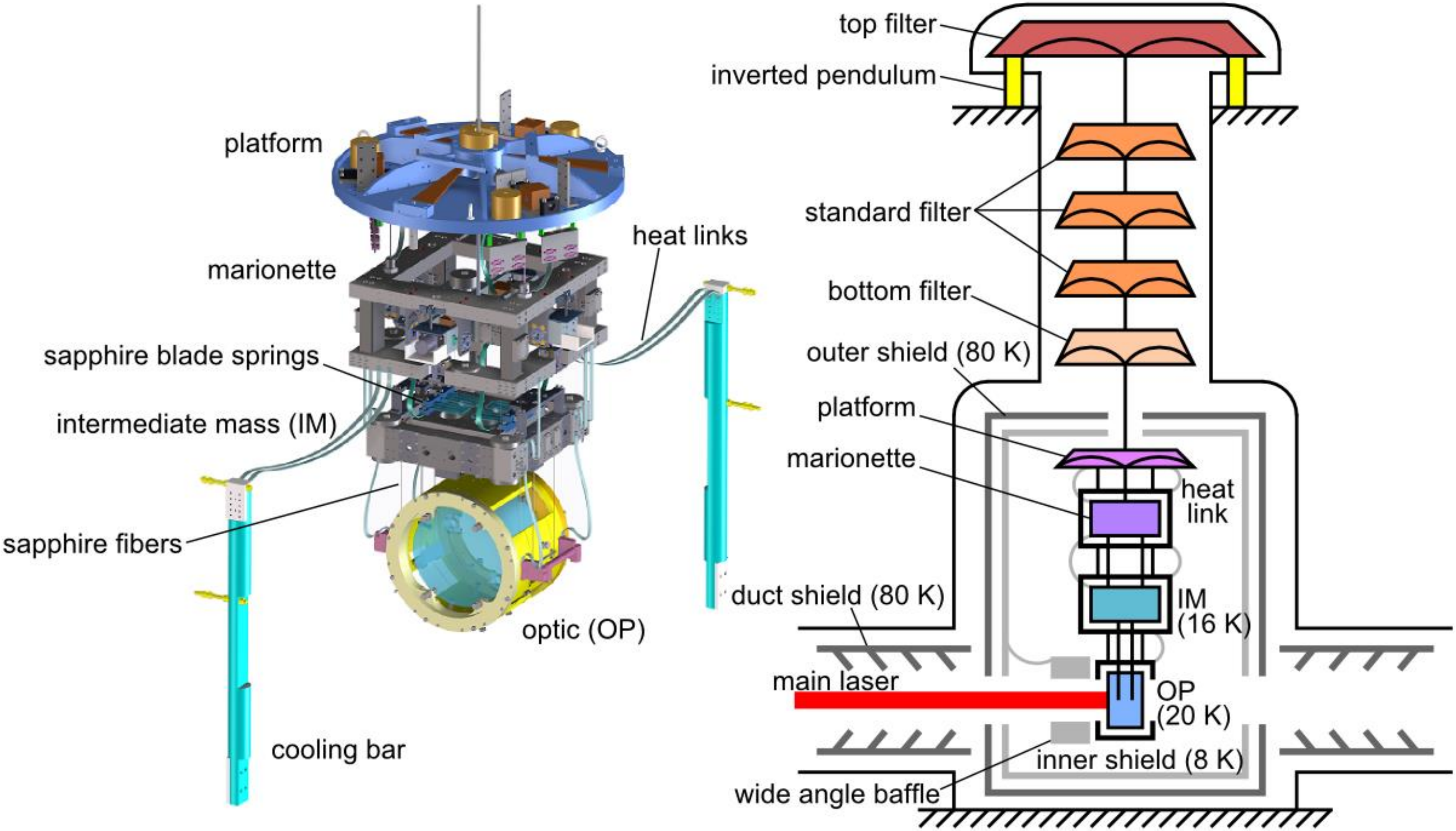
Heat link attached to MN

IM suspended by 4 CuBe fibers
(24 cm long, 0.6 mm dia)
IRM suspended by 4 CuBe fibers

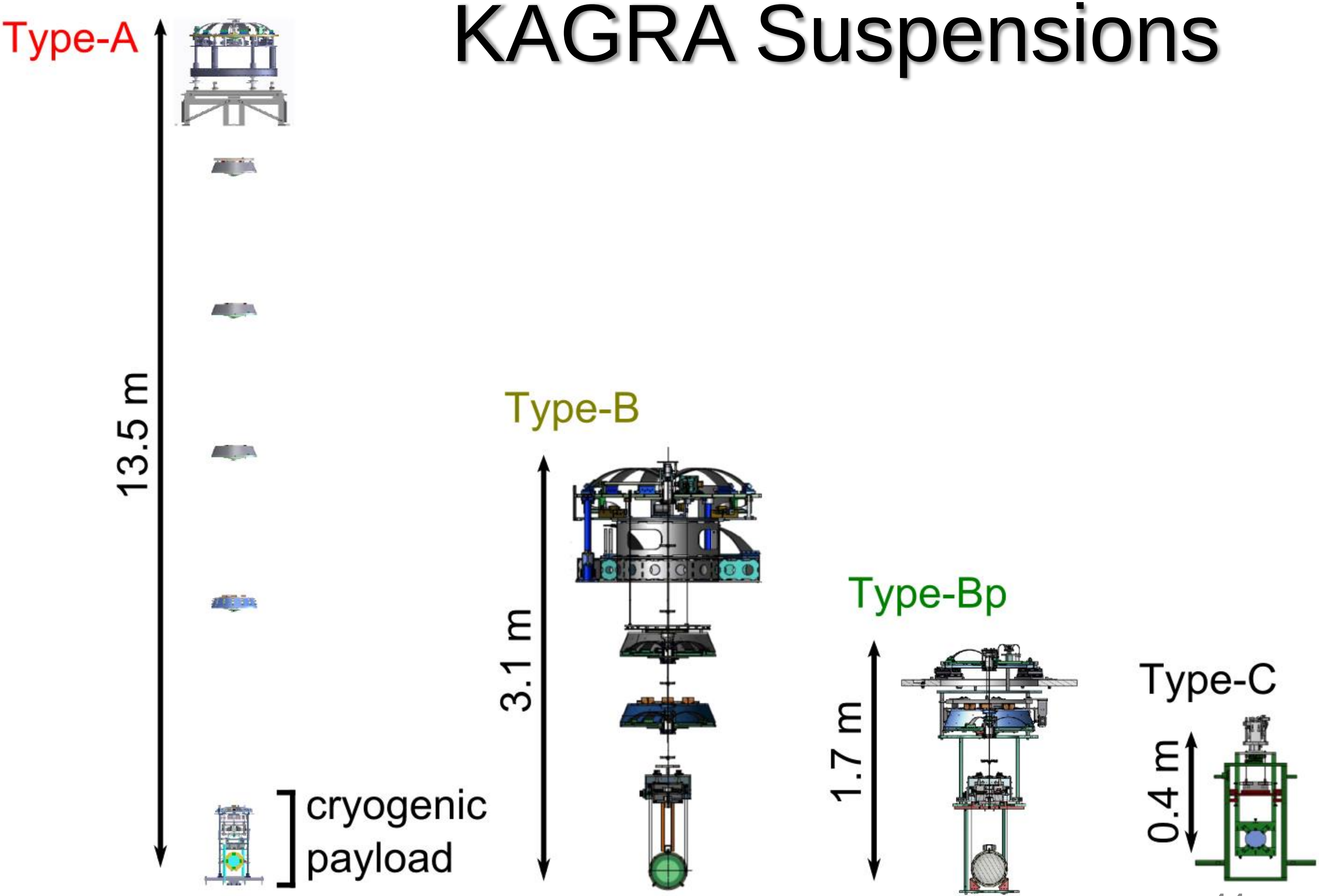
4 sapphire blades

TM suspended by 4 sapphire fibers
(35 cm long, 1.6 mm dia.)
RM suspended by 4 CuBe fibers

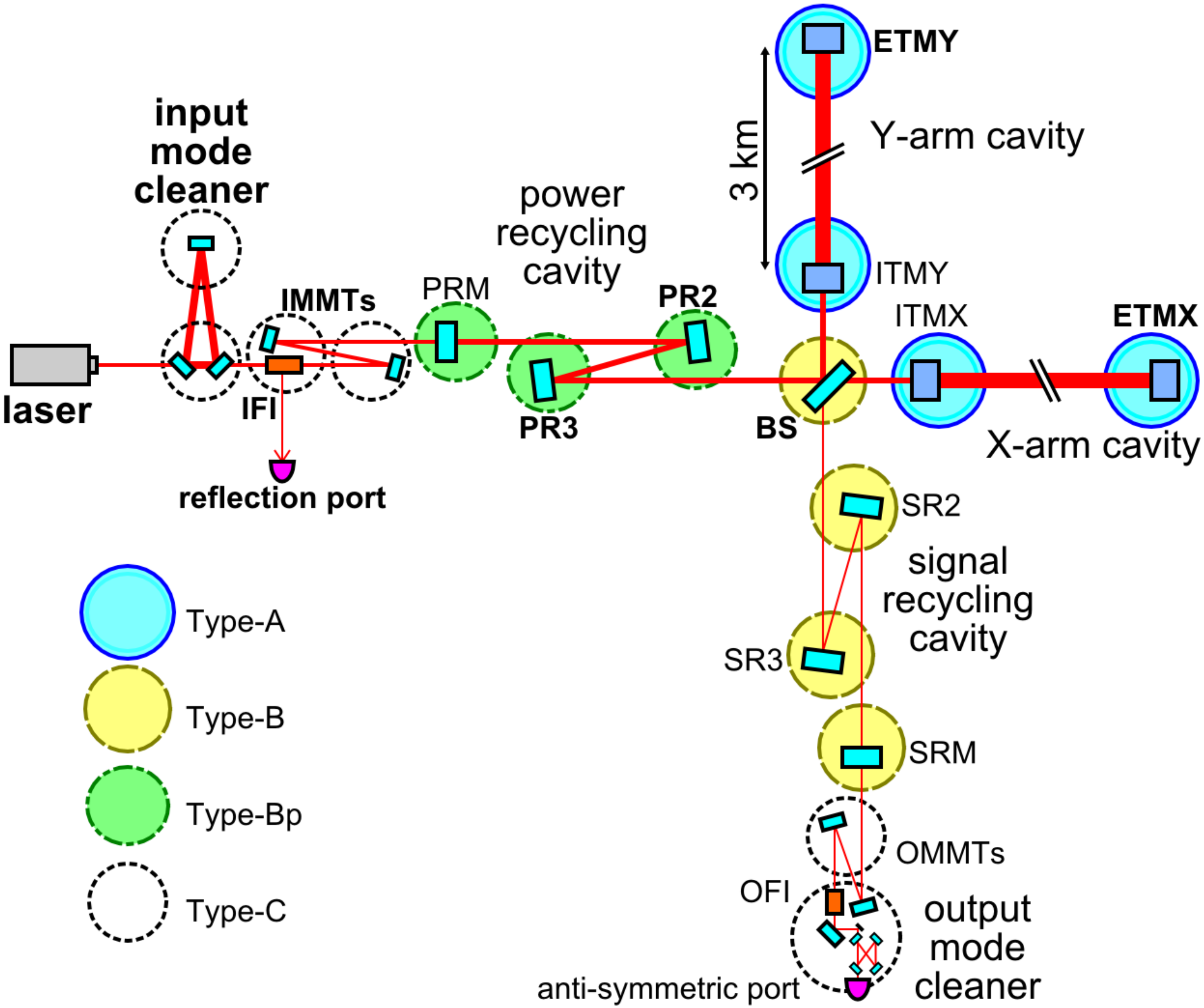
KAGRA Cryostat Schematic



KAGRA Suspensions



KAGRA Interferometer



KAGRA Data Tree

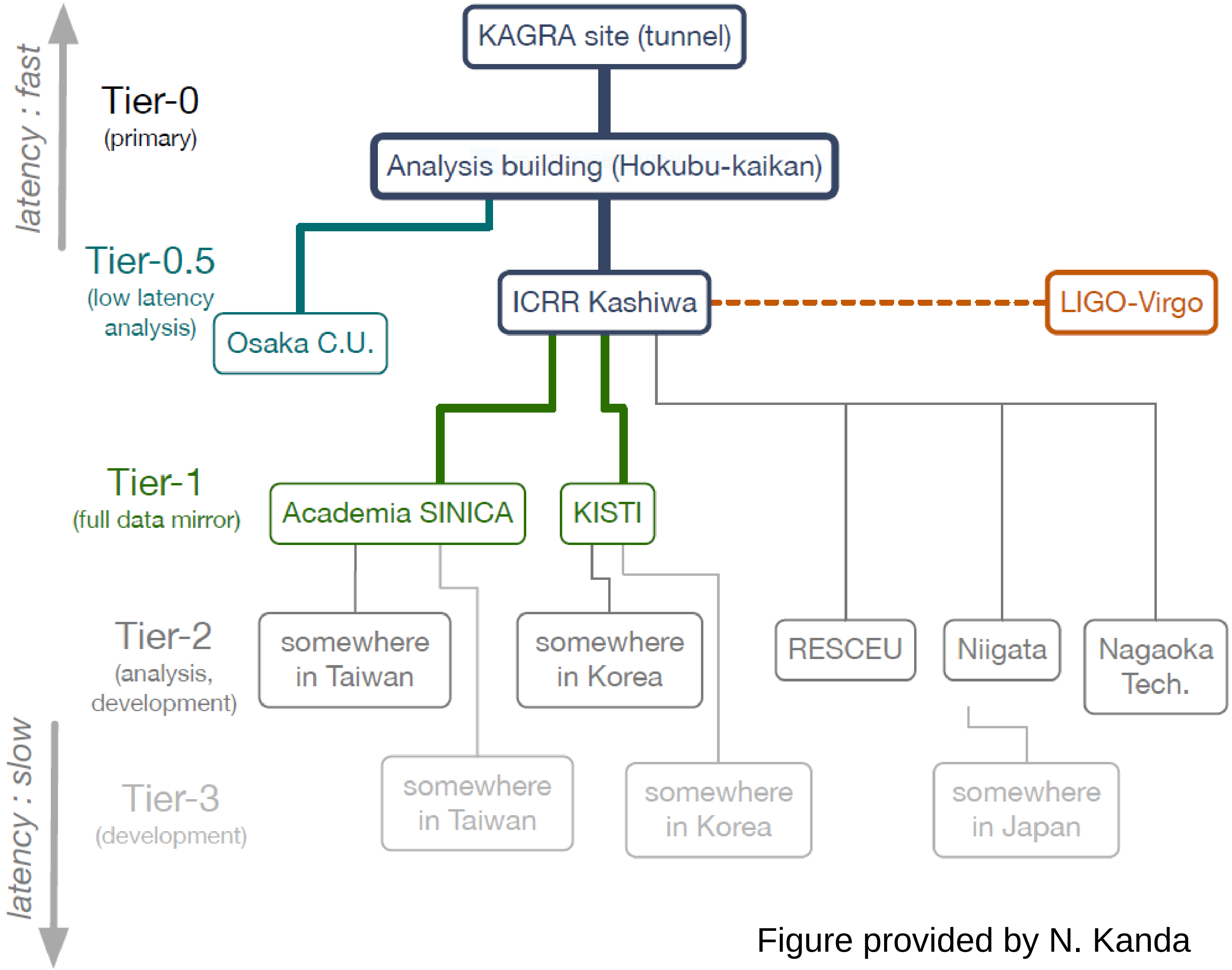
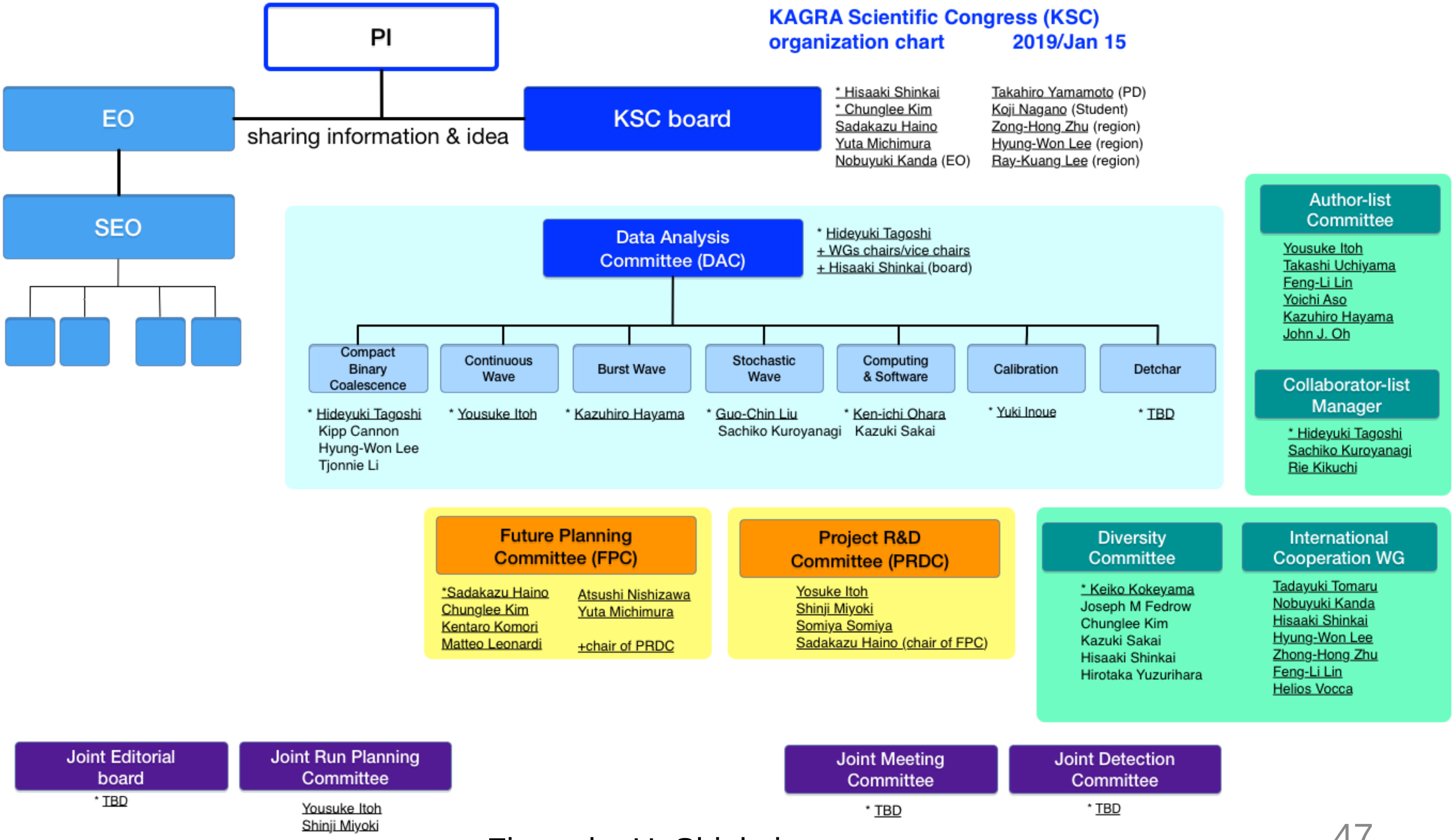


Figure provided by N. Kanda

KAGRA Scientific Congress



KAGRA Scientific Congress (KSC)
organization chart 2019/Jan 15

PI

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SEO

sharing information & idea

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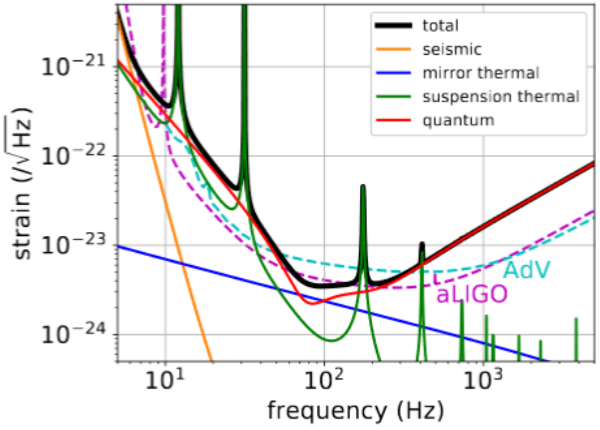
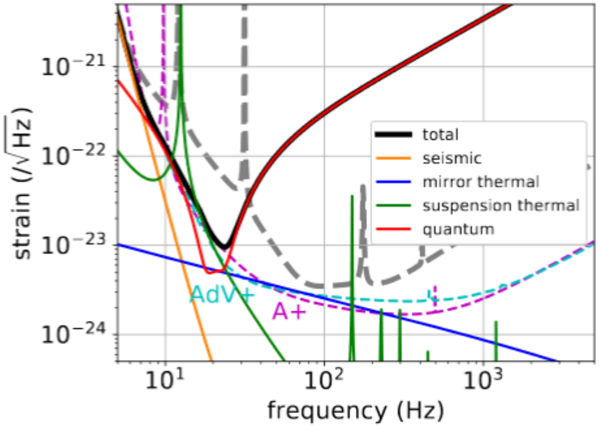
Figure by H. Shinkai

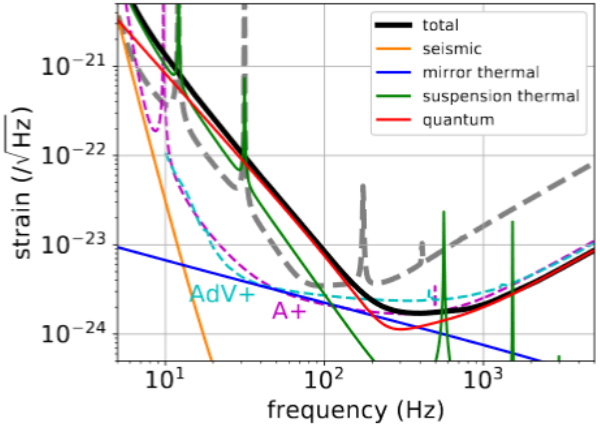
Possible KAGRA Upgrade Plans



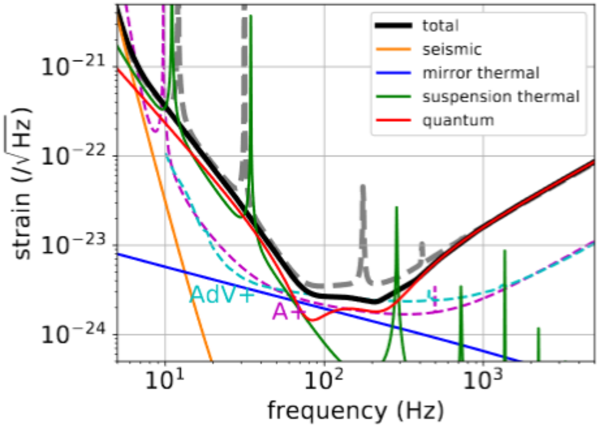
(a) bKAGRA



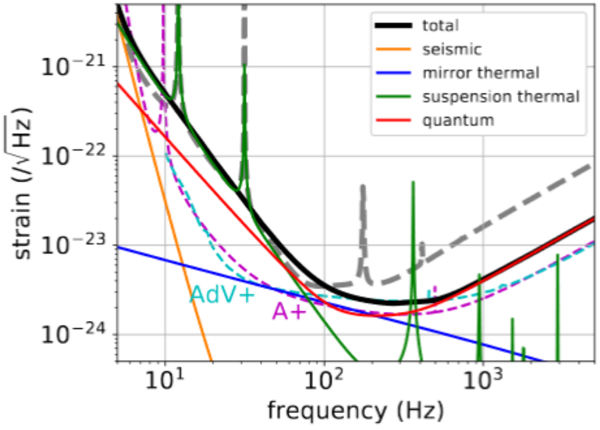
(b) LF



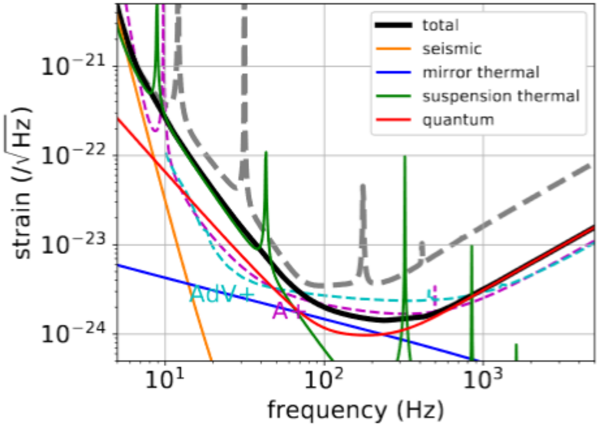
(c) HF



(d) 40kg



(e) FDSQZ

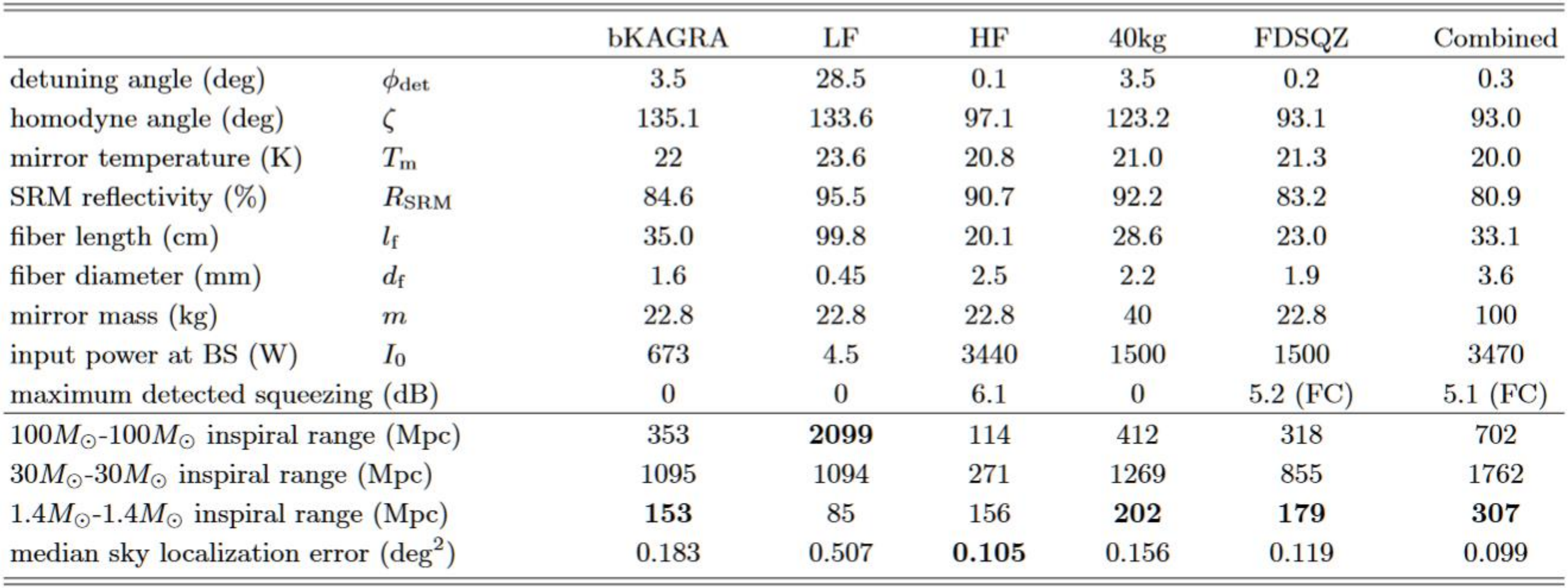


(f) Combined

Y. Michimura+,
PRD 97, 122003 (2018);
JGW-T1809537

Possible KAGRA Upgrade Plans

Y. Michimura+,
PRD 97, 122003 (2018);
JGW-T1809537



		bKAGRA	LF	HF	40kg	FDSQZ	Combined
detuning angle (deg)	ϕ_{det}	3.5	28.5	0.1	3.5	0.2	0.3
homodyne angle (deg)	ζ	135.1	133.6	97.1	123.2	93.1	93.0
mirror temperature (K)	T_{m}	22	23.6	20.8	21.0	21.3	20.0
SRM reflectivity (%)	R_{SRM}	84.6	95.5	90.7	92.2	83.2	80.9
fiber length (cm)	l_{f}	35.0	99.8	20.1	28.6	23.0	33.1
fiber diameter (mm)	d_{f}	1.6	0.45	2.5	2.2	1.9	3.6
mirror mass (kg)	m	22.8	22.8	22.8	40	22.8	100
input power at BS (W)	I_0	673	4.5	3440	1500	1500	3470
maximum detected squeezing (dB)		0	0	6.1	0	5.2 (FC)	5.1 (FC)
$100M_\odot$-$100M_\odot$ inspiral range (Mpc)		353	**2099**	114	412	318	702
$30M_\odot$-$30M_\odot$ inspiral range (Mpc)		1095	1094	271	1269	855	1762
$1.4M_\odot$-$1.4M_\odot$ inspiral range (Mpc)		**153**	85	156	**202**	**179**	**307**
median sky localization error (deg^2)		0.183	0.507	**0.105**	0.156	0.119	0.099