International Conference on the Physics of Two Infinities

KAGRA: Large Cryogenic Gravitational Wave Telescope

Masaki Ando (Univ. of Tokyo)

On behalf of the KAGRA collaboration

GW-Related Presentations

* Mon, March 27
 - Takahiro Tanaka: What can we learn from gravitational waves ?
 - Patrice Verdier: The Einstein Telescope project
 - Michael Page: Status of squeezing and quantum enhancement for gravitational wave detection at NAOJ

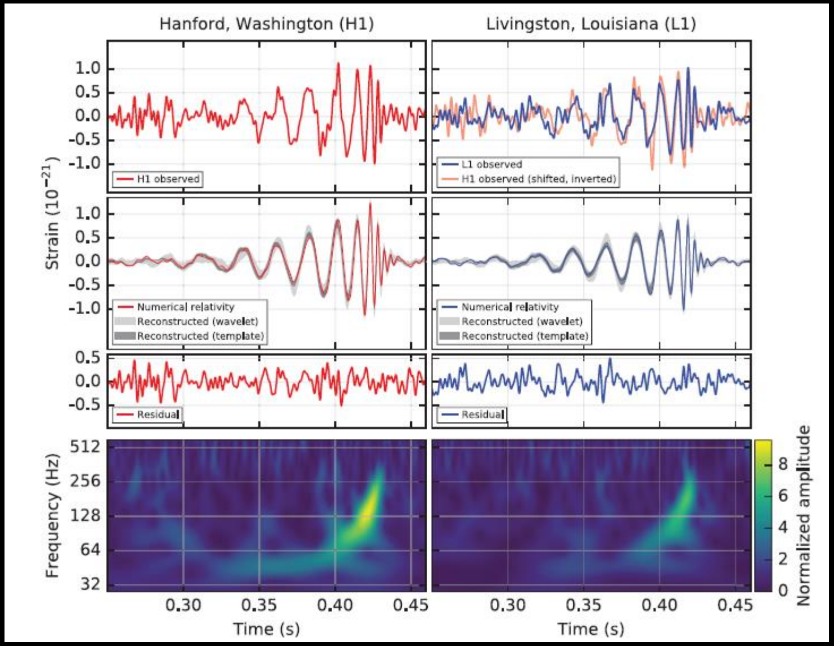
* Tue, March 28
 - Jonathan Gair: Machine learning for gravitational wave inference
 - Kipp Cannon: LIGO-Virgo-KAGRA Observational Results and Outlook

* Wed, March 29
 - Several presentations in the parallel session

* Thu, March 30
 - Masaki Ando: KAGRA: Large Cryogenic Gravitational Wave Antenna
 - Fabio Garufi: Advanced Virgo+ Status and Perspectives

First Detection of GW

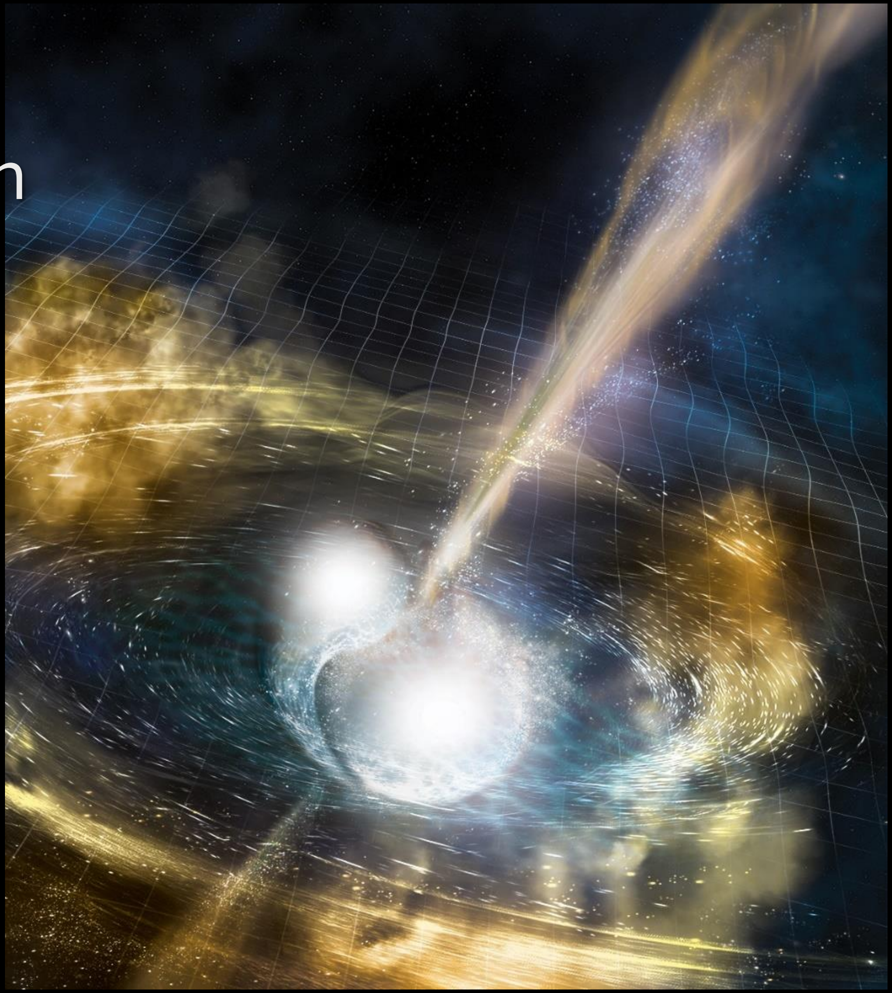
- On Feb. 11th, 2016, LIGO announced first detection of gravitational wave. The signal was from inspiral and merger of binary black hole at 410Mpc distance.
  ⇨ Opens a new field of 'GW astronomy'.



Courtesy Caltech/MIT/LIGO Laboratory

Merger of Binary Neutron Stars

- On Oct.16th, 2017, LIGO-VIRGO collaboration announced the first detection of gravitational-wave signal from merger of binary neutron stars



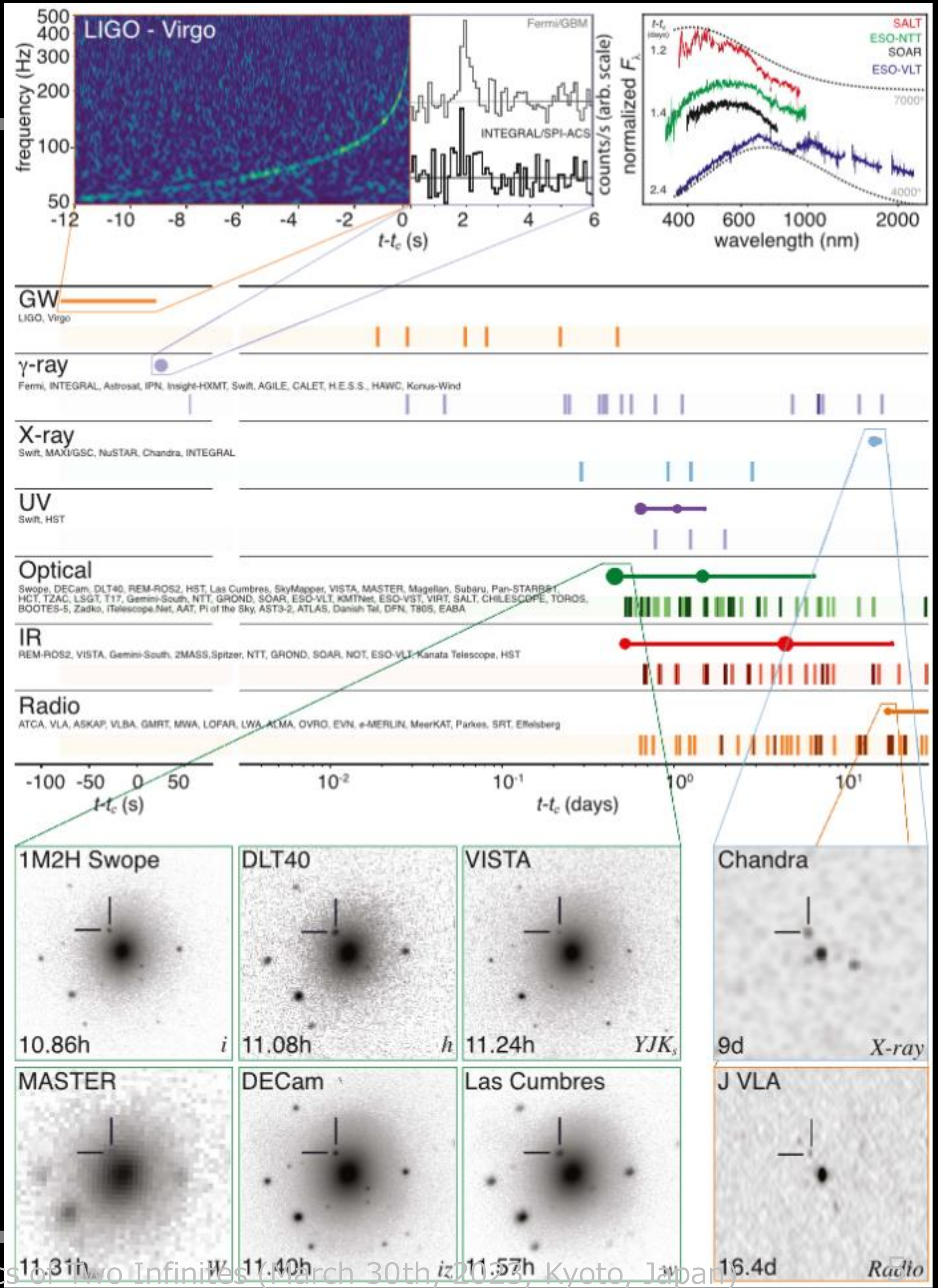
Courtesy Caltech/MIT/LIGO Laboratory

- The signal was detected on August 17th, 2017.
  → Named GW170817.
- Source Localization ~30deg^2

- EM counterpart was observed for the first time in GW170817.

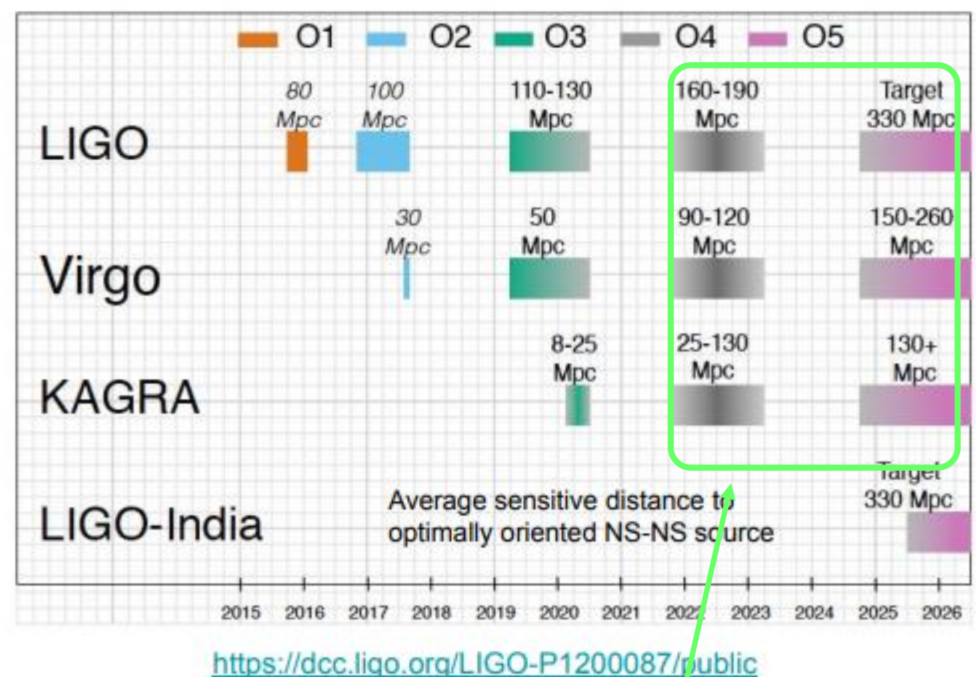
⇩

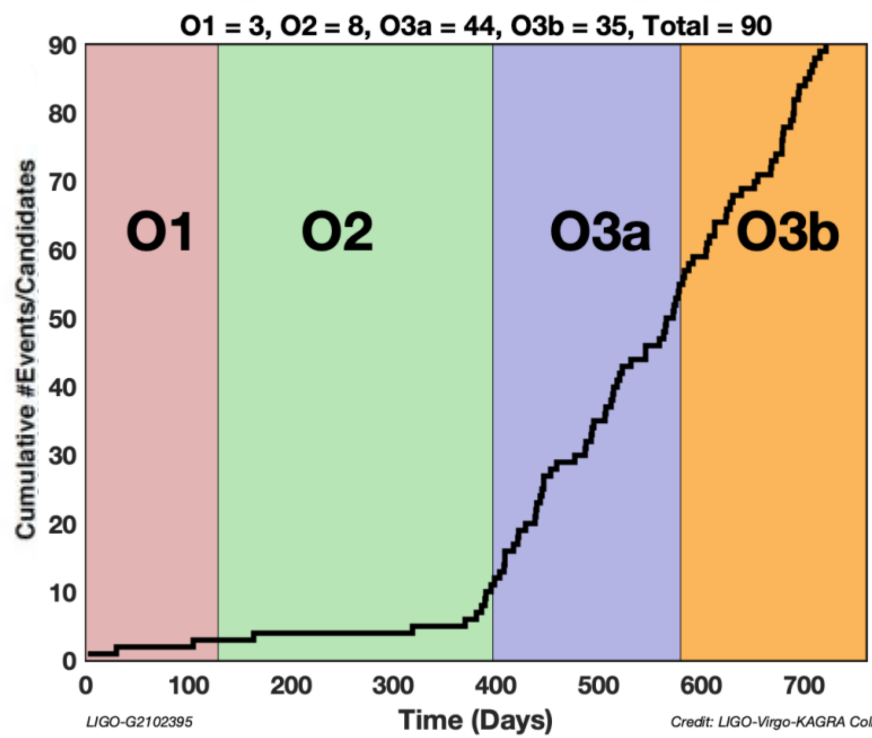
- New knowledge
  - * Origin of SGRB.
  - * Origin of heavy elements in the universe.
  - * EoS of neutron star
  - * Fundamental physics and cosmology: speed of GW, Hubble's constant, ⋯.



ApJL 848 L12 (2017)

Observation Run and Detections

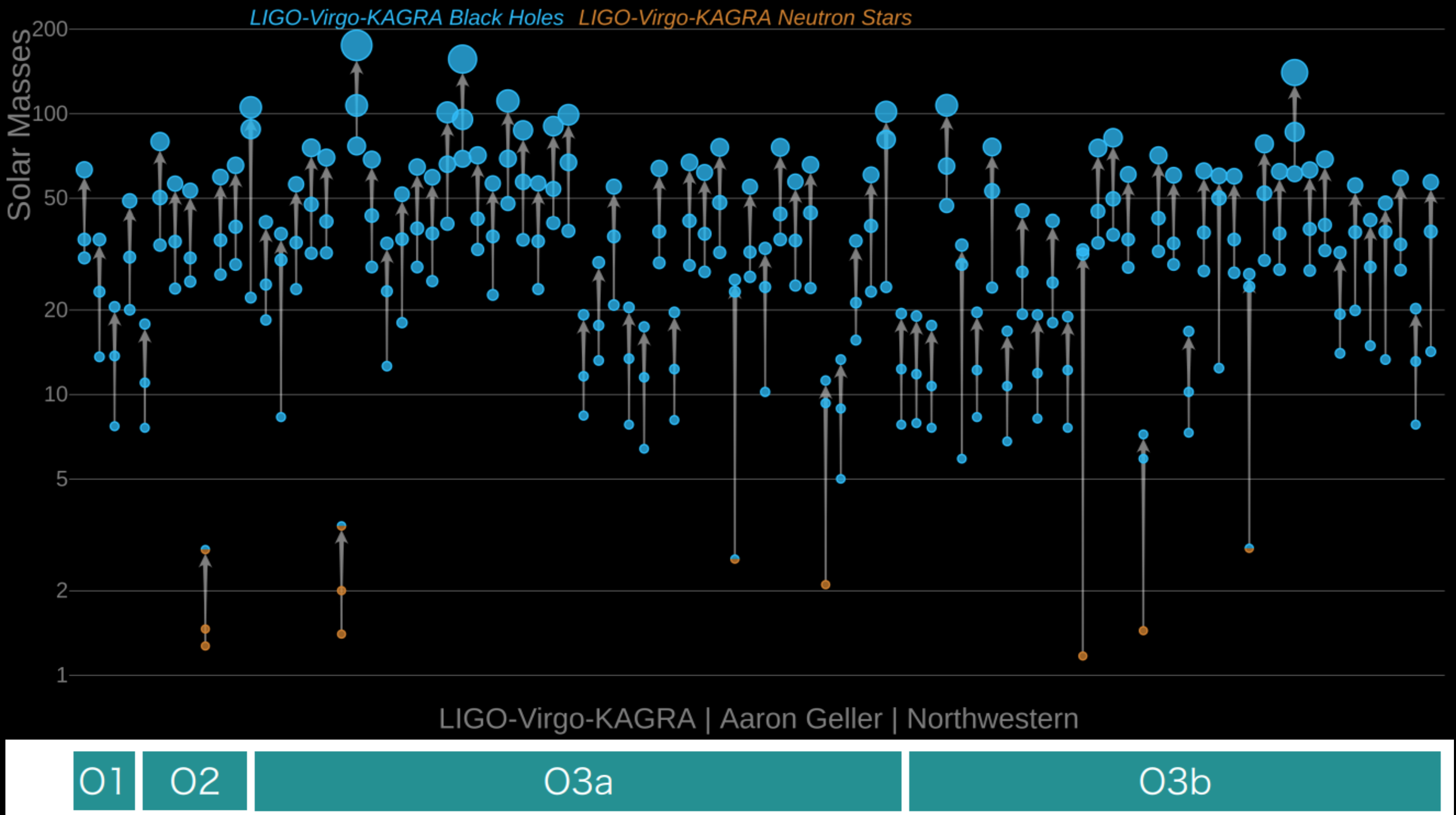




Being updated: O4 from March 2023
O5 is starting correspondingly later

[LIGO G2001426-v2 (2020)]

Detected Compact Binary Coalescences



https://media.ligo.northwestern.edu/gallery/mass-plot

After the First Detections …

- The first GW (and EM counter part) detections demonstrated new possibilities by GW astronomy, and also showed new mysteries, such as the origin of heavier mass BBHs, etc.

⇩

- Network of 2nd-gen. GW antennae (aLIGO, AdVIRGO, KAGRA, LIGO-India) is being formed.
- Two ways after that for Astronomy and Cosmology:
  - 3rd–gen. ground-based GW antennae (ET, CE).
  - Space GW antennae (LISA, B-DECIGO, ASTROD,…).

Outline

- Overview of KAGRA
- Observation Runs
- Activities for O4
- Summary

KAGRA (かぐら)

- Ground-based
  GW antenna in Japan-

Artwork Image of KAGRA

KAGRA

KAGRA（かぐら)

Large-scale Cryogenic Gravitational-wave Telescope

2nd generation GW detector in Japan

Artwork Image of KAGRA

Large-scale Detector
- Baseline length: 3km
- High-power Interferometer

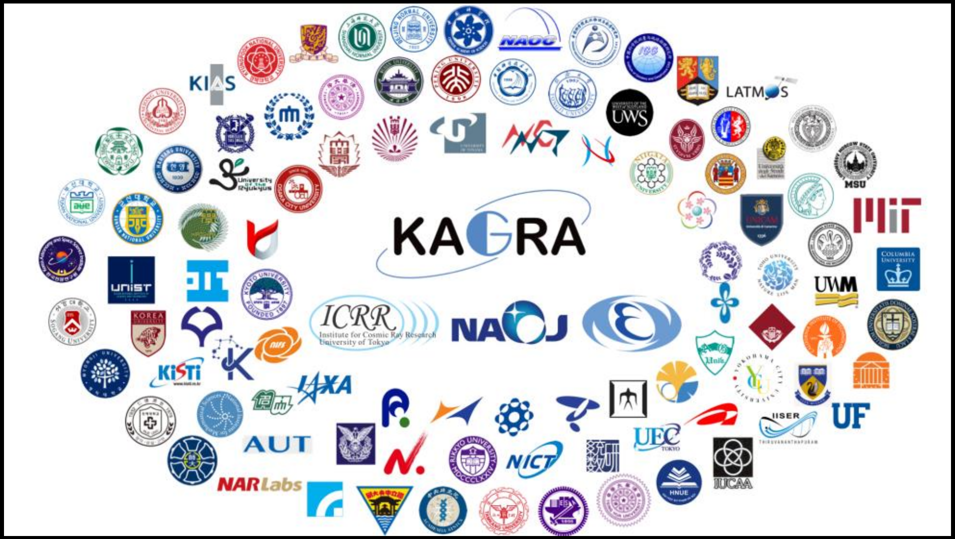
Cryogenic interferometer
- Mirror temperature: 20K

Underground site
- Kamioka site dedicated
- L-shaped tunnel

KAGRA Collaboration

KAGRA project is hosted by ICRR (Institute for Cosmic Ray Research, U. Tokyo) and co-hosted by NAOJ (National Astronomical Observatory of Japan) and KEK (High Energy Accelerator Research Organization)

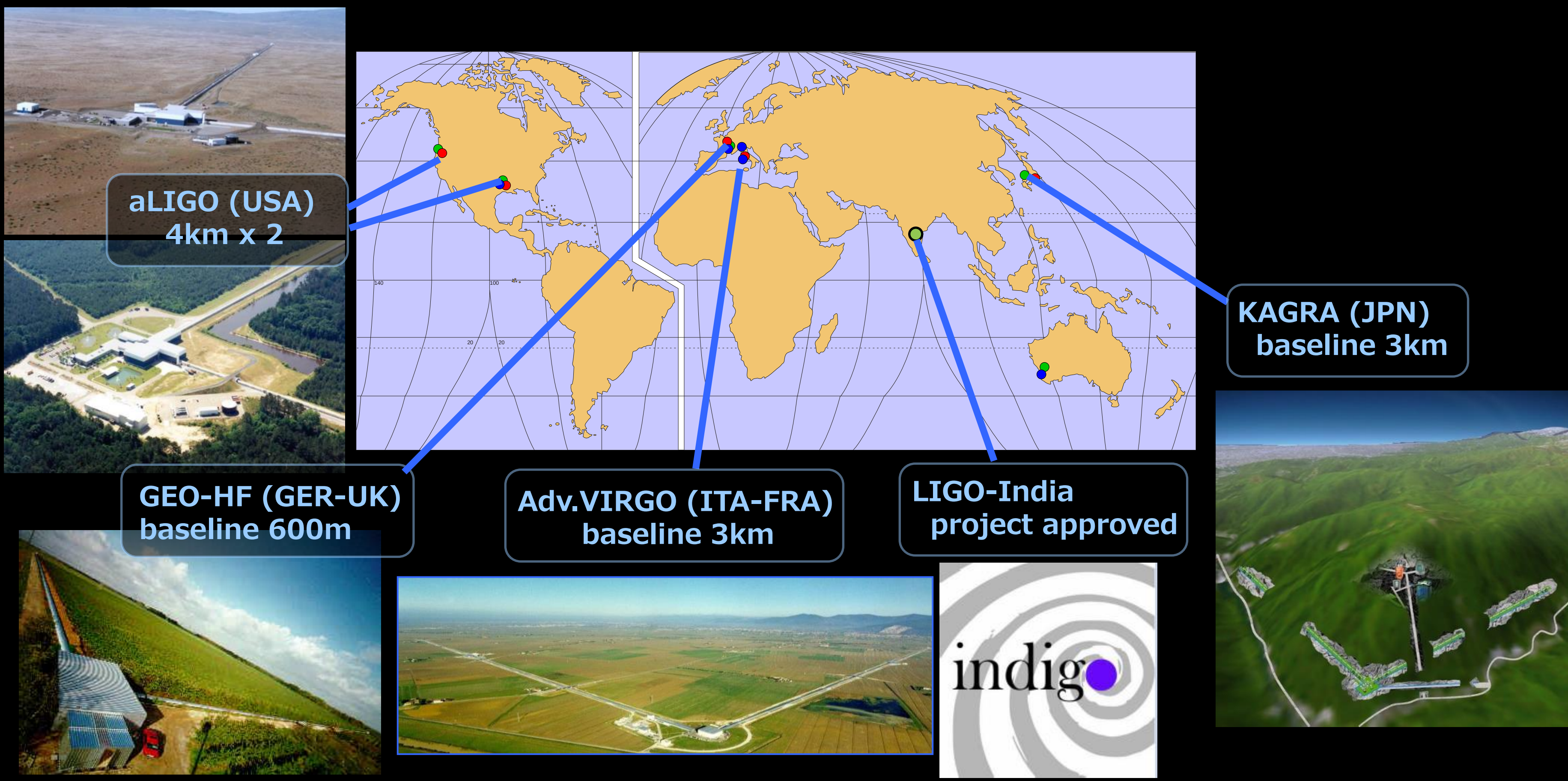
KAGRA collaboration:
- ~508 members from
- ~157 Research groups
- [as of Jan 25, 2023]



International GW Network

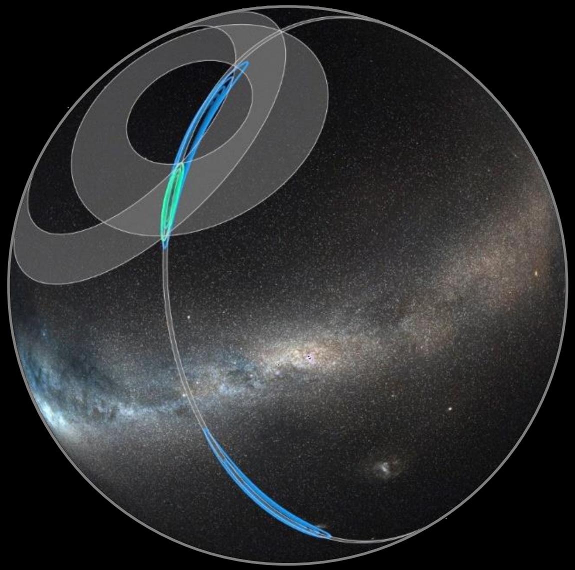
International network by 2nd–gen GW antennae.

→ GW astronomy (Detection, Parameter estimation, ⋯)

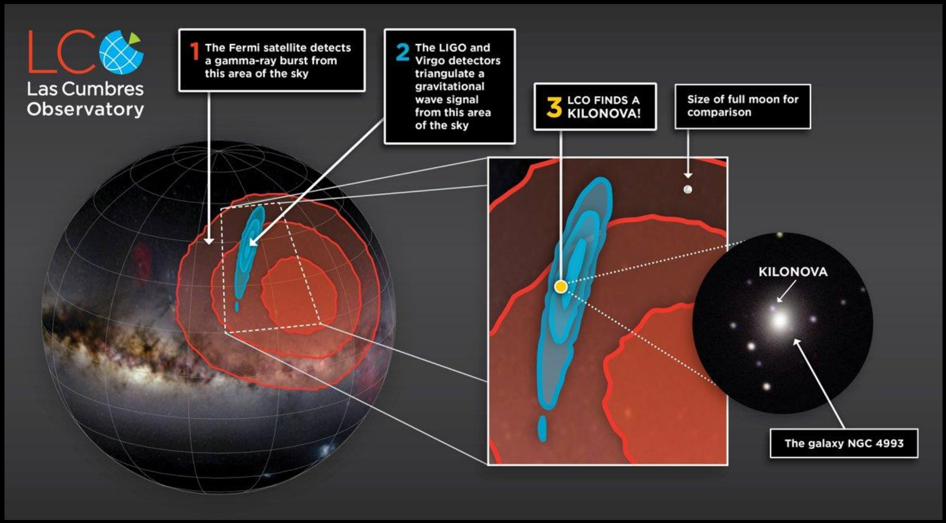


Importance of Sky Localization

- For GW astronomy, parameter estimation of the source is important. In particular, sky localization is critical for identification of EM counterpart.
- In GW170817, the sky position was localized with ~30deg^2 error by 2 LIGO + 1 VIRGO detectors. ~20 galaxies in this region.



Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way Image: Alex Mellinger)



Credit: Sarah Wilkinson / LCO
(Taken from https://youtu.be/wnwMhvdDcfI)

Antenna Pattern of GW Detector

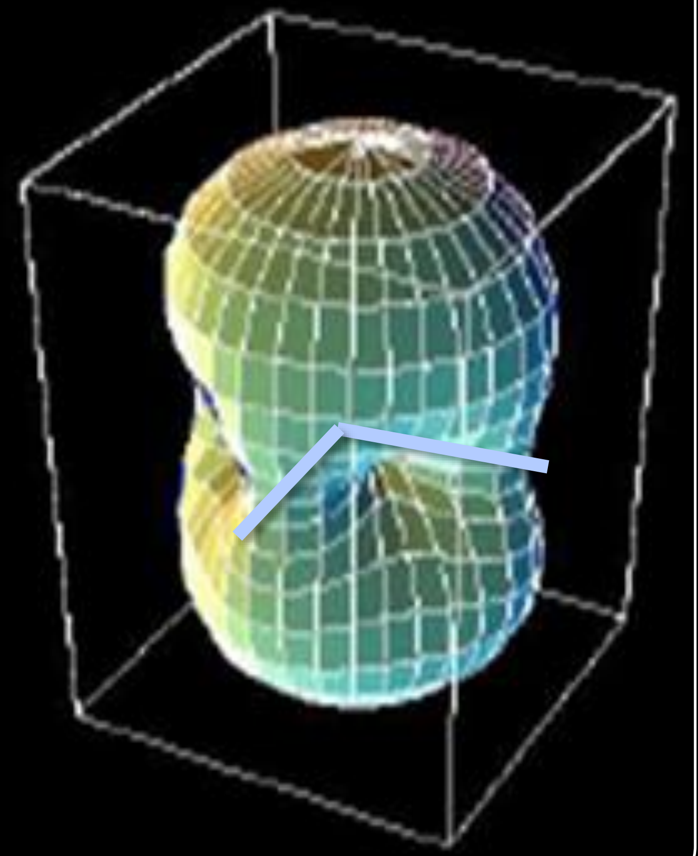
An Interferometric GW antenna has …

* Good sky coverage
* Poor angular resolution

⇩

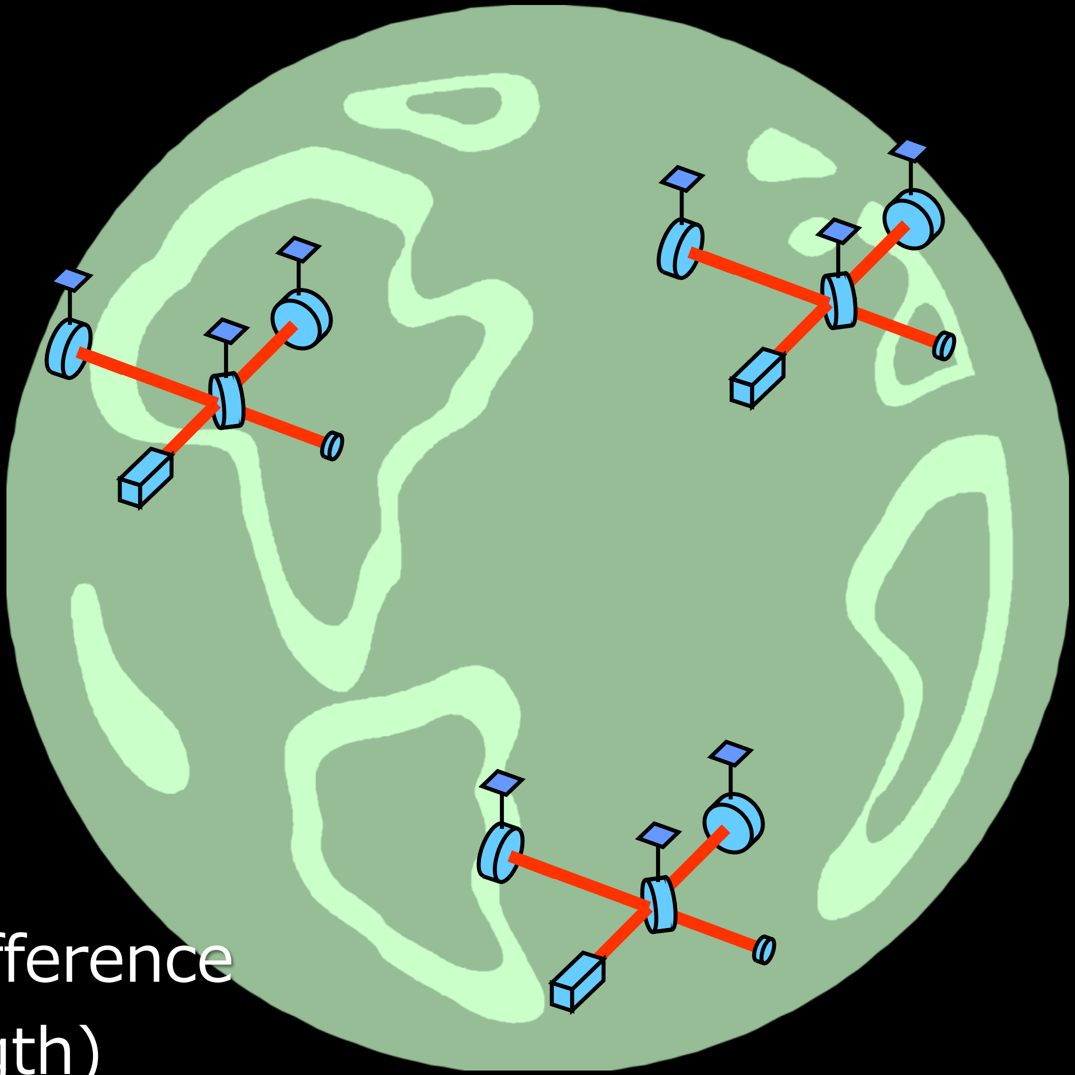
Difficult to determine the source sky position with single antenna.

Antenna Pattern



International Network for Astronomy

Animation :
S. Kawamura (ICRR)

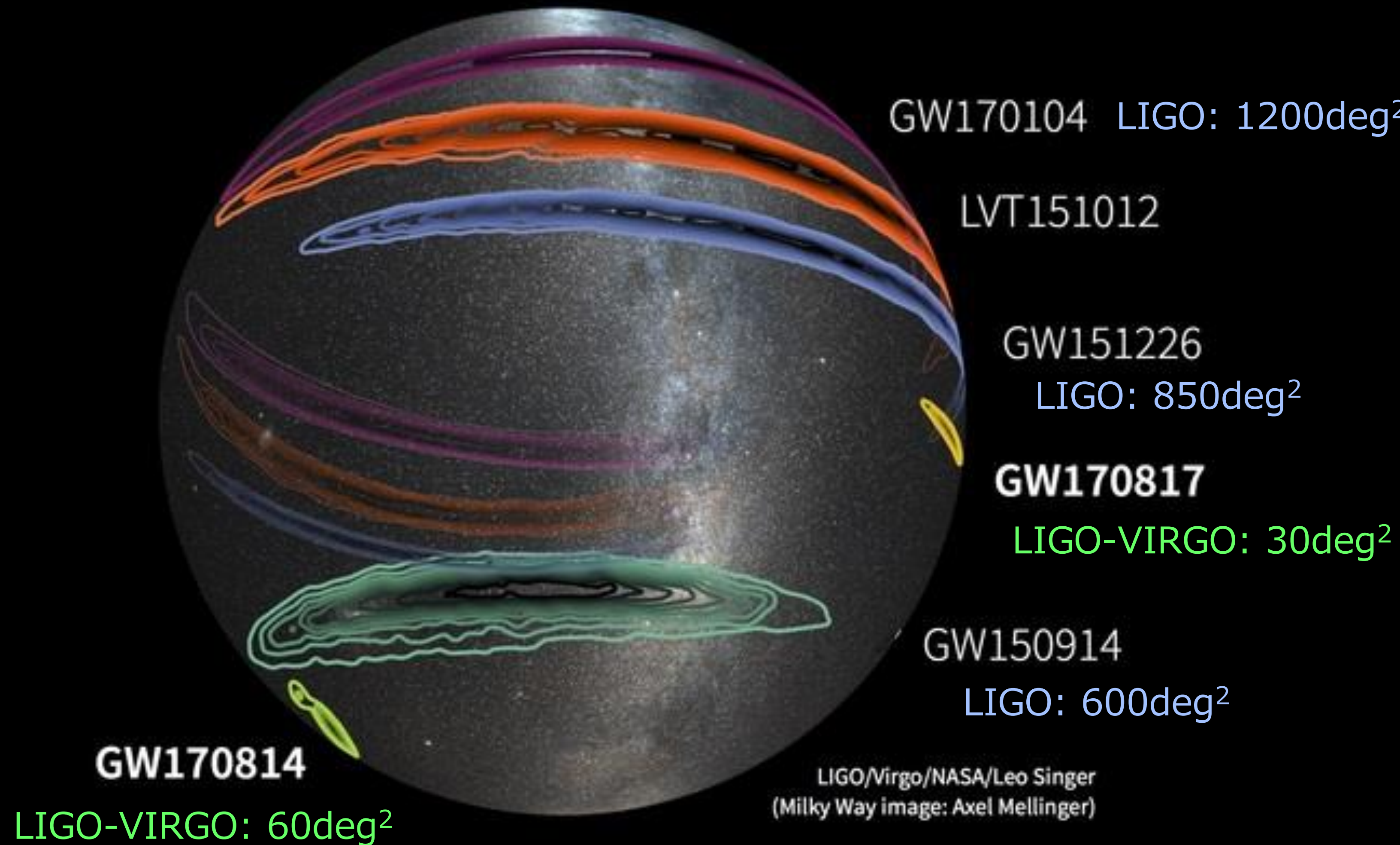


Multiple Detector

⇩

Identify the source
by the arrival-time difference
(and also signal strength)

Source Localization

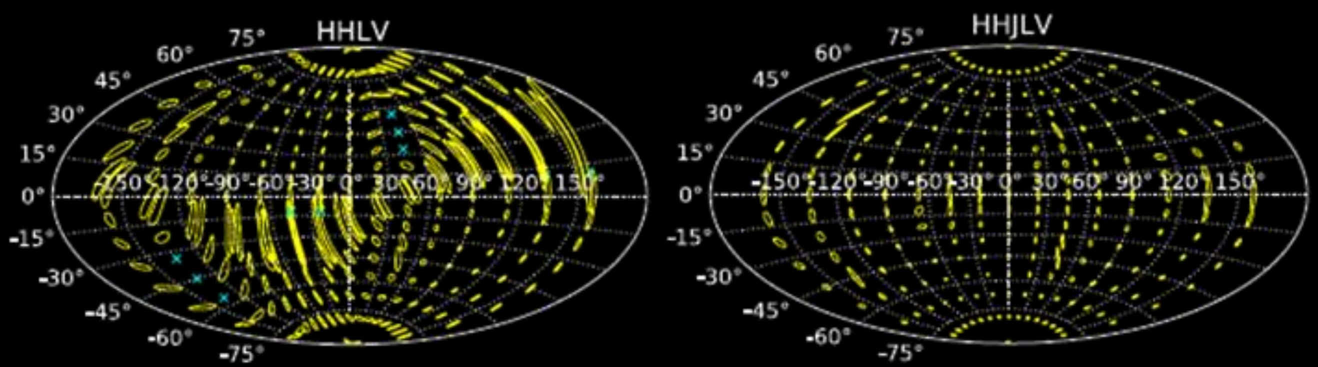


Sky Localization

NS-NS coalescence @180Mpc (95%CI)		
(1.4,1.4)Msun	LHV	LHVK
median of δΩ [Deg^2]	30.25	9.5

H: LIGO--Hanford
L: LIGO--Livingston
V: Virgo,
K: KAGRA
I: LIGO-Indea

From presentation by H. Tagoshi
J.Veitch+, PRD85, 104045 (2012)
Tagoshi+ (2014)



S.Fairhaurst
CQG 28(2011)
105021

Adding KAGRA to the network (aLIGO + adv. VIRGO)
→ Improvement of angular resolution by 3-4 times.

KAGRA GW Detector

- KAGRA as a 2.5-generation GW detector

Large-scale Detector
- Baseline : 3km
- Intra-cavity power ~400kW

Cryogenic interferometer
- Mirror temperature: 20K

Underground site :
- Underground site at Kamioka, Gifu

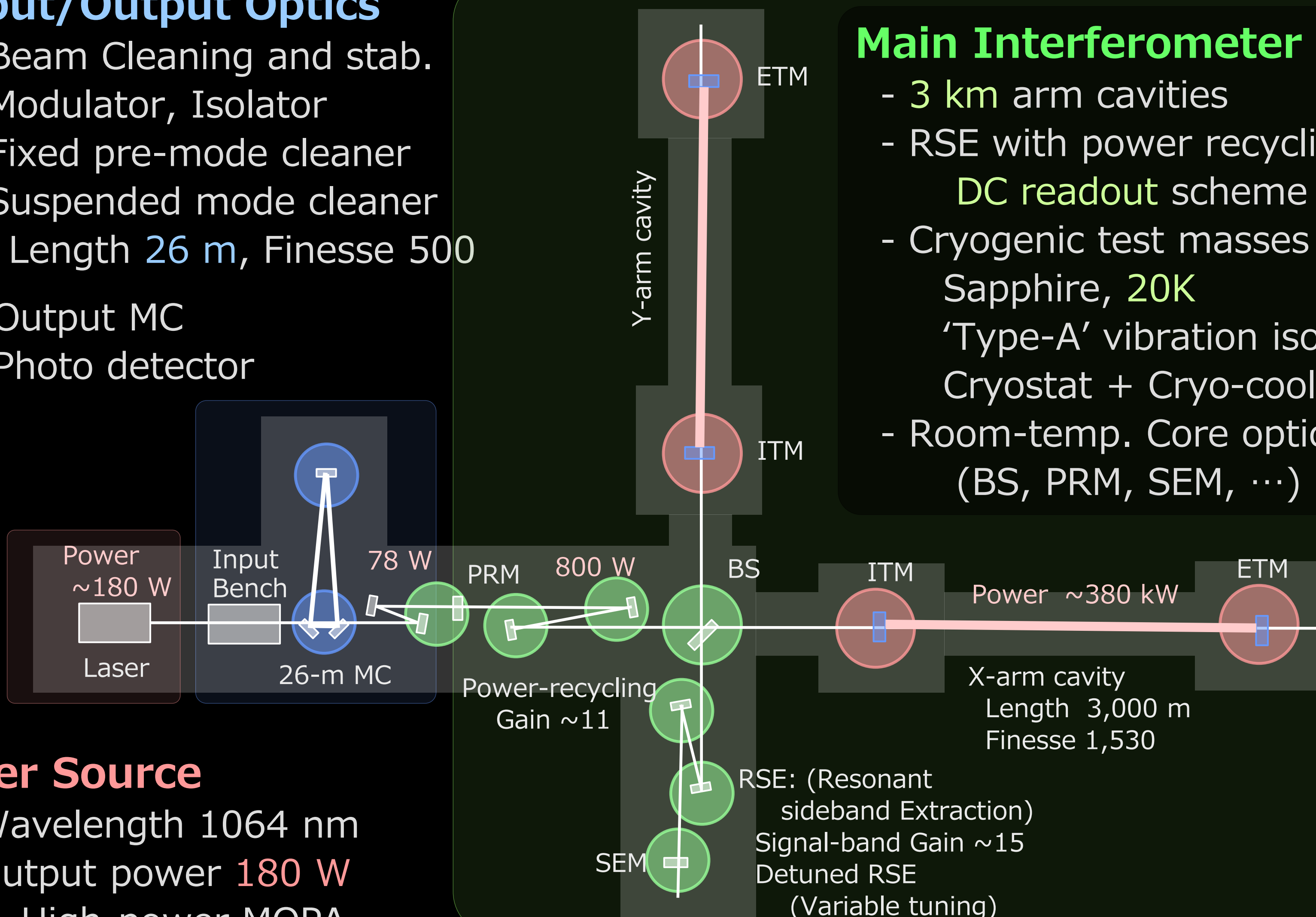
* International GW network with LIGO/VIRGO
* Advanced technologies: cryogenic and underground

KAGRA Optical Design

Input/Output Optics

- Beam Cleaning and stab.
- Modulator, Isolator
- Fixed pre-mode cleaner
- Suspended mode cleaner
  Length 26 m, Finesse 500

- Output MC
- Photo detector



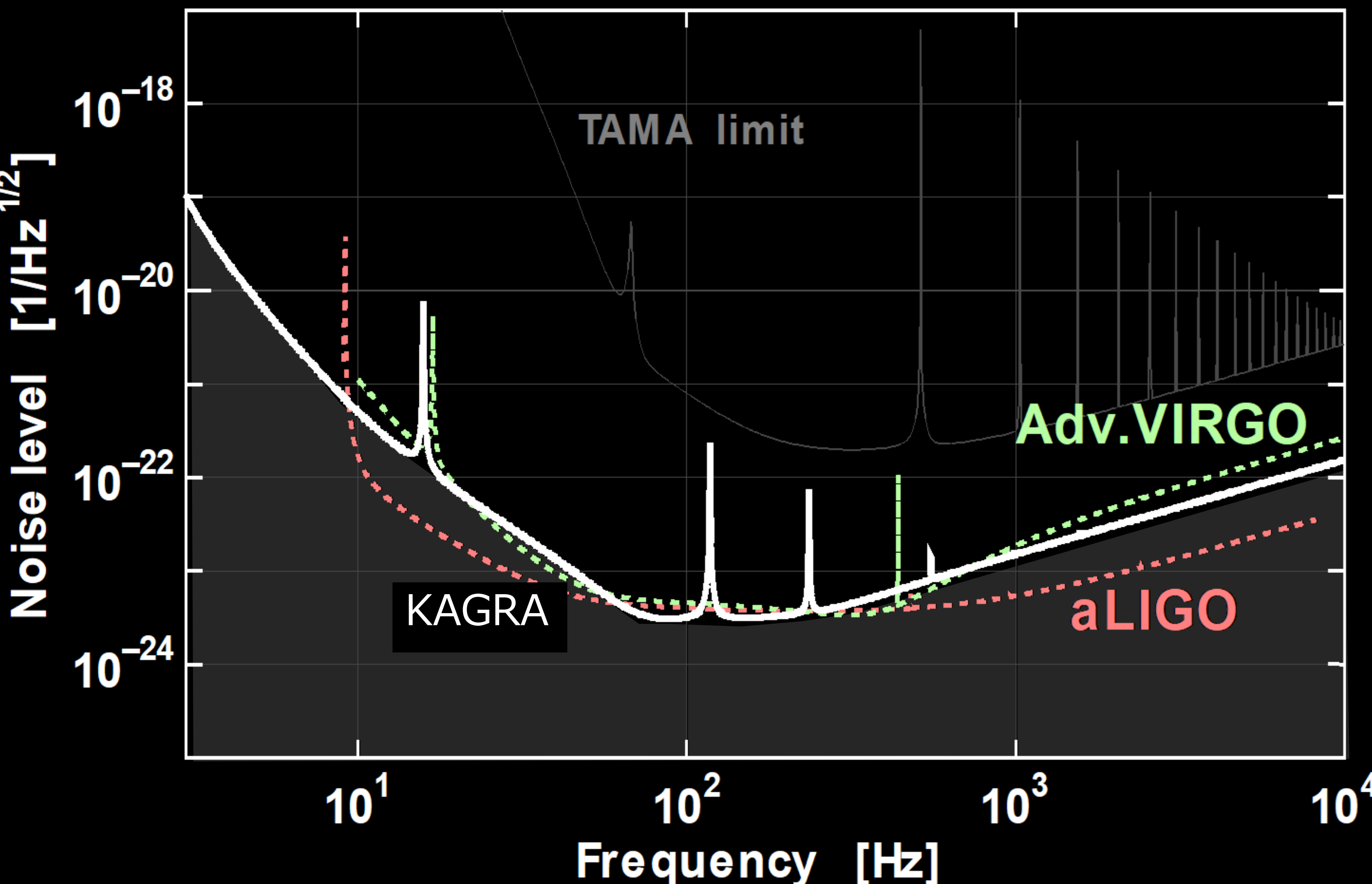
Main Interferometer

- 3 km arm cavities
- RSE with power recycling
  DC readout scheme
- Cryogenic test masses
  Sapphire, 20K
  'Type-A' vibration isolator
  Cryostat + Cryo-cooler
- Room-temp. Core optics
  (BS, PRM, SEM, ···)

Laser Source

- Wavelength 1064 nm
- Output power 180 W
  High-power MOPA

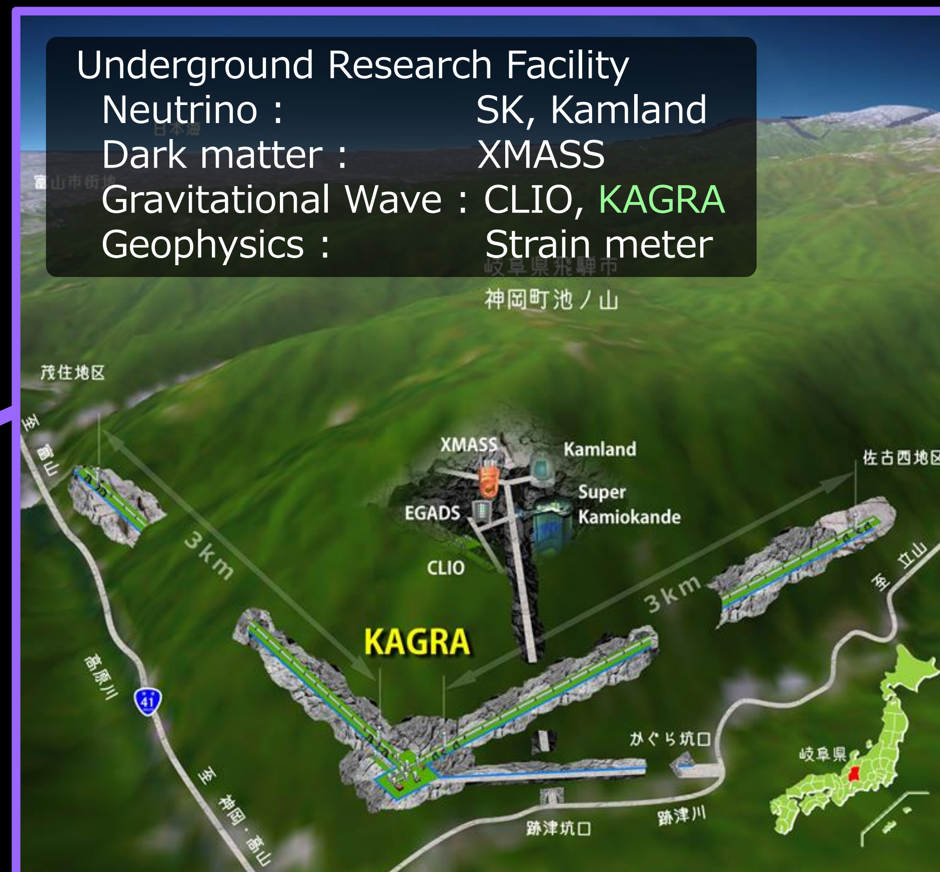
Sensitivity Comparison



KAGRA Site

Underground site at Kamioka, Gifu prefecture

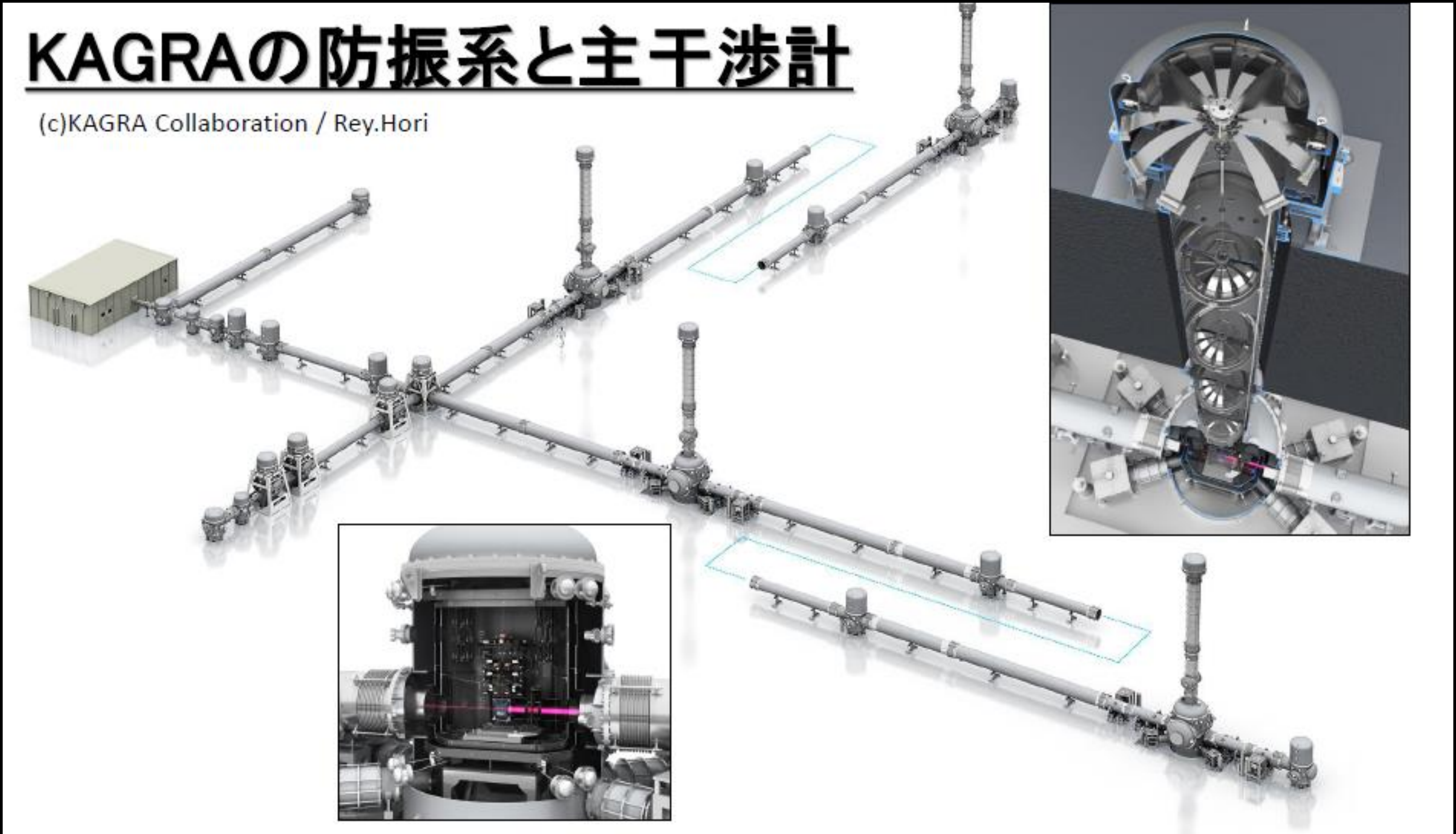
Facility of the Institute of Cosmic-Ray Research (ICRR), Univ. of Tokyo.



Map by Google

KAGRA Photo

3-km Tunnel and Beam Duct (Photo by S. Miyoki)

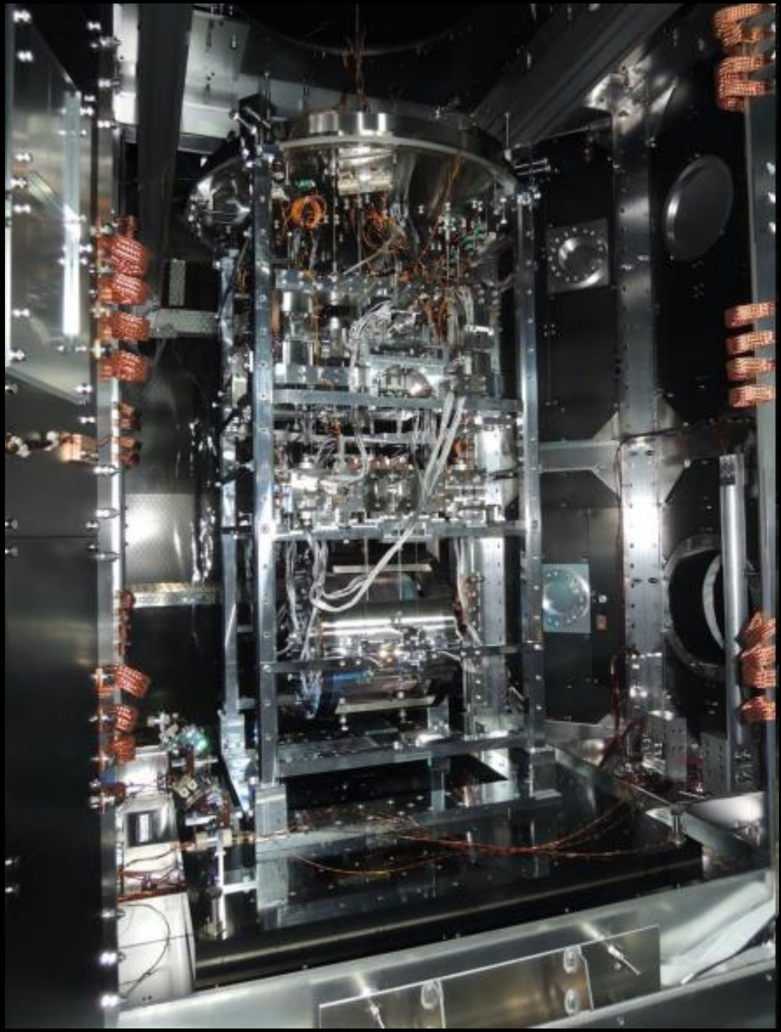


From presentation by Washimi

KAGRA Photos

Sapphire Mirror: Diameter 22cm, Thickness 15cm

KAGRA Photo



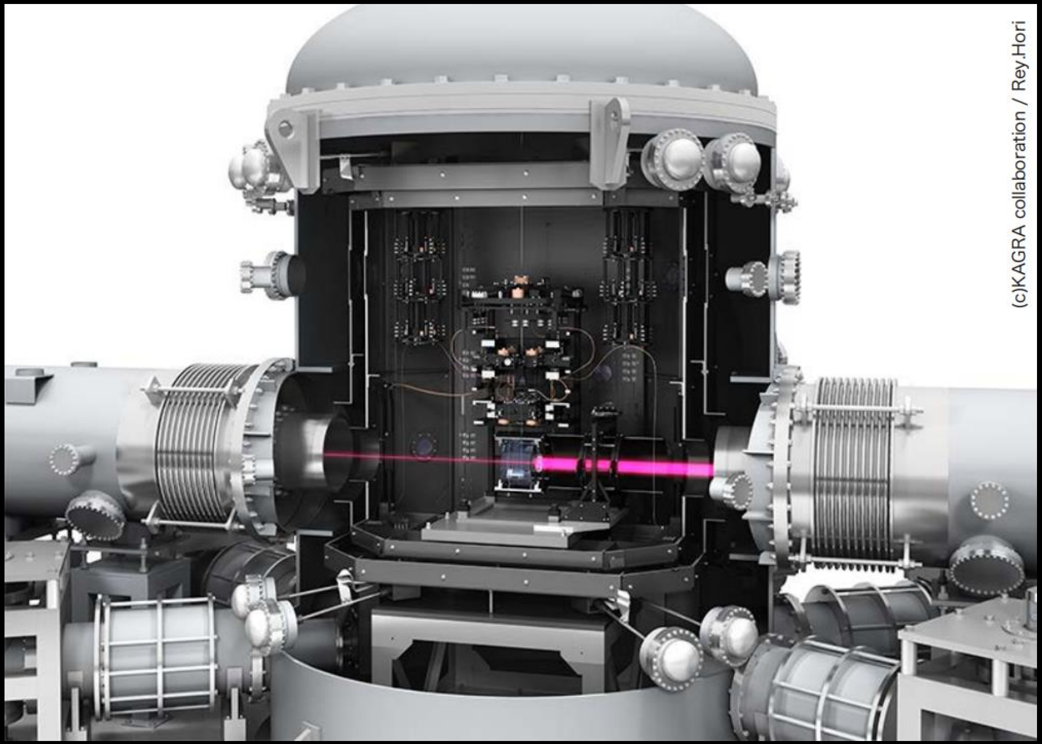
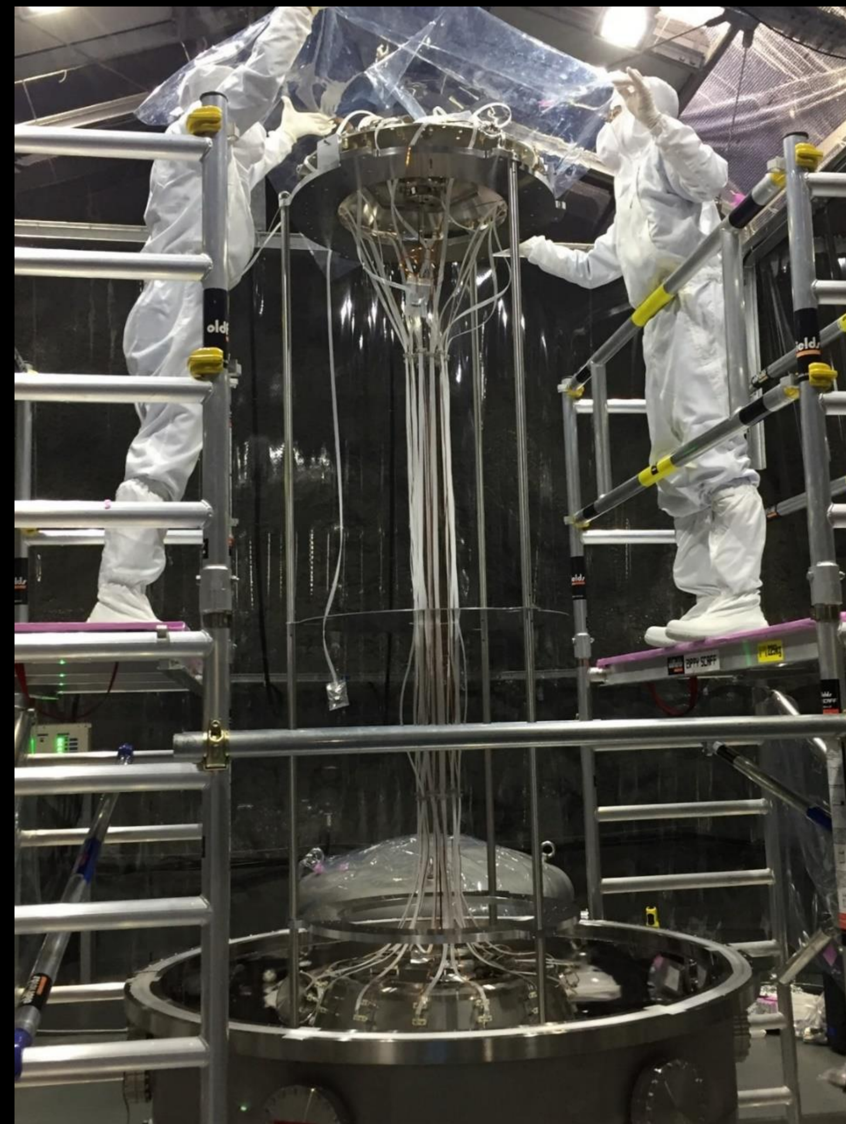


Photo and CG model of cryogenic payload

KAGRA Photos

Vibration Isolation



KAGRA Observation Runs

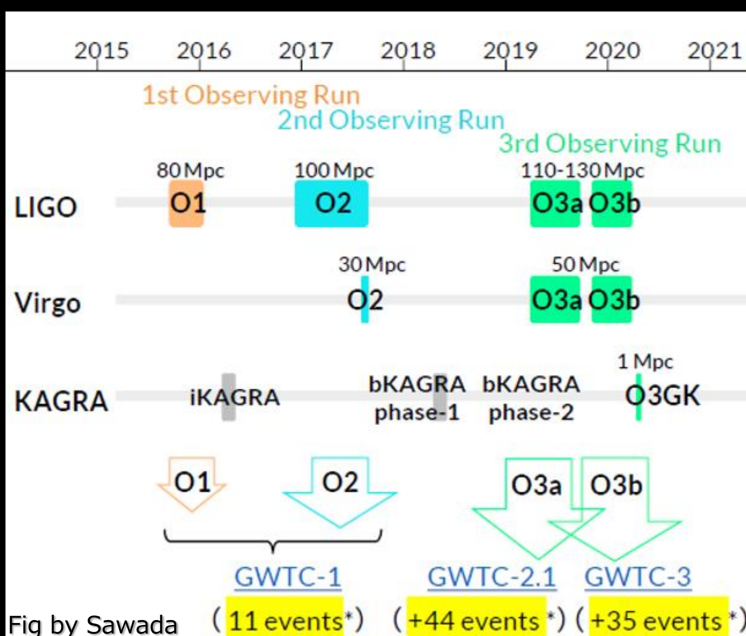
KAGRA Observation Run History

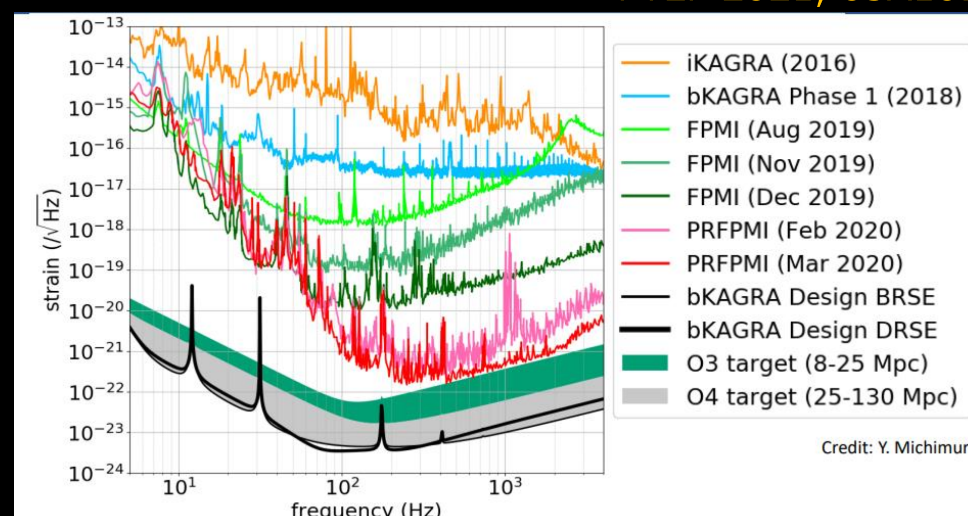
- ~Mar 2016: iKAGRA (Room Temperature MI)
- ~Mar 2018: bKAGRA phase-1 (Cryogenic MI)
- ~ Apr 2019: bKAGRA phase-2 (Most items installed)
- May 2019 ~ April 2020: bKAGRA phase-3 to O3

  PRFPMI configuration. Stable operation, Noise hunting.

  BNS range sensitivity of ~1 Mpc (March 2020).

PTEP 2021, 05A101





✓ The best sensitivity has reached 970 kpc (~1Mpc)!

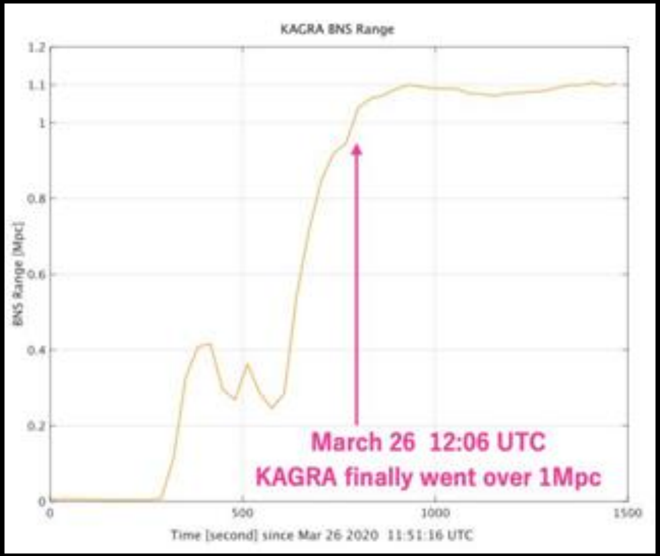
✓ 4 orders of magnitude improvement between Aug. 2019 and March 2020 @300Hz!

O3GK

- Initial plan was to join the O3 with LIGO and VIRGO, once KAGRA reached the ~1Mpc sensitivity, based on MoA.
- KAGRA realized it in March 2020. However, LIGO and VIRGO stopped their operation due to COOVID-19 situation.

- GEO600 at Germany and KAGRA had a joint observation run in April 2020 : O3GK

From presentation by H. Takahashi (2021)

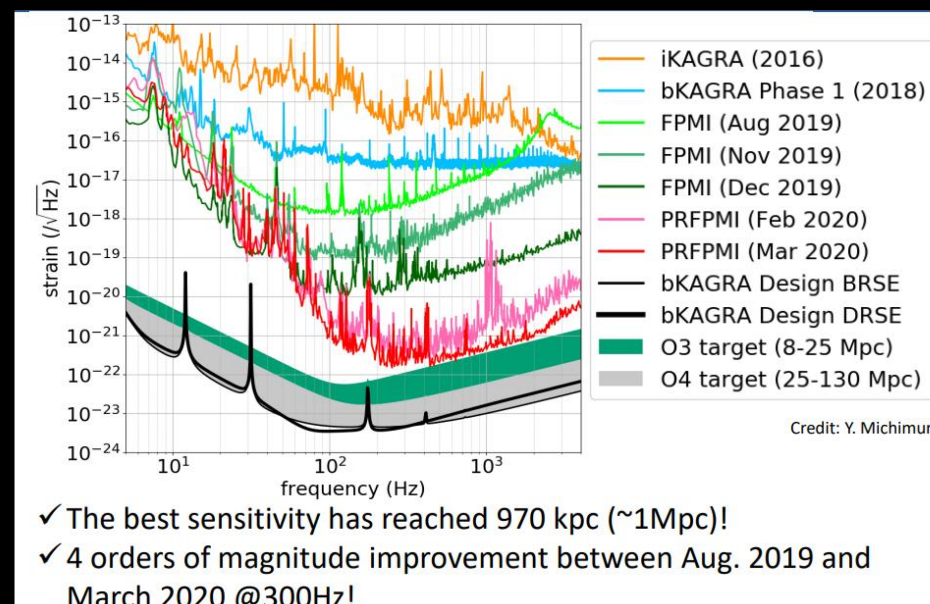


KAGRA Observation Run

- KAGRA started observation run in 2020
  - * KAGRA solo : 2 weeks (Feb. 25 – Mar. 10)
  - * O3GK : 2 weeks (Apr. 7 – Apr. 21)
  - * Science-mode duty factor 54%
  - * Typical binary range ~600 kpc (Best ~970 kpc)

From KAGRA web site (Feb 25, 2020)

※ BNS range here: sky averaged range

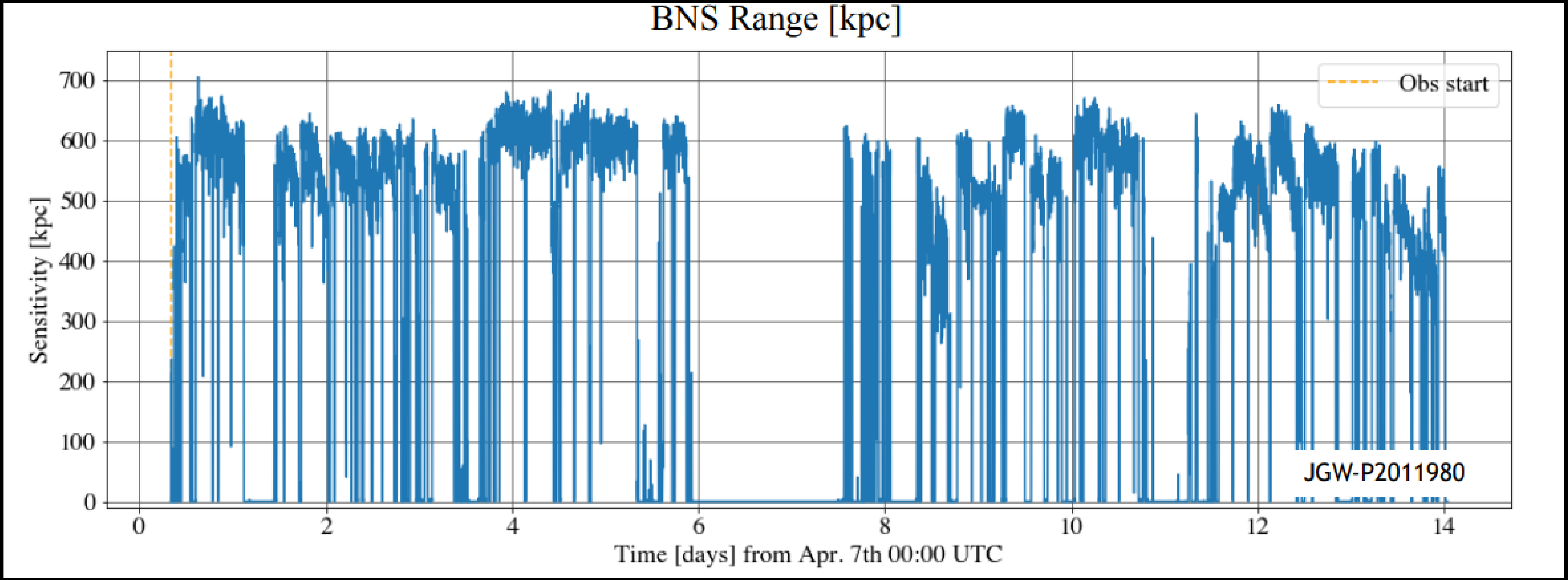


From presentation by T.Kajita (May 27, 2020)

PTEP 2021, 05A101

KAGRA Observation Run

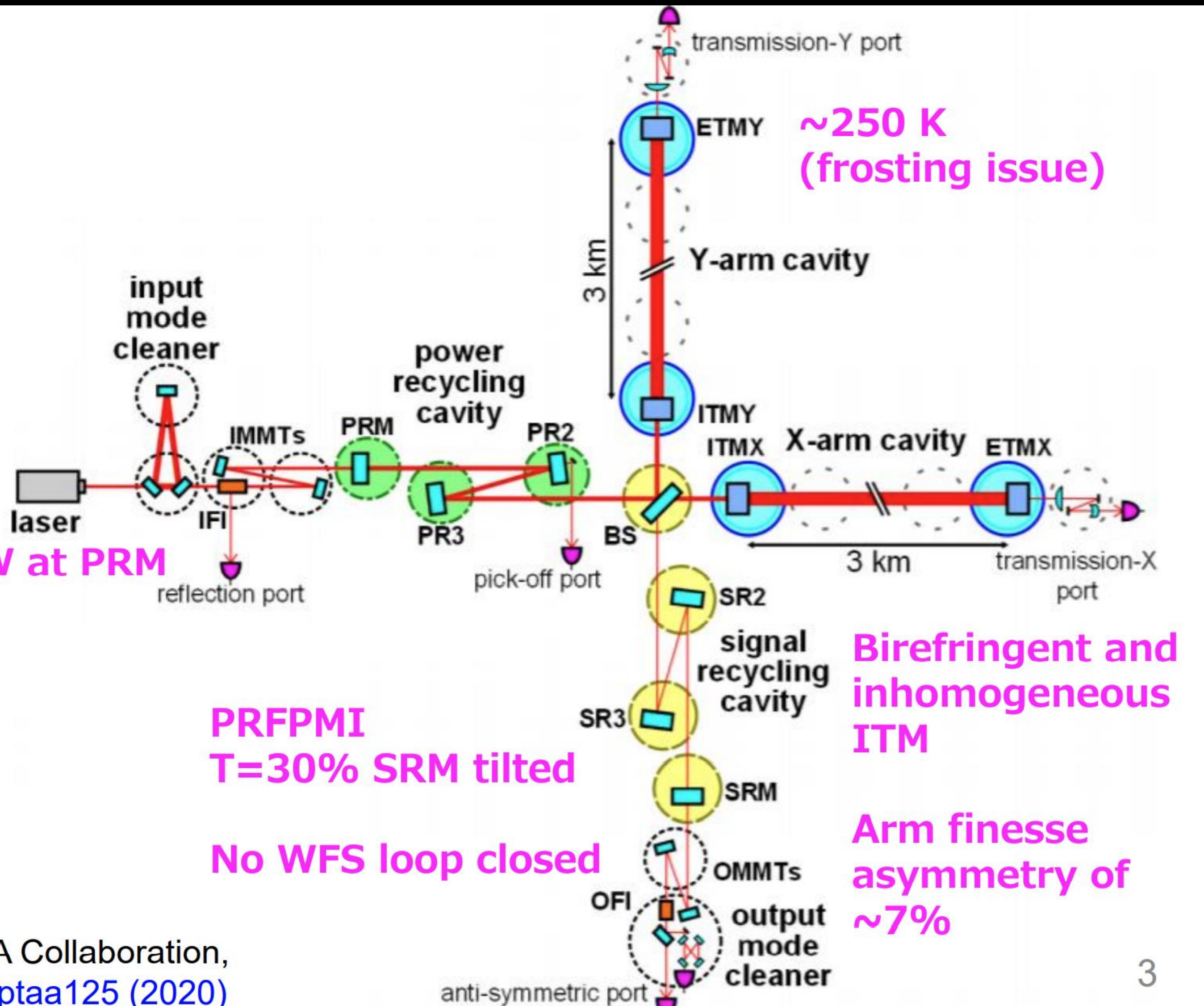
- KAGRA started observation run in 2019
  - * KAGRA solo : 2 weeks (Feb. 25 – Mar. 10)
  - * O3GK : 2 weeks (Apr. 7 – Apr. 21)



From presentation at JPS meeting by T. Yamamoto (Sep 14-17, 2020)

※ BNS range here: sky averaged range

O3GK Interferometer Configuration



~250 K
(frosting issue)

3-5 W at PRM

Birefringent and
inhomogeneous
ITM

PRFPMI
T=30% SRM tilted

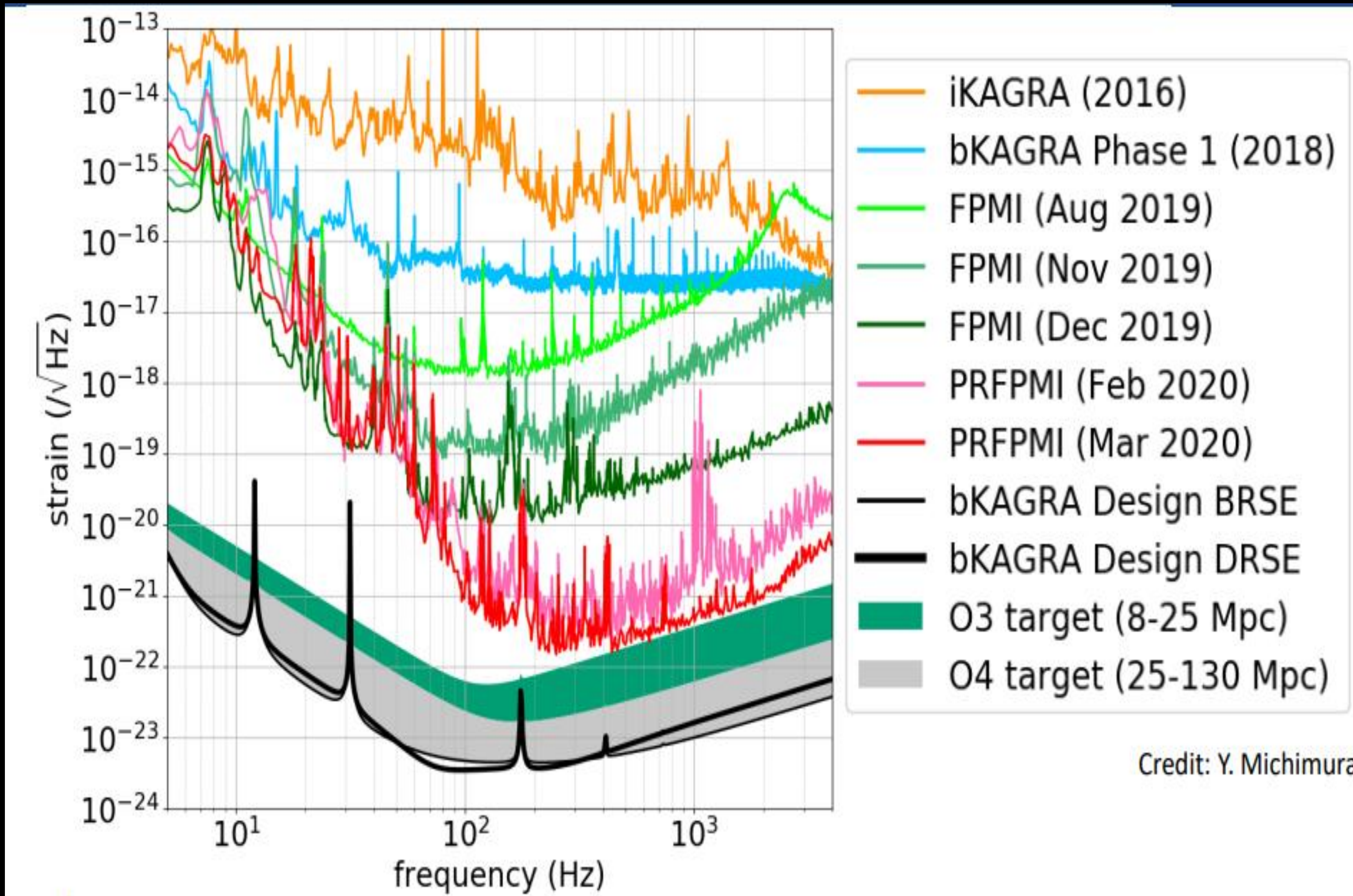
No WFS loop closed

Arm finesse
asymmetry of
~7%

KAGRA Collaboration,
PTEP, ptaa125 (2020)

Figure: Y. Michimura (LVK Meeting March 2021)

KAGRA Sensitivity



PTEP 2021, 05A101

BNS Observable Range History

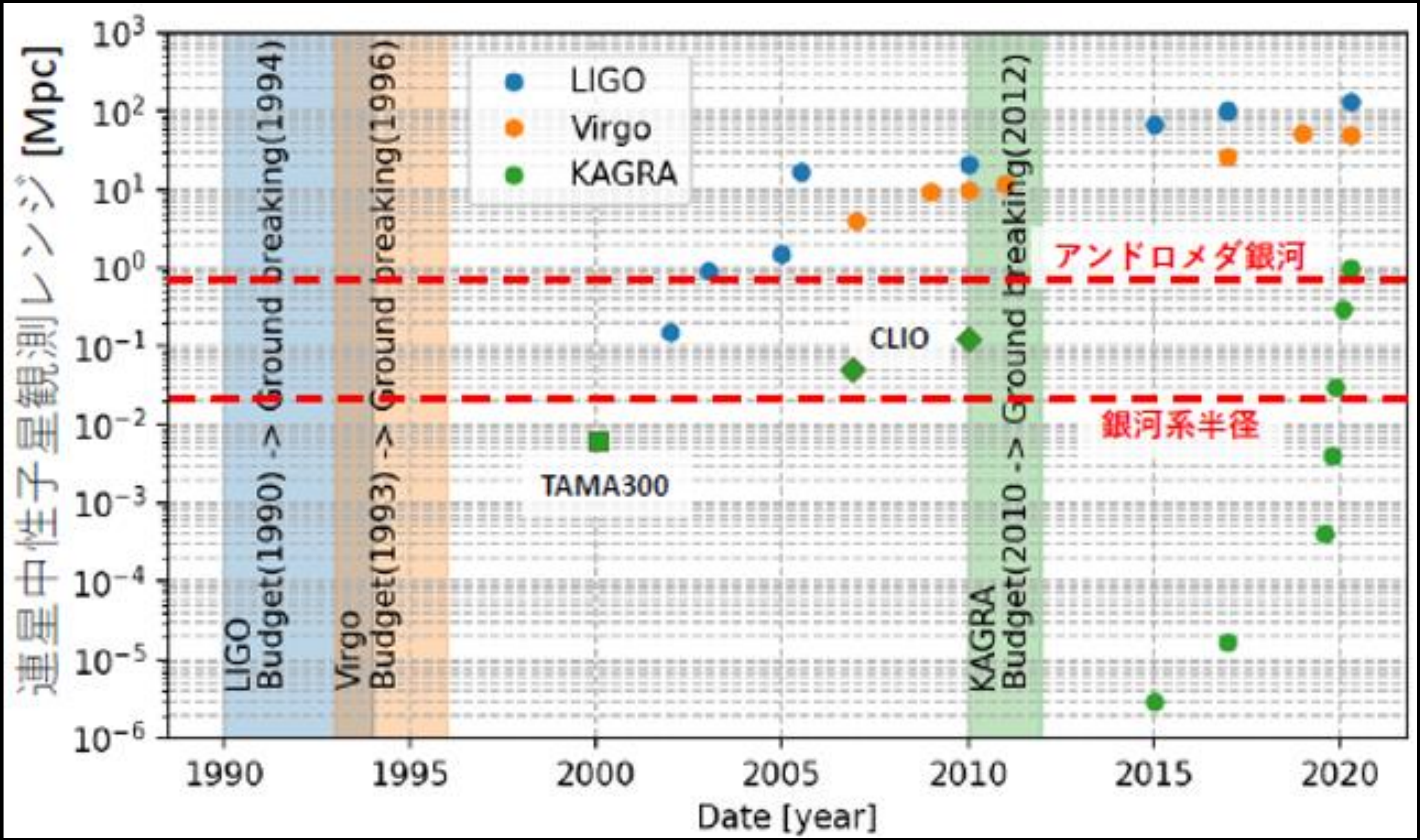
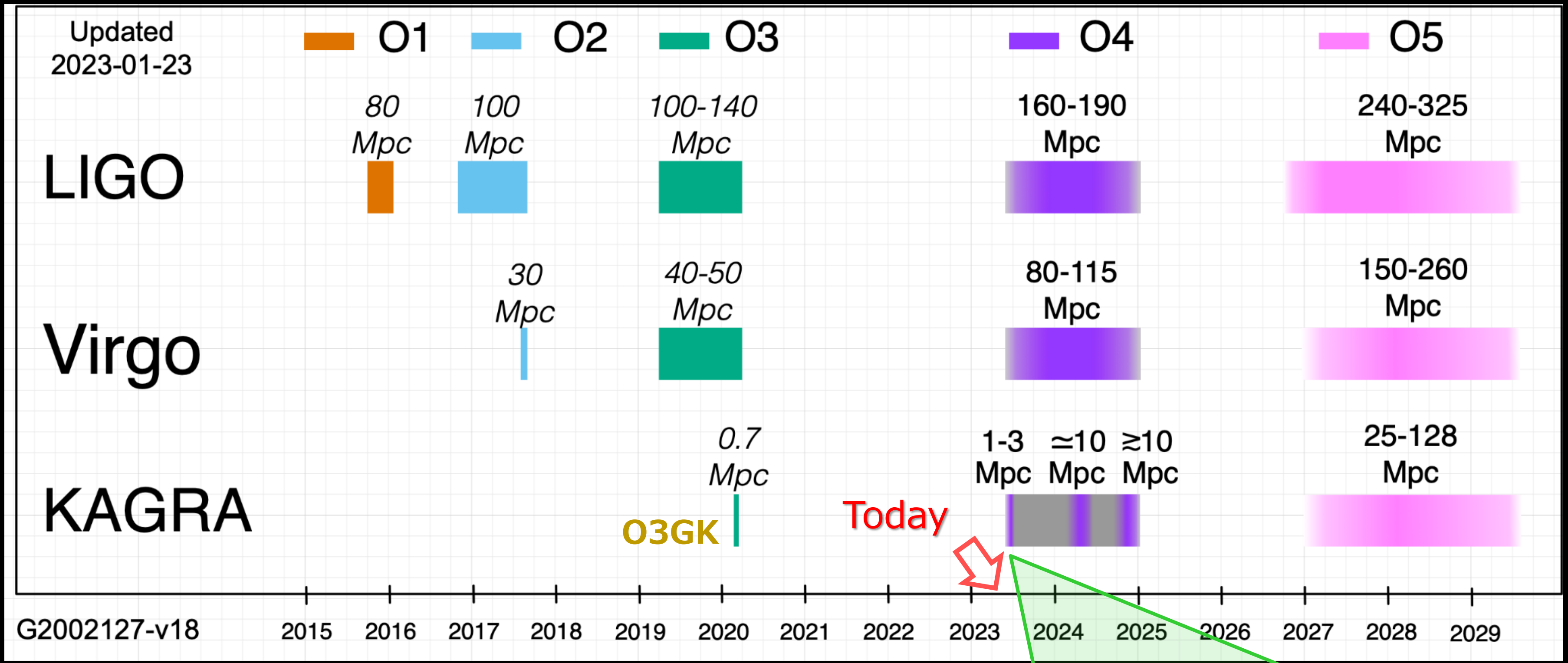


Fig. from Presentation by Washimi

Activities Toward O4

- KAGRA will join to O4 with improved sensitivity.



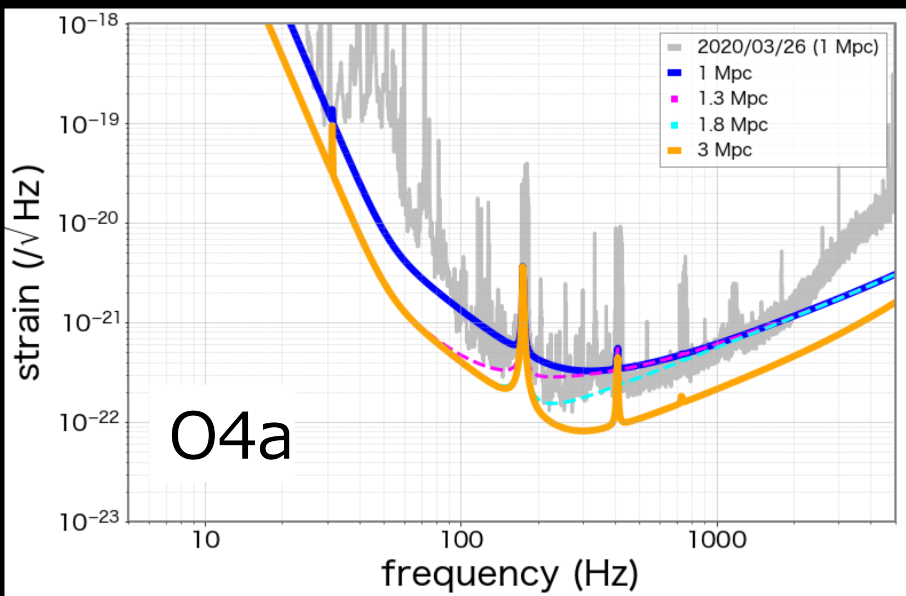
O4 start : 24 May 2023 in the current plan
(19 Jan 2023 announcement)

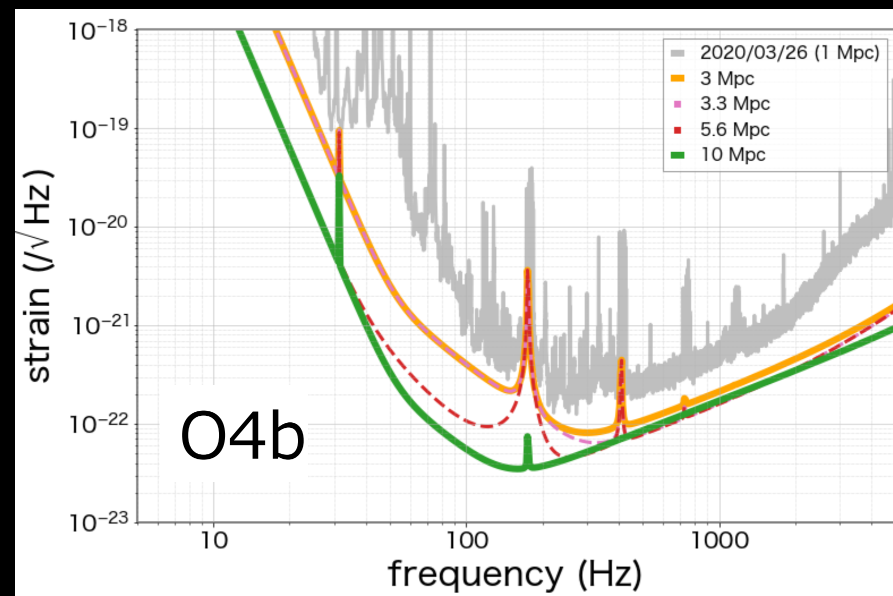
https://www.ligo.org/scientists/GWEMalerts.php

Expected Sensitivities

We aim to start O4 (O4a) with a sensitivity of 1-3 Mpc, and achieve 3-10 Mpc at the end of O4 (O4b).

Fig. by Yuzurihara

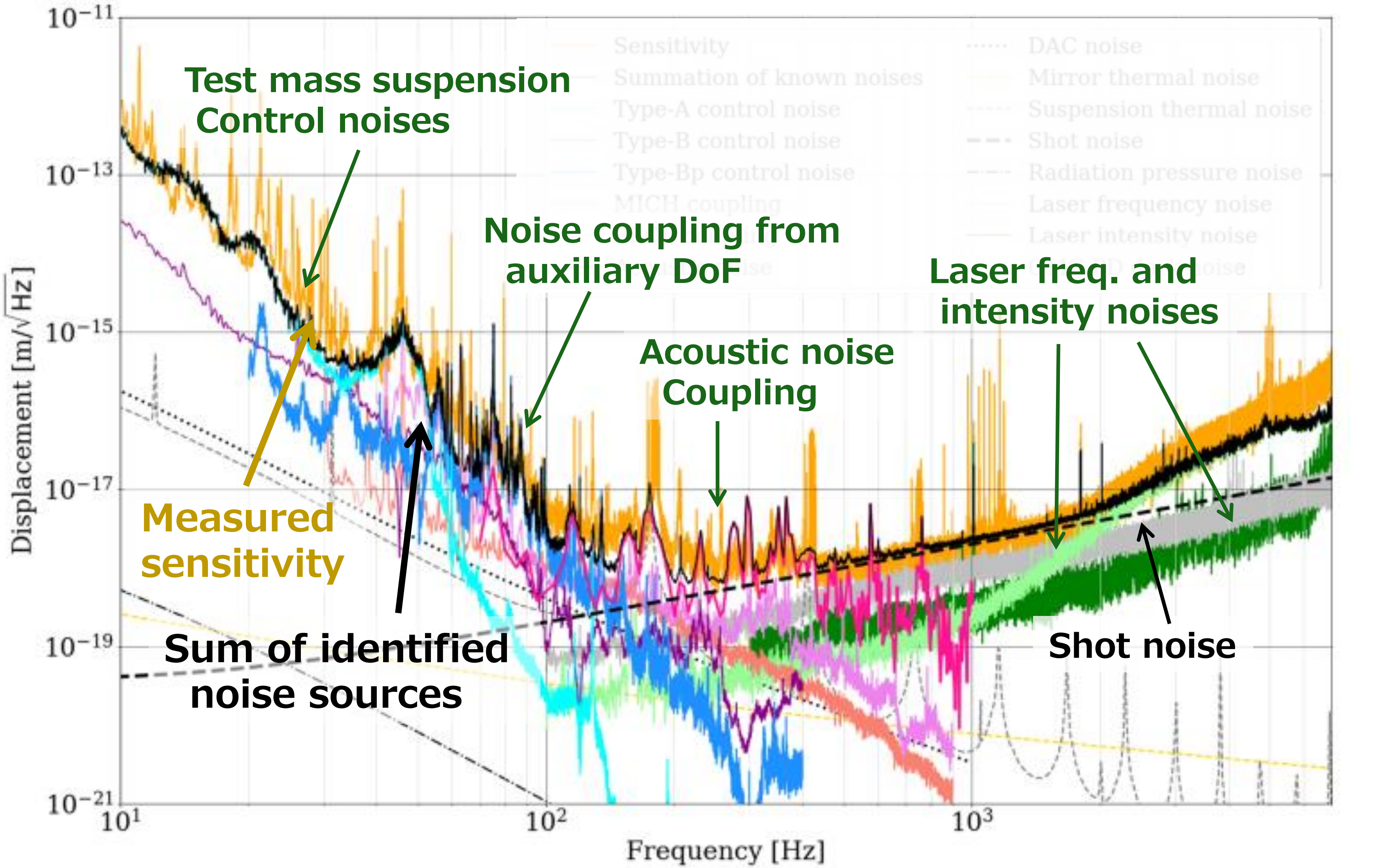




KAGRA is planning to have an extended commissioning break between O4a and O4b.

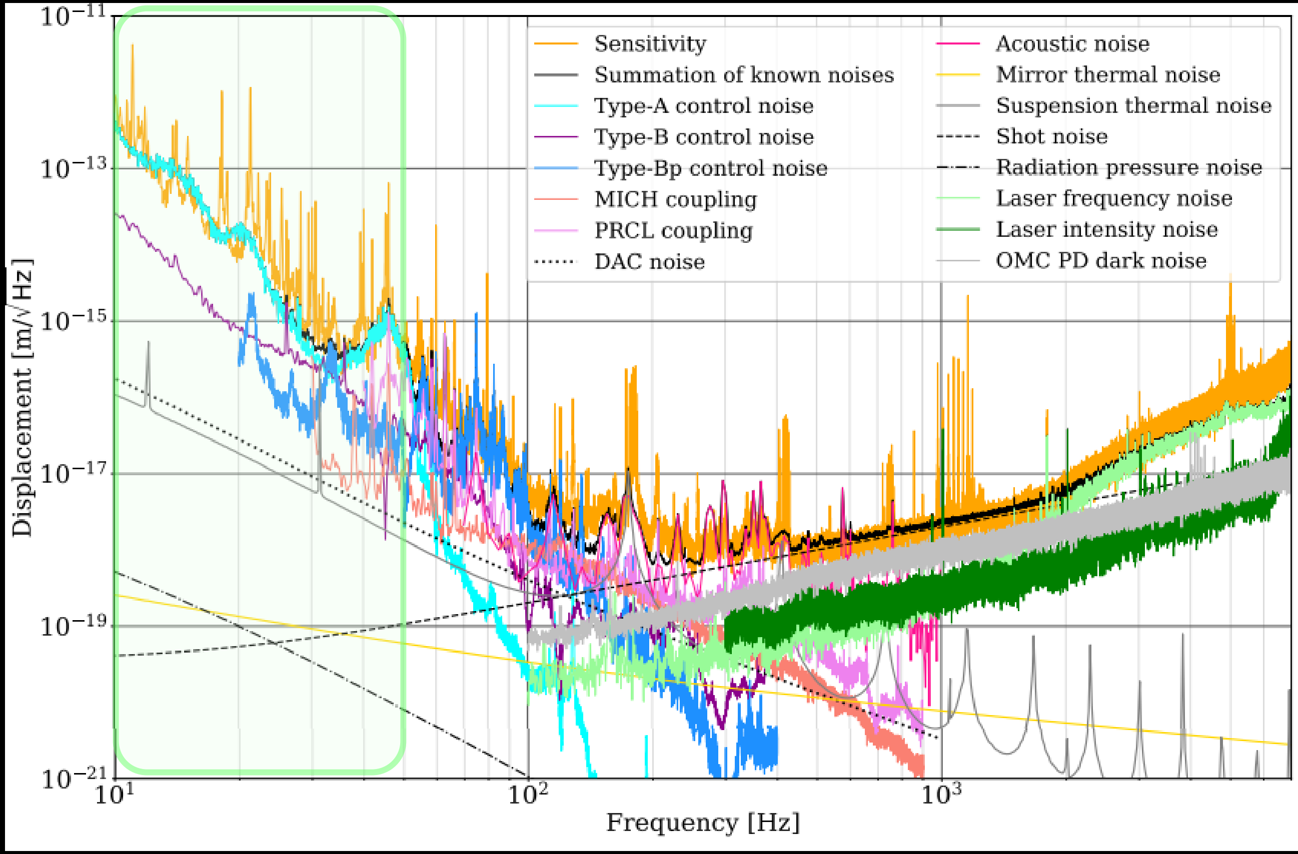
O3GK Noise Budget

PTEP 2022 [DOI: 10.1093/ptep/ptac093]



Sensitivity Improvement (1/4)

- Low Frequency (- 50 Hz):
  - Type-A control noise: Type-A mitigation and Health Check.
  - Optimization of control loops

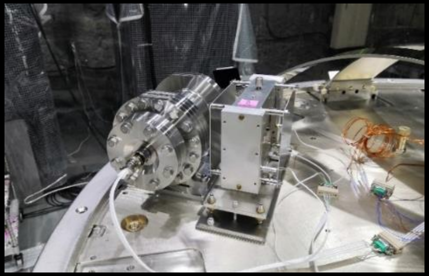


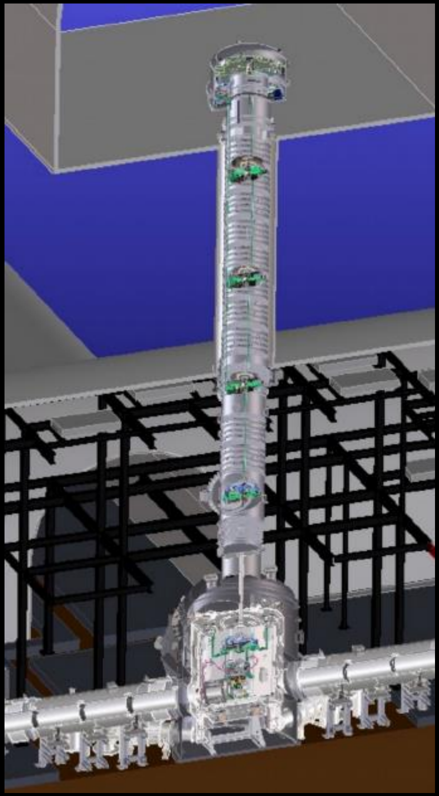
PTEP 2022 [DOI: 10.1093/ptep/ptac093]

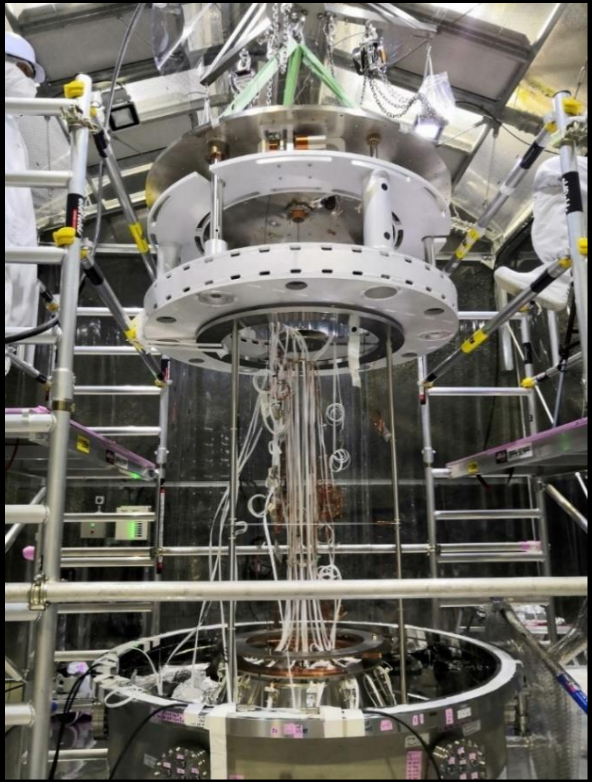
Type-A Mitigation and Improvement

- Re-installation of Type-A suspensions for mitigation of several GAS filter stages.
- Installation of new aaccelerometer at top filter.
- Installation of optical levers for local damping of payload.
- Temperature control for GAS in Type-A/B/Bp.

R. Takahashi

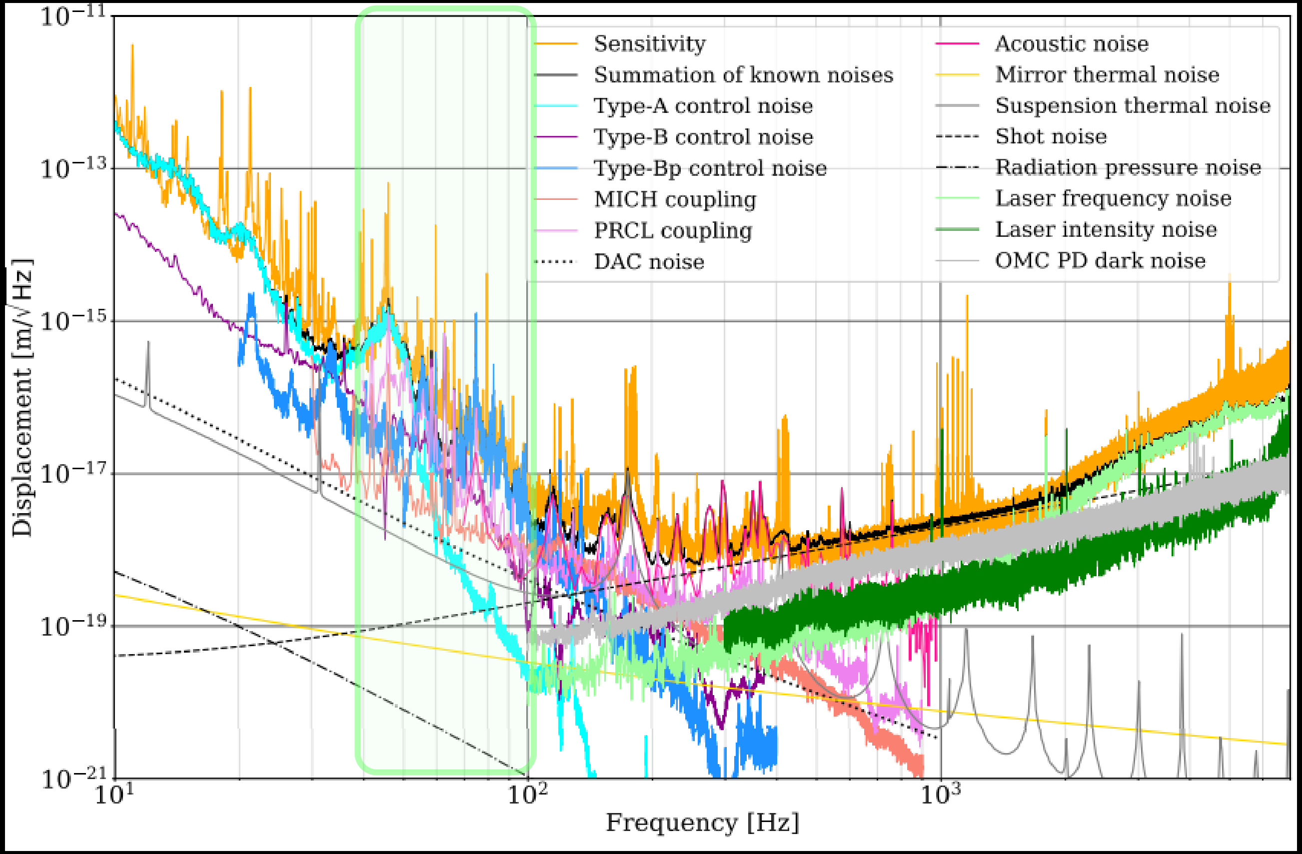






Sensitivity Improvement (2/4)

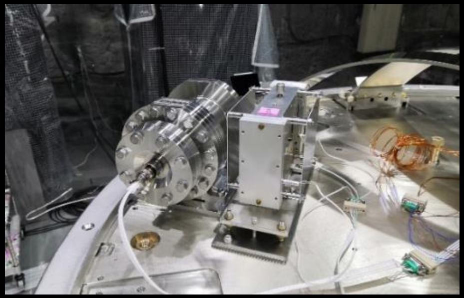
- Mid Frequency (50 - 100Hz):
  - Type-B/Bp control noise : Filter optimization
  - Thermal noise : Cryogenic mirror and suspension.

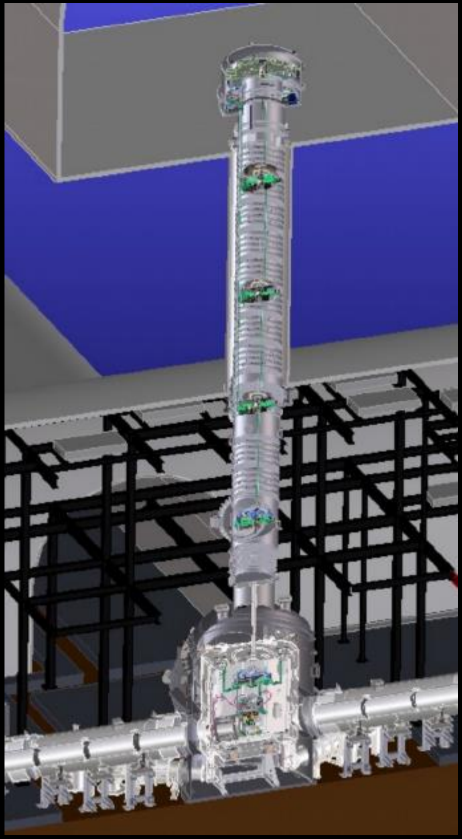


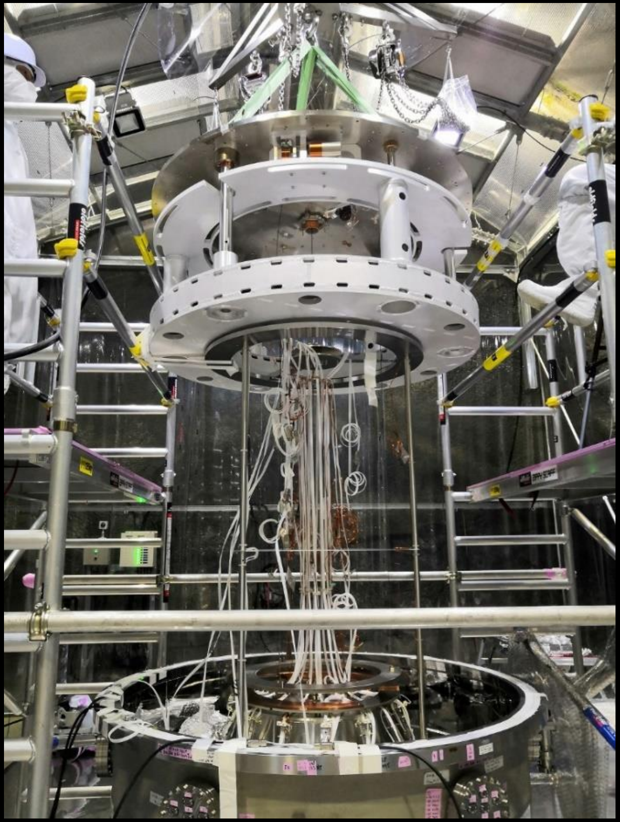
PTEP 2022 [DOI: 10.1093/ptep/ptac093]

Type-B/Bp Improvement

- Identification of the Type-Bp (PR2/3) unstable performance.
  PR2 was fixed. PR3 was improved but not fully fixed.
- Mitigation for Type-B (SRMs/BS).

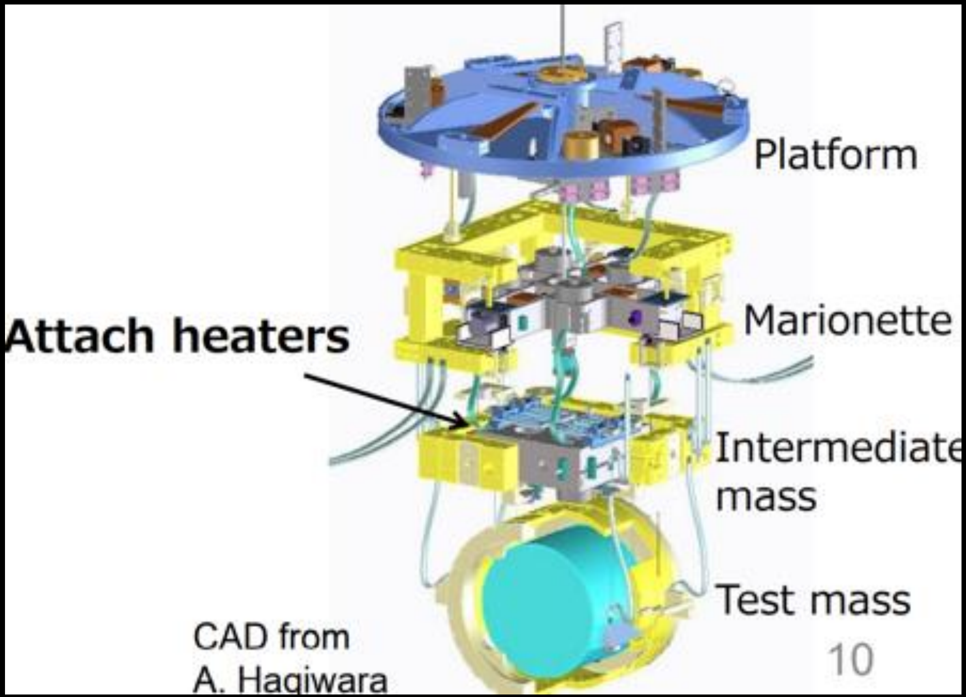






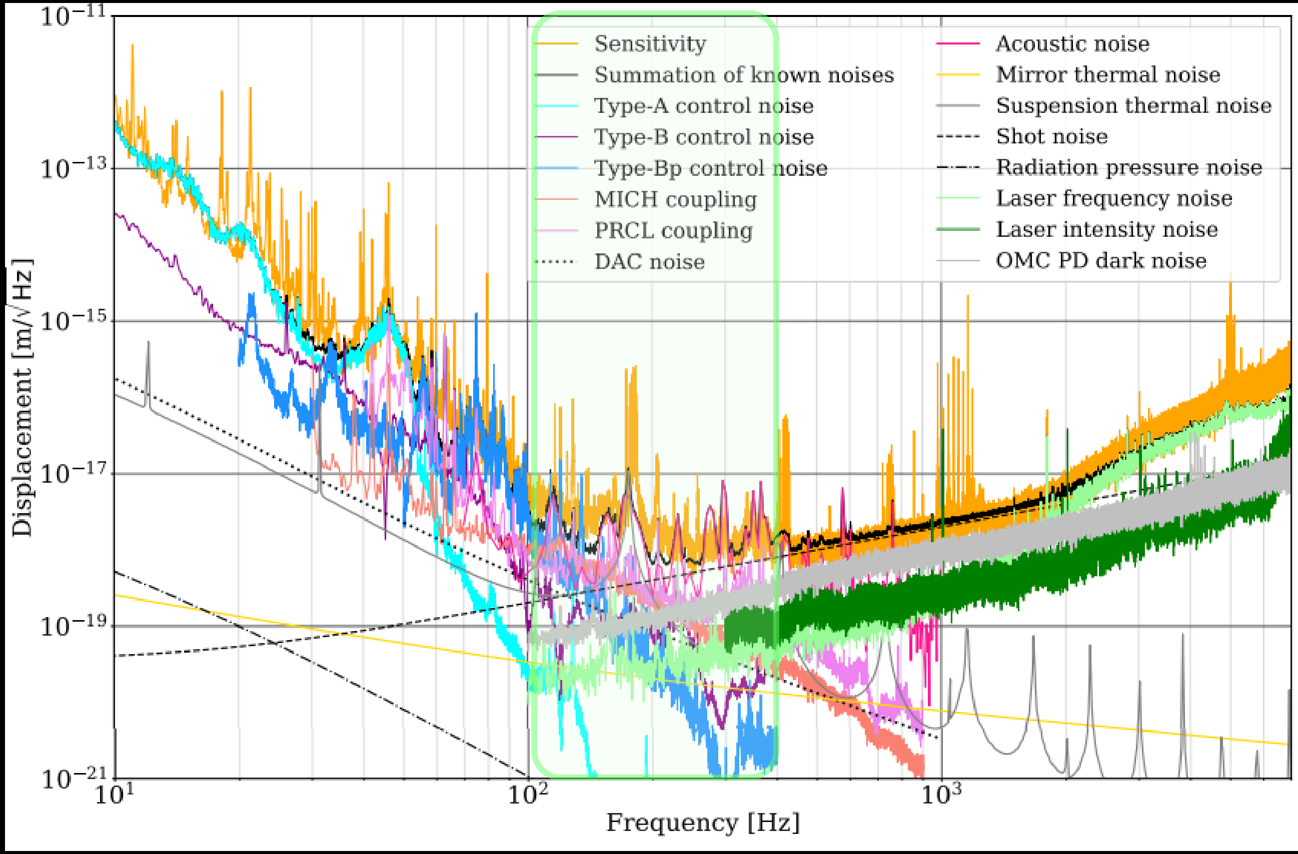
Improvement for Cryogenic Operation

- Mitigation of cryogenic payload: Stuck of a moving mass for the rough alignment of mirrors at cryogenic temp. Newly designed moving mass was installed.
- Frosting on Mirrors and cryostat viewport on the oplev. optical pass. Heaters are attached to the intermediate mass stages and viewports for defrosting. Test in IYC was successfully done.



Sensitivity Improvement (3/4)

- Mid Frequency (100Hz ~ 400 Hz):
  - Acoustic noise due to stray-light coupling → Install Baffles.
  - PRMI control noise → Filter optimization / tuning, Feedforward.

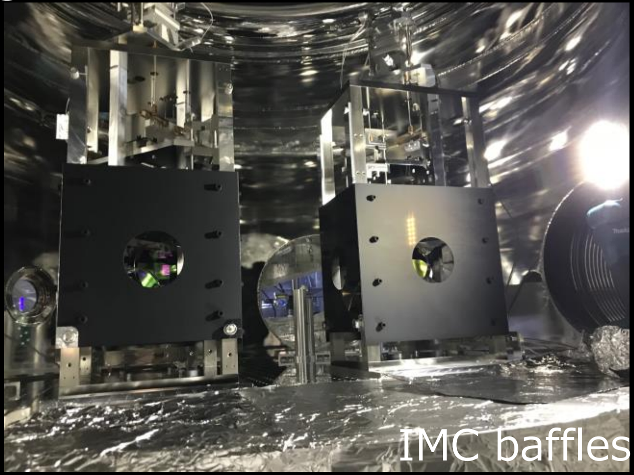


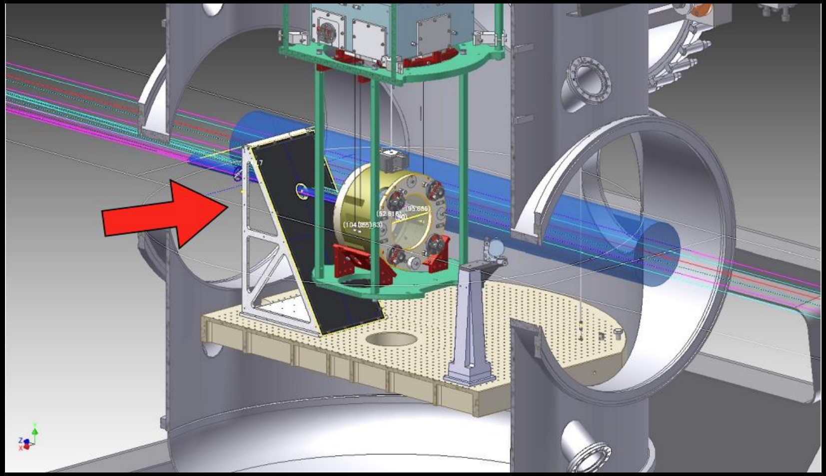
PTEP 2022 [DOI: 10.1093/ptep/ptac093]

Stray-light Mitigation

T.Akutsu

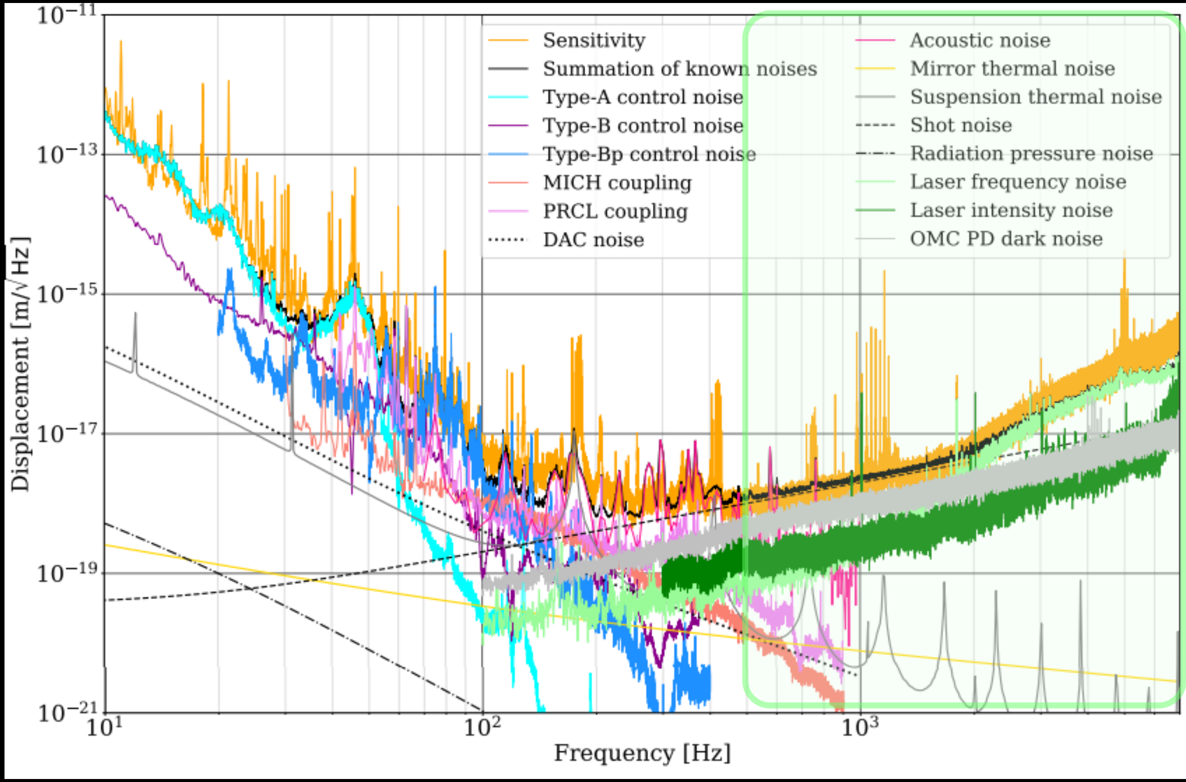
- Mid-size baffles for stray-light reduction
  - Installation of Baffles for IMC suspensions was completed.
  - Support frames for baffle for Type-B/Bp suspensions are being installed. PR2 baffle is installed.





Sensitivity Improvement (4/4)

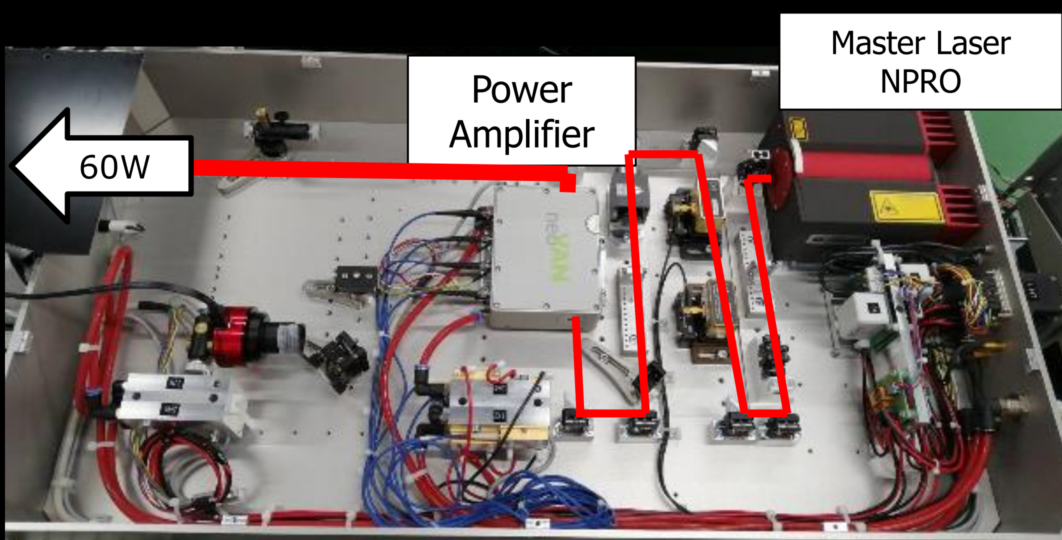
- High Frequency (400 Hz -):
  - Shot Noise: 0% SRM, High-Power Laser, OMC/PD improvement
  - Laser freq. and Int. noise: Reduction of noise and coupling with better alignment (Control with wave-front sensors).



PTEP 2022 [DOI: 10.1093/ptep/ptac093]

Shot noise and Laser noises

- Larger coupling from laser frequency and intensity noise, probably due to birefringence of sapphire test masses. Not an issue for O4 sensitivity.
- Higher-power laser source and stabilization system.
- Improvement of photo detector.



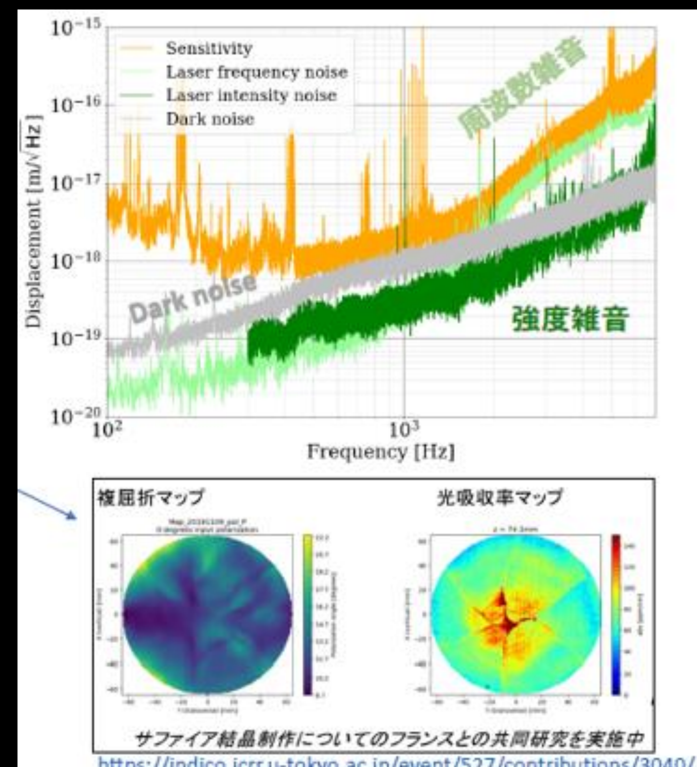


Fig. taken from presentation at LVK meeting March 2023 by J. Yokoyama

Current Status

- Recovered full operation of the interferometer
  - FPMI config.: Low-freq. noise improvement.
  - PRFPMI: High-freq. noise improvement.
- Commissioning for stability and sensitivity.

- Preparation is ongoing to join O4a.
  O4a start : May 24th, 2023 in the current plan.

Summary

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- First direct detection of GW was achieved by LIGO in 2015. ~90 events were detected so far by LIGO and VIRGO.
- KAGRA in Japan has original feature of cryogenic interferometer placed at underground site. It is a 2.5-generation GW antenna.
- Joining KAGRA to the international network will improve the source parameter estimation accuracy and polarization separation. KAGRA will join O4 in 2023.

End