Introduction to KAGRA

Department of Physics
SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

Jun'ichi Yokoyama
(RESCEU, The University of Tokyo)

On behalf of KAGRA Collaboration

Gravitational wave Physics and Astronomy
New Eyes to Observe the Universe

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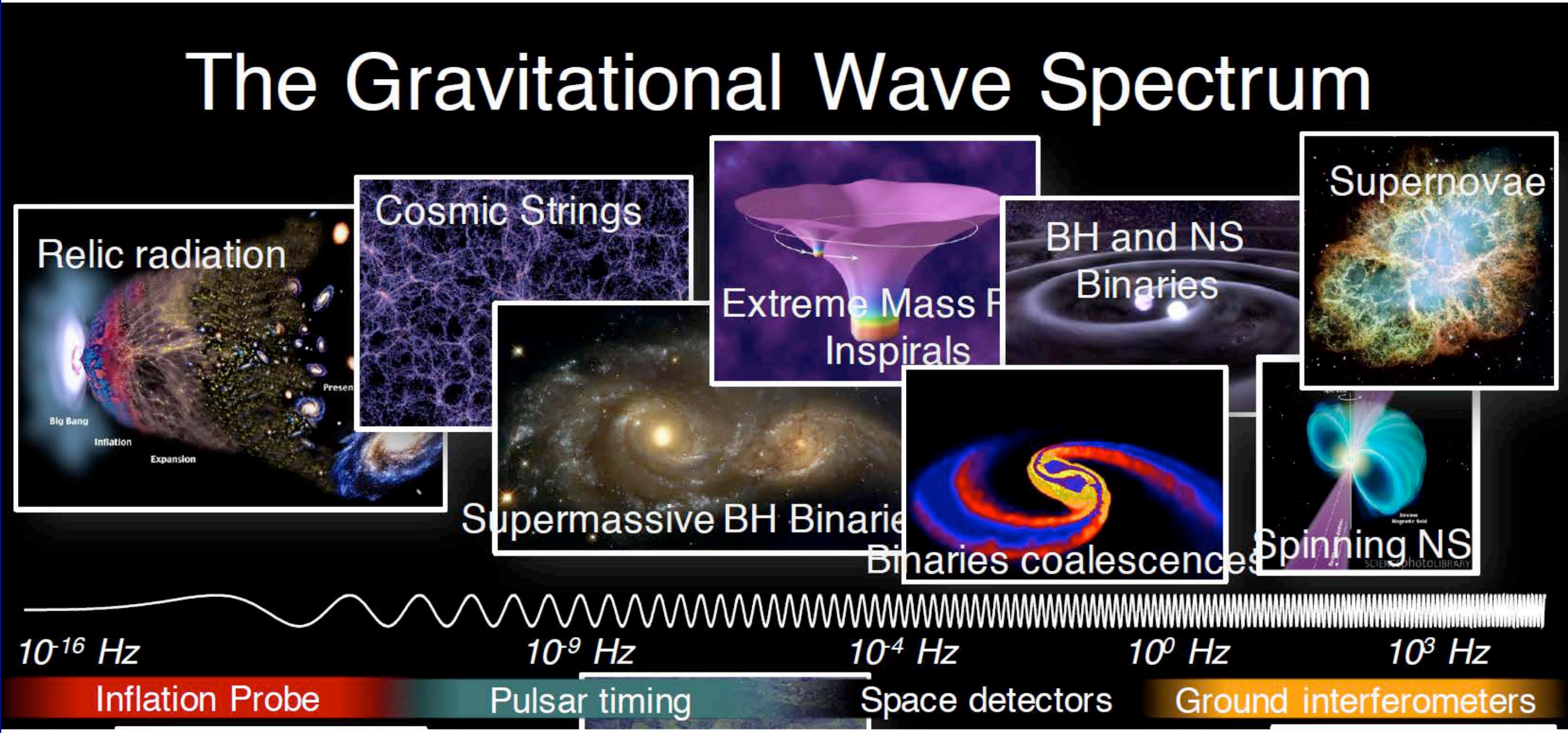
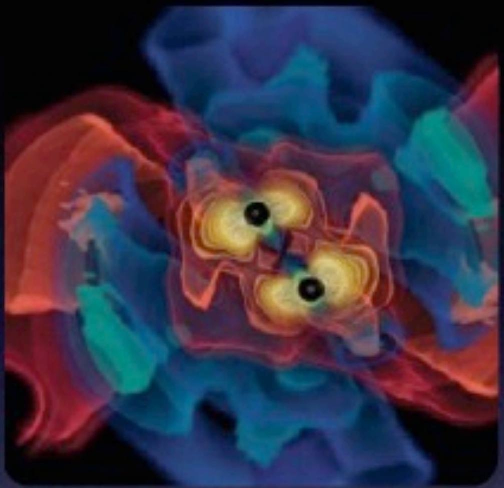


K. Kokeyama JGW-G1808116 Figure: M Evans

Gravitational wave Physics and Astronomy Science Goals

- Fundamental Physics
  - Is GR the correct theory of gravity?
  - Do black holes really have “no hair” ?
  - What is the neutron star equation of state?
- Astrophysics
  - What is the black hole mass distribution?
  - How did supermassive BHs grow?
  - What are the progenitors of GRBs?
- Cosmology
  - Can we directly see before the CMB era?
  - Can we directly see before the BBN era?

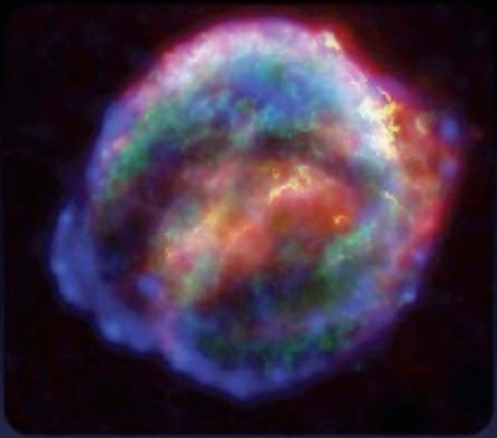
Gravitational Wave Sources



Credit: AEI, CCT, LSU

Coalescing Binary Systems

Neutron Stars,
Black Holes



Credit: Chandra X-ray Observatory

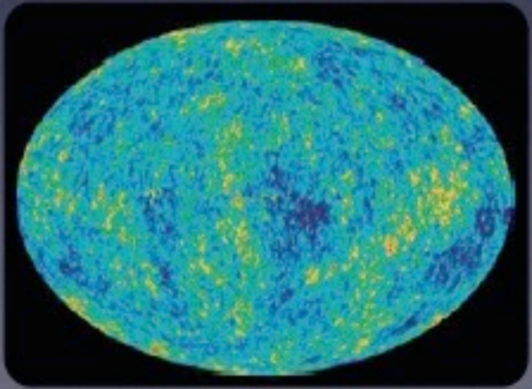
'Bursts'

asymmetric core
collapse supernovae
cosmic strings
???

Casey Reed, Penn State

Continuous Sources

Spinning neutron stars
crustal deformations,
accretion

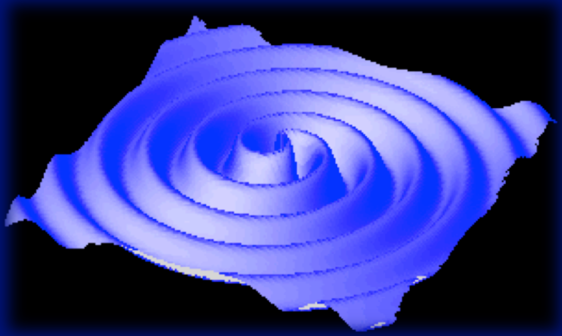


NASA/WMAP Science Team

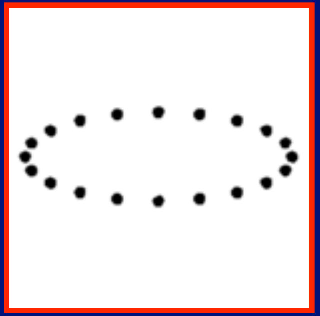
Cosmic GW background

stochastic,
incoherent
background

Gravitational Waves

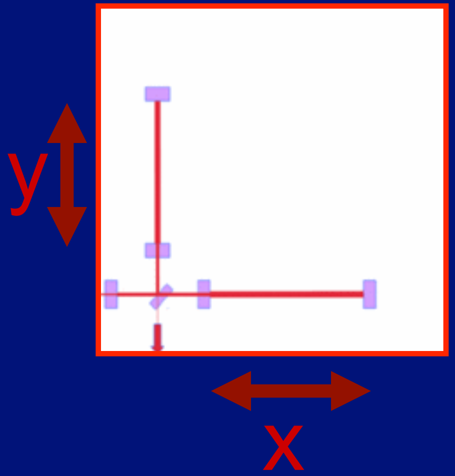


- Transverse waves with
  2 polarizations in General Relativity:

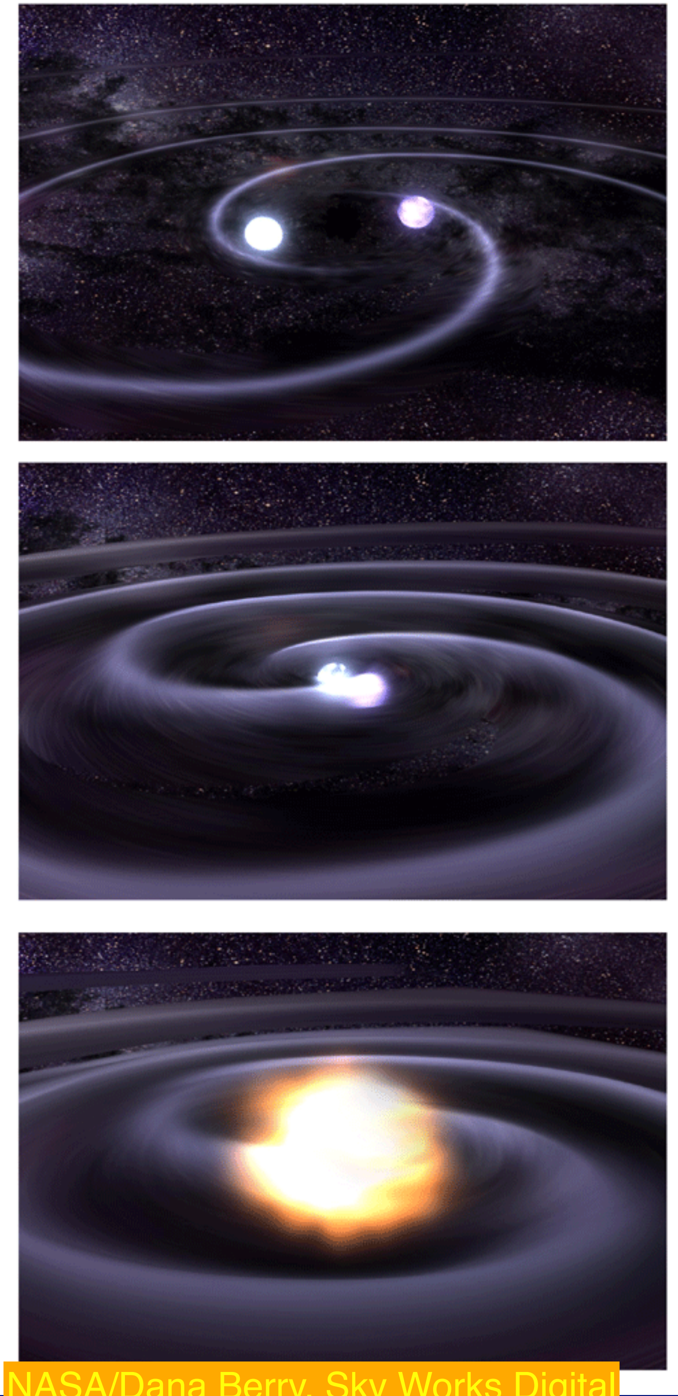


+ polarization

x polarization



- Interferometer measures:
  dL=x-y



The weakness of Gravity

$$ds^2 = -dt^2 + (\delta_{ij} + h_{ij}^{TT})dx^i dx^j$$

- Gravitational waves produced by orbiting masses:

$$\boxed{h_{ij} = \frac{2G}{c^4 d}\ddot{I}_{ij}}$$

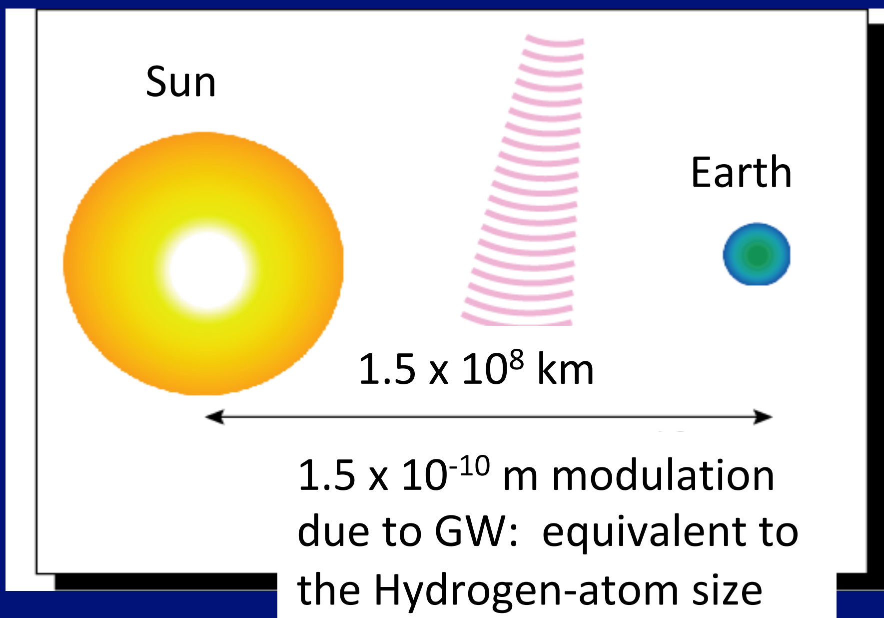
I : Quadrupole moment

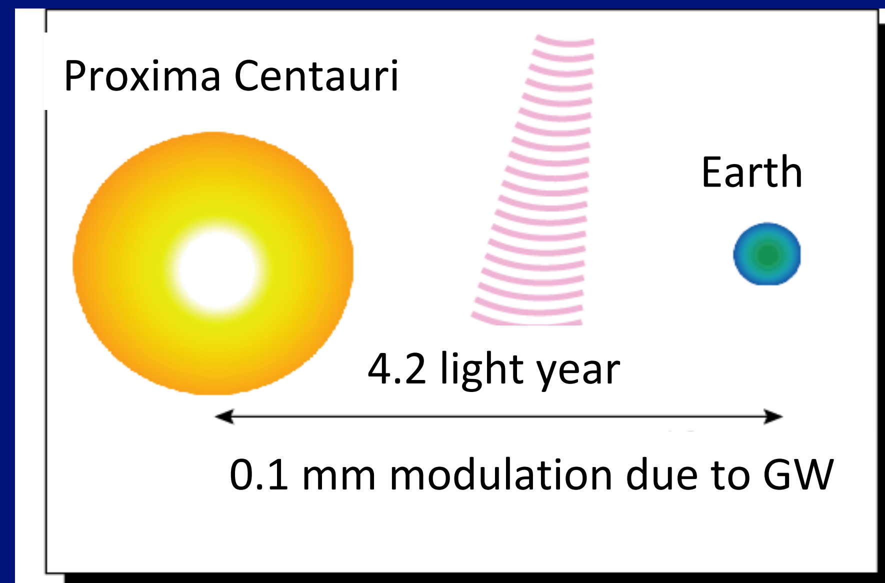
- For 2 1.4 $M_{\odot}$ Neutron stars at 1 Mpc (3 million light years):

$$\boxed{h = \frac{\Delta L}{L} \approx 3\times 10^{-21}}$$

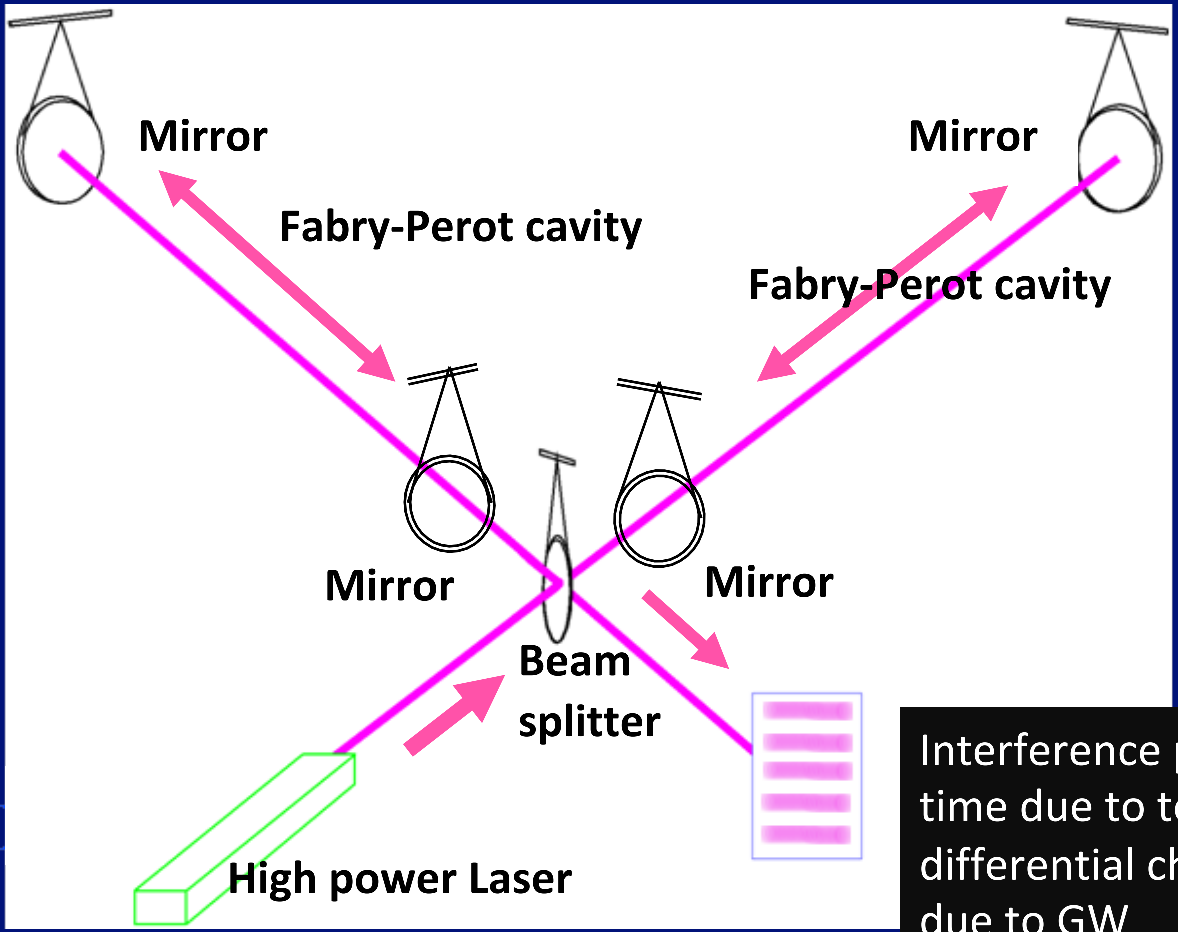
A strain (displacement) of

$$h = \frac{\Delta L}{L} \approx 3\times10^{-21}$$





Use a Laser interferometer to detect GWs



Interference pattern changes in time due to temporal differential change in distances due to GW

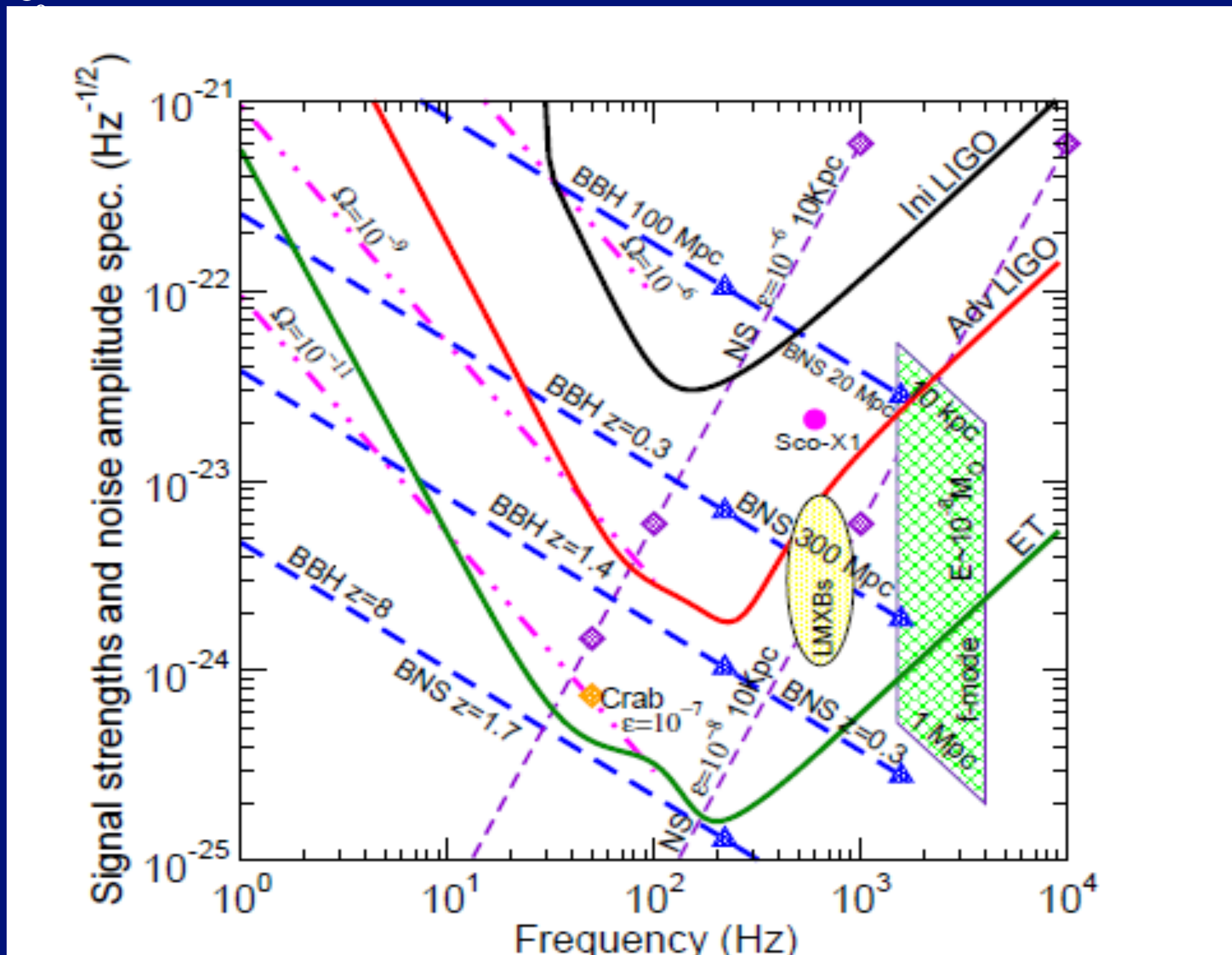
World wide network of km class laser interferometers

$$\left\langle h_{ij}h^{ij}\right\rangle = \int_{-\infty}^{\infty} df\, S_h^2(f) \qquad S_h(f) \equiv h(f)$$

: signal strength in Fourier space or strain. unit: $1/\sqrt{\mathrm{Hz}}$

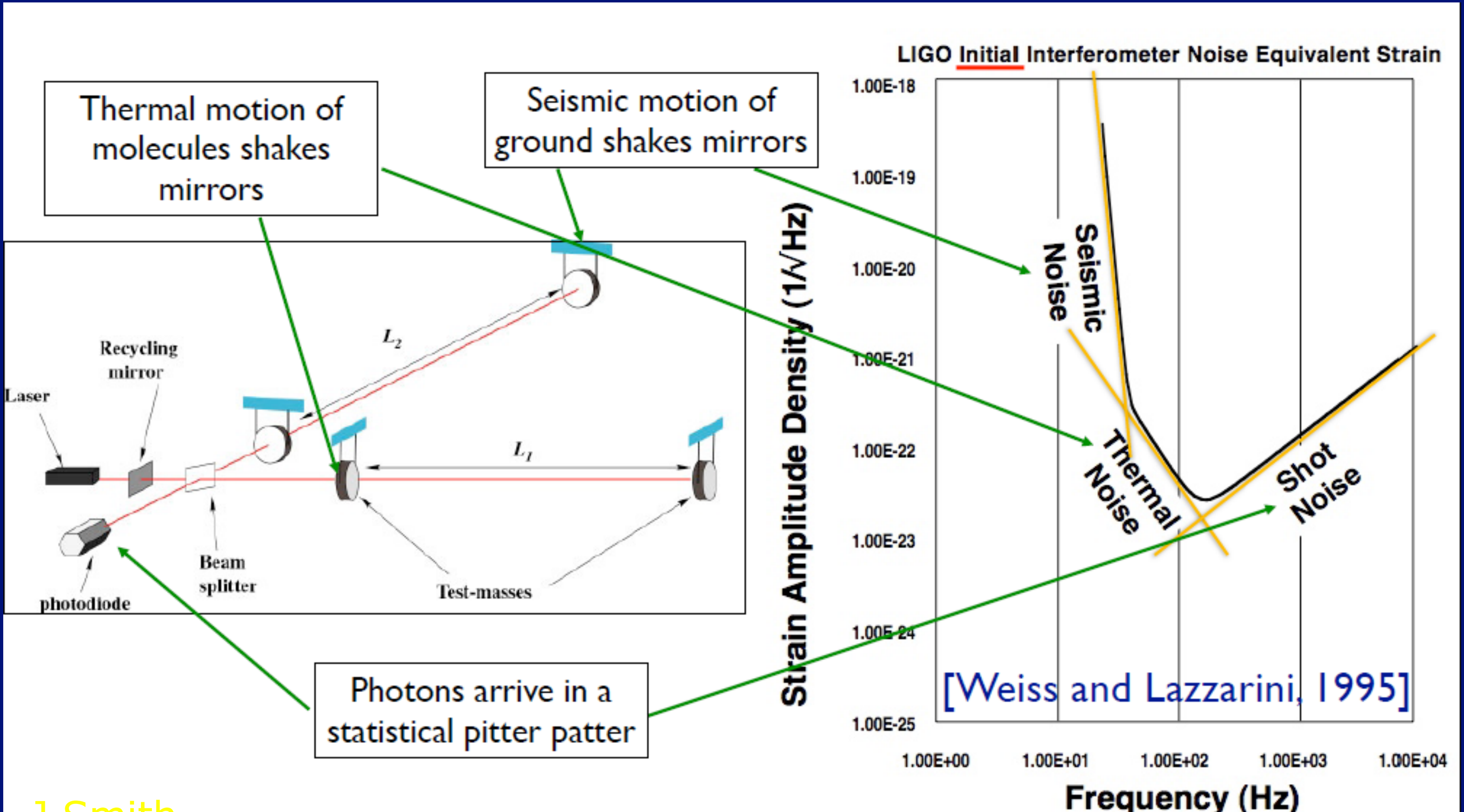
$$\left\langle n^2(t)\right\rangle = \int_{-\infty}^{\infty} df\, S_n^2(f) \qquad S_n(f)$$

: noise amplitude, unit $1/\sqrt{\mathrm{Hz}}$



Sathyaprakash & Schutz Liv. Rev. Rel. (2009)

Origin of the noise curve



J Smith

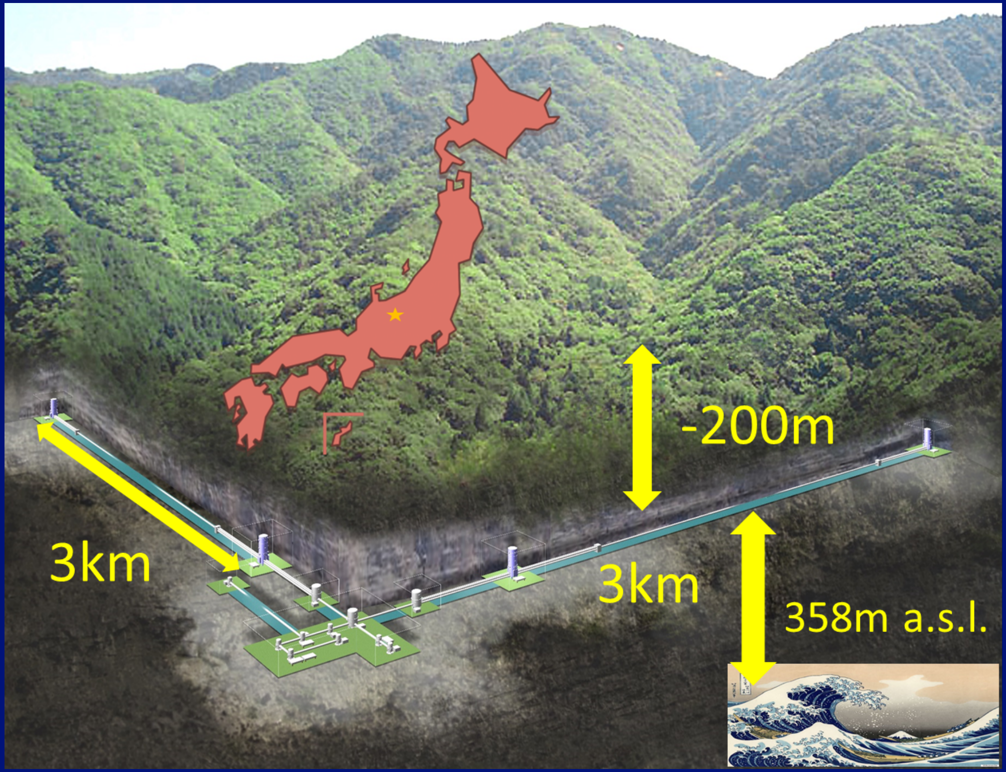
KAGRA

Large-scale Cryogenic Gravitational wave Telescope underground in Kamioka, Hida-city, Gifu, Japan

http://gwcenter.icrr.u-tokyo.ac.jp/en/

Host institutions:

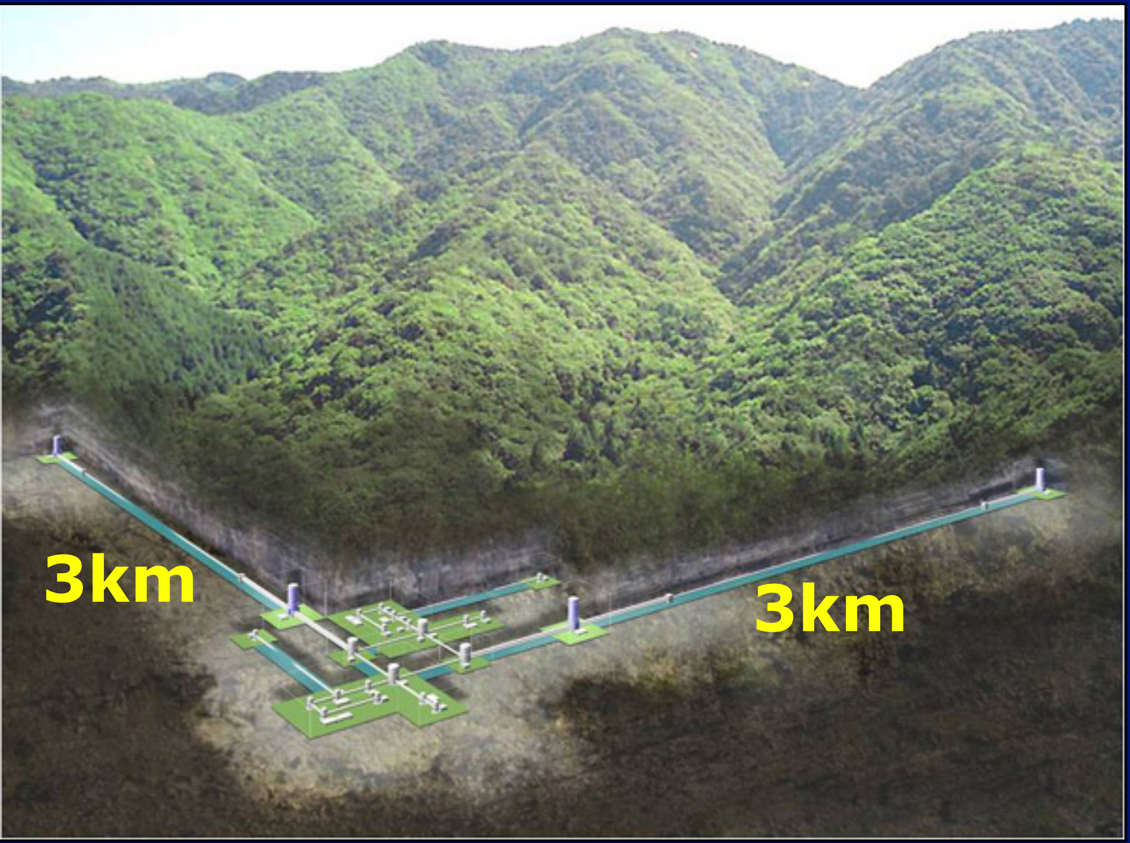
* ICRR (Institute for Cosmic Ray Research, U. Tokyo)
* NAOJ (National Astronomical Observatory of Japan)
* KEK (High Energy Accelerator Research Organization)



505 members in 14 countries and regions
200 authorship holders, 112 research groups

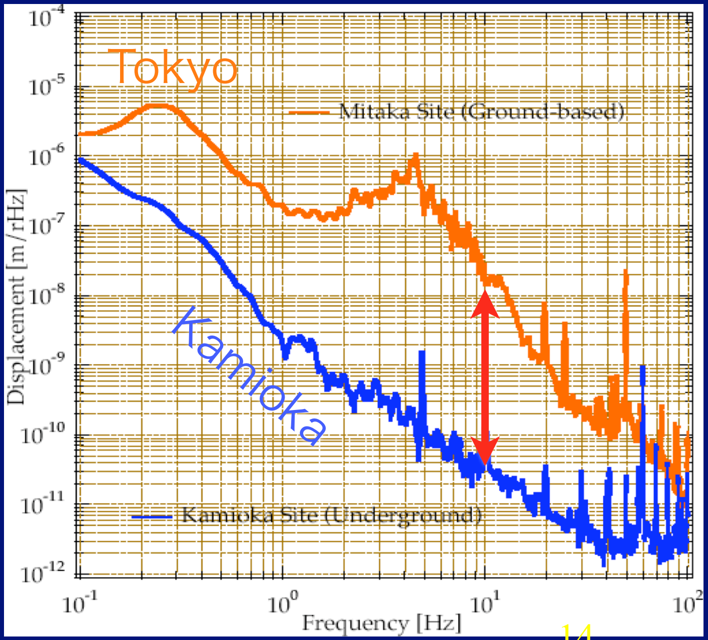
KAGRA

World's first
2.5th generation GW detector



Cryogenic to reduce thermal noises (T=20K @mirrors)

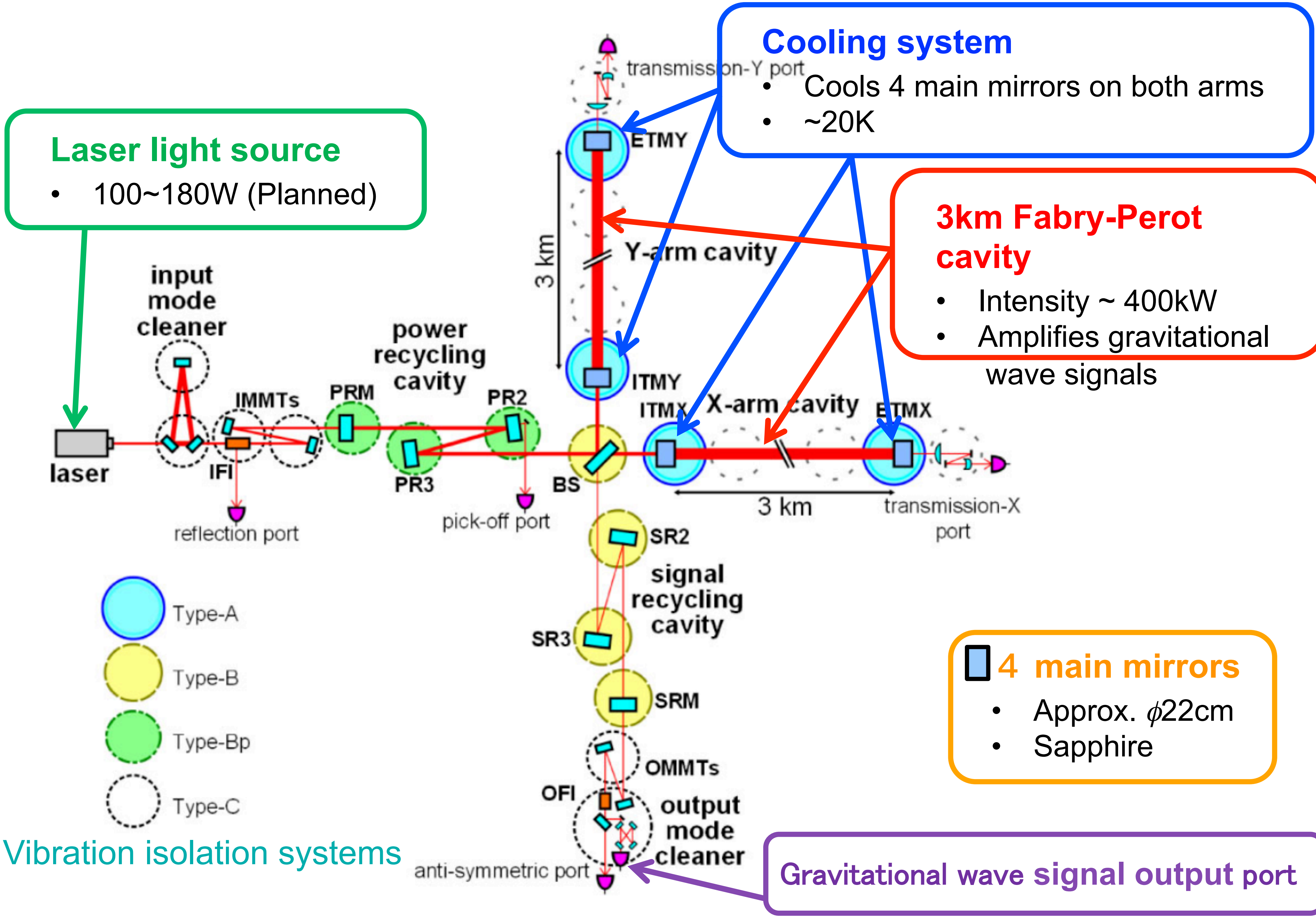
Underground to reduce seismic noises



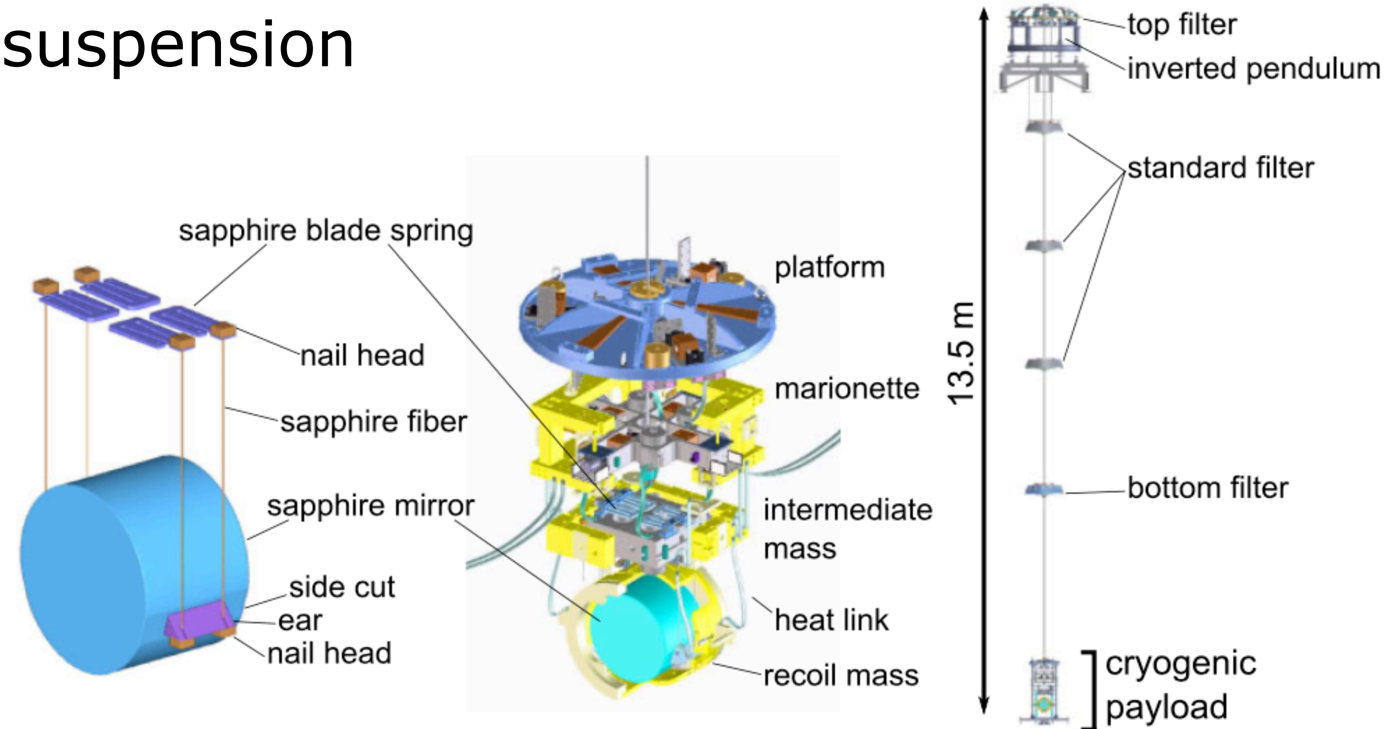
Amplitude of seismic motion

Fabry-Perot Michelson type
Laser interferometer

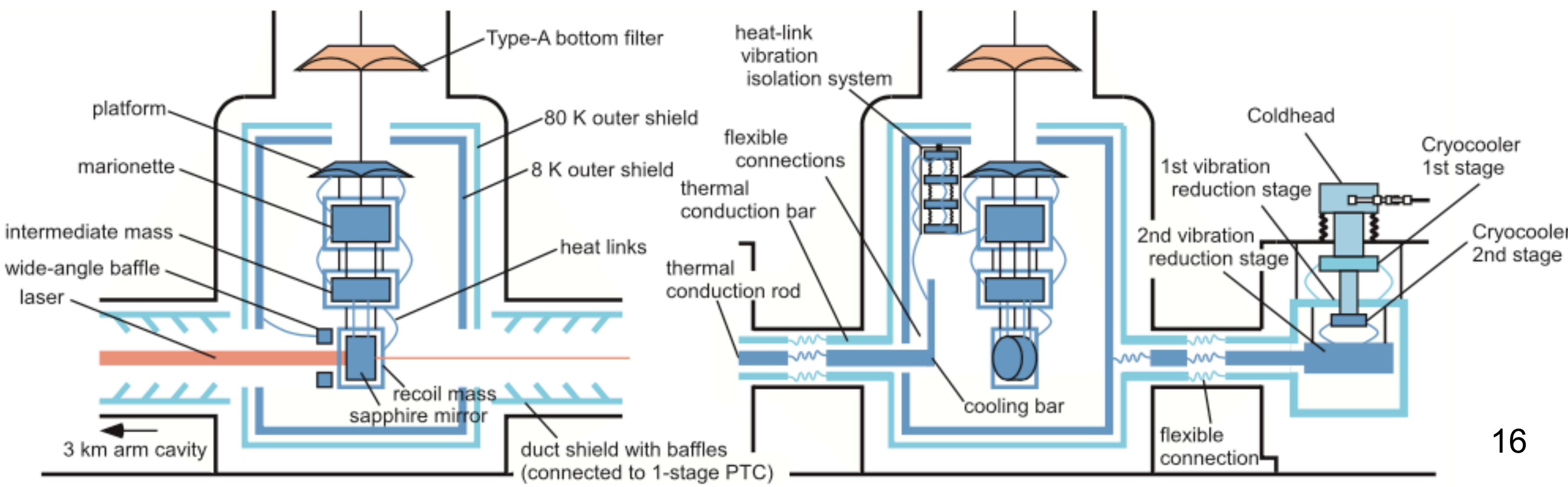
Detector configuration (cf Uchiyama-san's talk for O3 & O4 config.)



Type A suspension



Cooling system



History of KAGRA I Timeline as of 2014 (1-year delay due to the great eastern Japan earthquake on 2011/3/11)

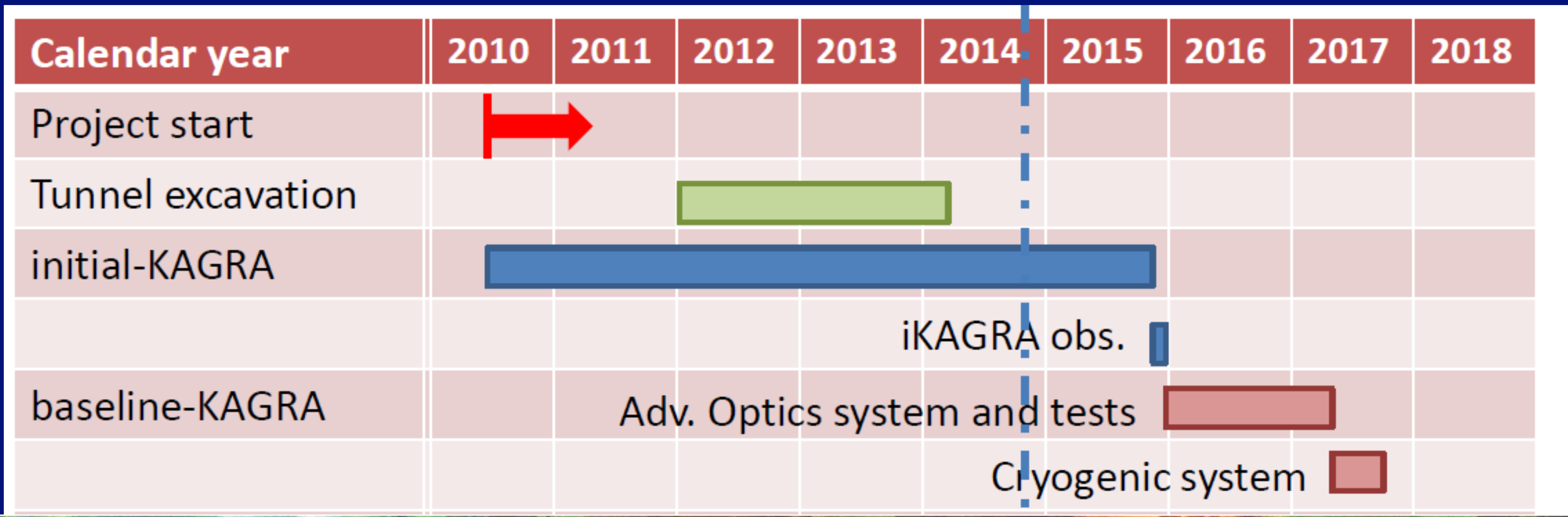


Fig. 3: A panorama photo taken in December 2012 at the central branching point near the Atotsu entrance.

Tunnel excavation was completed just on (revised) schedule in March 2014.


ASSOCIATION OF ASIA PACIFIC PHYSICAL SOCIETIES

AAPPS

Volume 24 | Number 4 | AUGUST 2014

Bulletin

High-intensity 100-MeV Proton Linac at KOMAC

Completion of KAGRA Tunnel Excavation

ISSN:0218-2203

Feature Articles

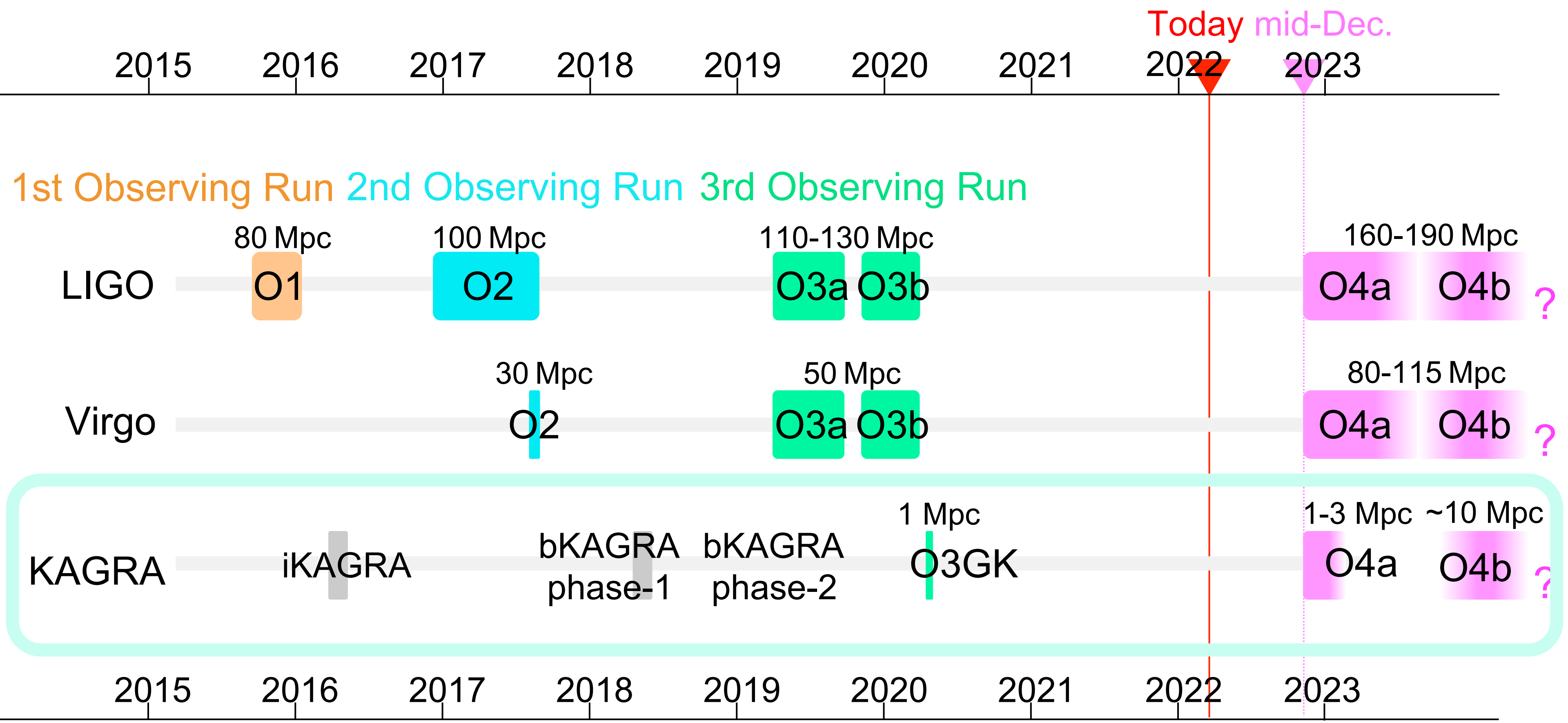
- Ultra-high Power Lasers and Strong Field Science Research in Asia
- Petawatt Laser at KPSI, Japan
- Sappire Laser Facility at IBS, Korea
- Femtosecond Petawatt Laser in China
- High Intensity Laser Science in India
- High Power Laser at ILE, Japan

Physics Focus

- First-principle Calculations Reveal How High-performance Magnets Are Achieved by Interstitial Nitrogen
- Perspectives on the PandaX Dark Matter Experiment

Activities and Research News

- EAST Starts a New Phase of Experiments
- Coordinated Access to Light Sources
- The Commissioning of KOMAC, a 100-MeV Proton Linac
- KAGRA Tunnel Excavation Is Complete

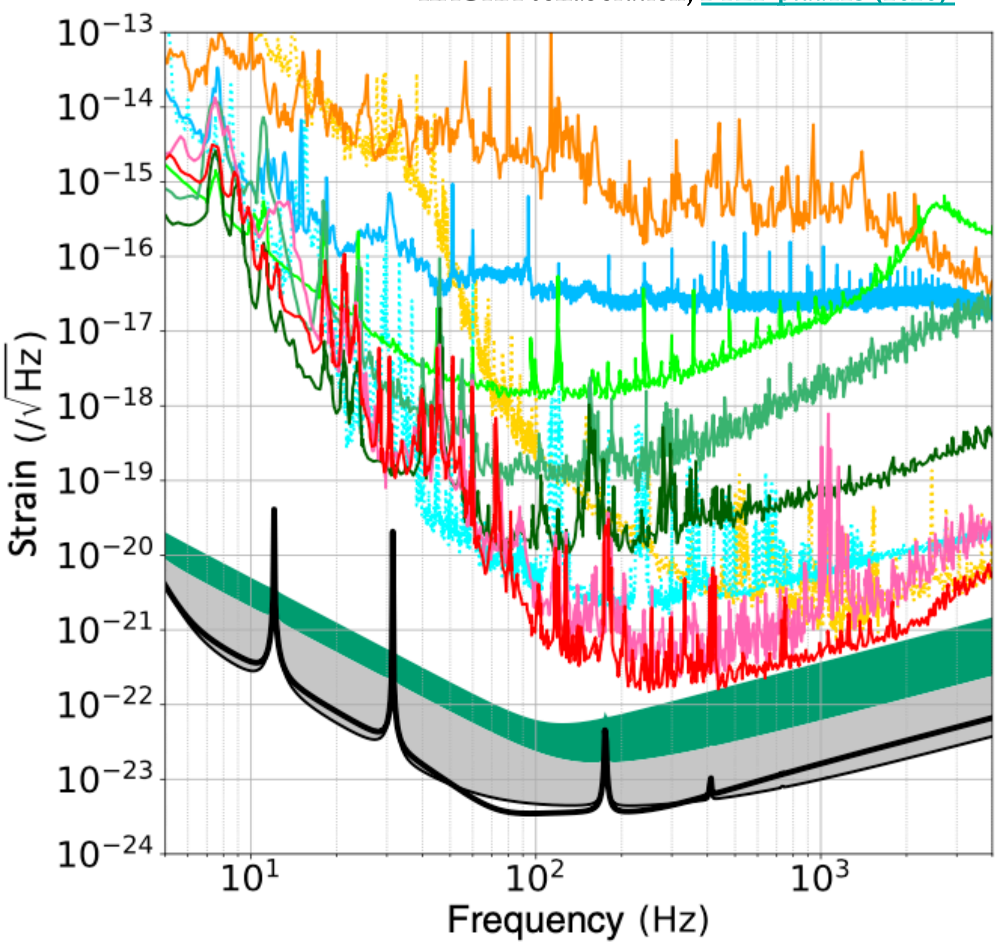


- iKAGRA - Michelson interferometer at room temperature.
- bKAGRA phase-1 - Michelson interferometer with **cryogenic operation**.
- bKAGRA phase-2 - All elements have been installed.
- O3GK - **Power-Recycling Fabry-Perot** Michelson interferometer at room temperature.

T. Sawada

History of KAGRA II

KAGRA collaboration, PTEP ptaa125 (2020)



2010 Funded by MEXT Japan
2012 Construction Started
2016 Test Operation @ normal temp. (iKAGRA)

We published the first paper using the KAGRA data

PTEP

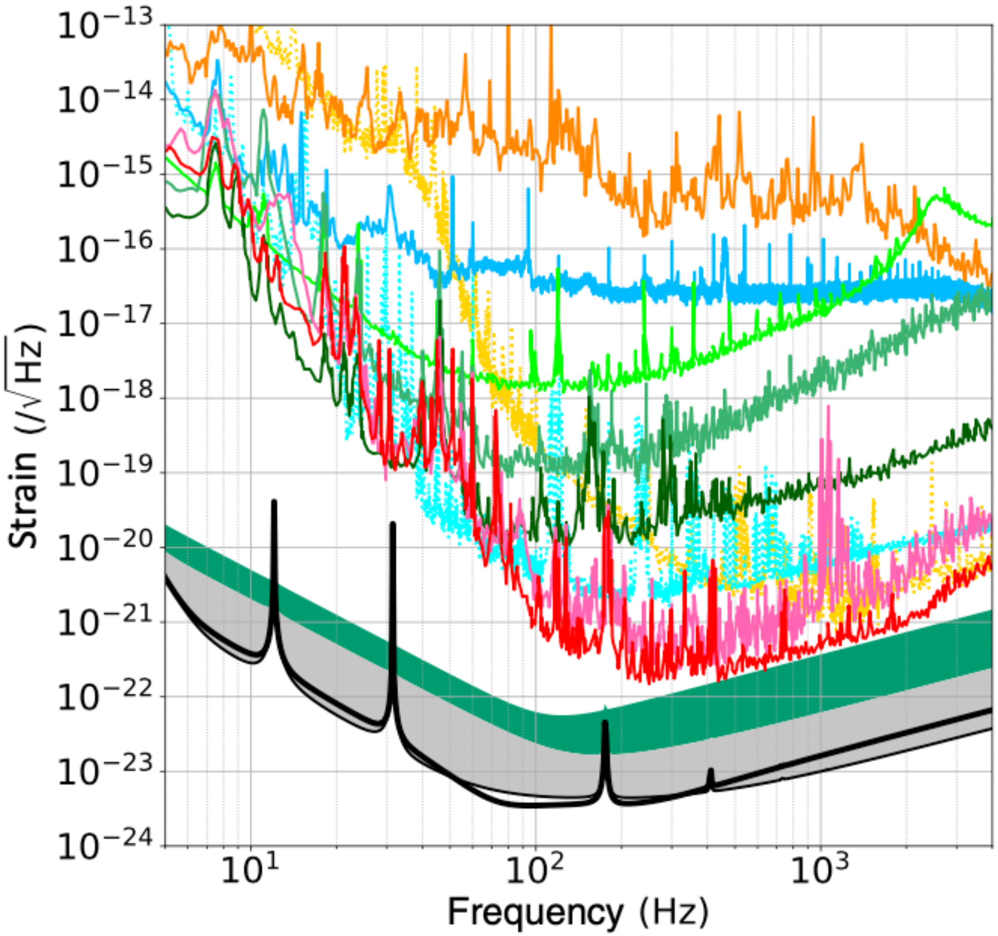
Prog. Theor. Exp. Phys. **2020**, 053F01 (19 pages)
DOI: 10.1093/ptep/ptaa056

Application of independent component analysis to the iKAGRA data

KAGRA Collaboration

T. Akutsu[1,2], M. Ando[3,4,1], K. Arai[5], Y. Arai[5], S. Araki[6], A. Araya[7], N. Aritomi[3], H. Asada[8], Y. Aso[9,10], S. Atsuta[11], K. Awai[12], S. Bae[13], Y. Bae[14], L. Baiotti[15], R. Bajpai[16], M. A. Barton[1], K. Cannon[4], E. Capocasa[1], M. Chan[17], C. Chen[18,19], K. Chen[20], Y. Chen[19], H. Chu[20], Y-K. Chu[21], K. Craig[5], W. Creus[21], K. Doi[22], K. Eda[4], S. Eguchi[17], Y. Enomoto[3], R. Flaminio[23,1], Y. Fujii[24], M.-K. Fujimoto[1], M. Fukunaga[5], M. Fukushima[1], T. Furuhata[22], G. Ge[25], A. Hagiwara[5,26], S. Haino[21], K. Hasegawa[5], K. Hashino[22], H. Hayakawa[12], K. Hayama[17], Y. Himemoto[27], Y. Hiranuma[28], N. Hirata[1], S. Hirobayashi[29], E. Hirose[5], Z. Hong[30], B. H. Hsieh[31], G-Z. Huang[30], P. Huang[25], Y. Huang[21], B. Ikenoue[1], S. Imam[30], K. Inayoshi[32], Y. Inoue[20], K. Ioka[33], Y. Itoh[34,35], K. Izumi[36], K. Jung[37], P. Jung[12], T. Kaji[35], T. Kajita[38], M. Kakizaki[22], M. Kamiizumi[12], S. Kanbara[22], N. Kanda[34,35], S. Kanemura[39], M. Kaneyama[35], G. Kang[13], J. Kasuya[11], Y. Kataoka[11], K. Kawaguchi[5], N. Kawai[11], S. Kawamura[12], T. Kawasaki[3], C. Kim[40], J. C. Kim[41], W. S. Kim[14], Y.-M. Kim[37], N. Kimura[26], T. Kinugawa[42], S. Kirii[12], N. Kita[3], Y. Kitaoka[35], H. Kitazawa[22], Y. Kojima[43], K. Kokeyama[12], K. Komori[3], A. K. H. Kong[19], K. Kotake[17], C. Kozakai[9], R. Kozu[44], R. Kumar[45], J. Kume[4,3,*], C. Kuo[20], H-S. Kuo[30], S. Kuroyanagi[46], K. Kusayanagi[11], K. Kwak[37], H. K. Lee[47], H. M. Lee[48,49], H. W. Lee[41], R. Lee[19], M. Leonardi[1], C. Lin[37], C-Y. Lin[50], F-L. Lin[30], G. C. Liu[18], Y. Liu[51], L. Luo[21], E. Majorana[52], S. Mano[53], M. Marchio[1], T. Matsui[54], F. Matsushima[22], Y. Michimura[3], N. Mio[55], O. Miyakawa[12], A. Miyamoto[35], T. Miyamoto[44], Y. Miyazaki[3], K. Miyo[12], S. Miyoki[12], W. Morii[56], S. Morisaki[4], Y. Moriwaki[22], T. Morozumi[5], M. Musha[57], K. Nagano[5], S. Nagano[58], K. Nakamura[1], T. Nakamura[59], H. Nakano[60], M. Nakano[22,5], K. Nakao[35], R. Nakashima[11], T. Narikawa[59], L. Naticchioni[52], R. Negishi[28], L. Nguyen Quynh[61], W.-T. Ni[25,62,63], A. Nishizawa[4], Y. Obuchi[1], T. Ochi[5], W. Ogaki[5], J. J. Oh[14], S. H. Oh[14], M. Ohashi[12], N. Ohishi[9], M. Ohkawa[64], K. Okutomi[12], K. Oohara[28], C. P. Ooi[3], S. Oshino[12], K. Pan[19], H. Pang[20], J. Park[65], F. E. Peña Arellano[12], I. Pinto[66], N. Sago[67], M. Saijo[68], S. Saito[1], Y. Saito[12], K. Sakai[69], Y. Sakai[28], Y. Sakai[3], Y. Sakuno[17], M. Sasaki[70], Y. Sasaki[71], S. Sato[72], T. Sato[64], T. Sawada[34], T. Sekiguchi[4], Y. Sekiguchi[73], N. Seto[59], S. Shibagaki[17], M. Shibata[33,74], R. Shimizu[1], T. Shimoda[3], K. Shimode[12], H. Shinkai[75], T. Shishido[10], A. Shoda[1], K. Somiya[11], E. J. Son[14], H. Sotani[1], A. Suemasa[57], R. Sugimoto[22], T. Suzuki[64], T. Suzuki[5], H. Tagoshi[5], H. Takahashi[71], R. Takahashi[1], A. Takamori[7], S. Takano[3], H. Takeda[3], M. Takeda[28], H. Tanaka[31], K. Tanaka[35], K. Tanaka[31], T. Tanaka[5], T. Tanaka[59], S. Tanioka[1,10], E. N. Tapia San Martin[1], D. Tatsumi[1], S. Telada[76], T. Tomaru[1], Y. Tomigami[34], T. Tomura[12], F. Travasso[77,78], L. Trozzo[12], T. Tsang[79], K. Tsubono[3], S. Tsuchida[34], T. Tsuzuki[1], D. Tuyenbayev[21], N. Uchikata[80], T. Uchiyama[12], A. Ueda[26], T. Uehara[81,82], S. Ueki[71], K. Ueno[4], G. Ueshima[71], F. Uraguchi[1], T. Ushiba[5], M. H. P. M. van Putten[83], H. Vocca[78],

History of KAGRA II



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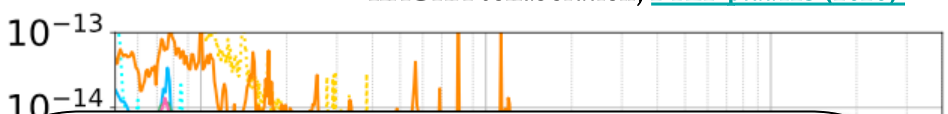
2012 Construction Started
2016 Test Operation @ normal temp. (iKAGRA)
2018 Cryogenic Test Operation (bKAGRA)
2019/8 FPMI
2019/10 Joint Research MoA with LIGO-VIRGO
2019/11 FPMI
2019/12 FPMI
2020/2 PRFPMI
2020/3 Joined O3 PRFPMI (@normal temp.)
2020/4 Observation O3GK

FPMI=Fabry-Perot Michelson Interferometer
PRFPMI=Power Recycling Fabry-Perot Michelson Interferometer

History of KAGRA II

KAGRA collaboration, PTEP ptaa125 (2020)



Joint Research MoA with LIGO-VIRGO

Signed on Oct. 4, 2019

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2019/10 Joint Research MoA with LIGO-VIRGO
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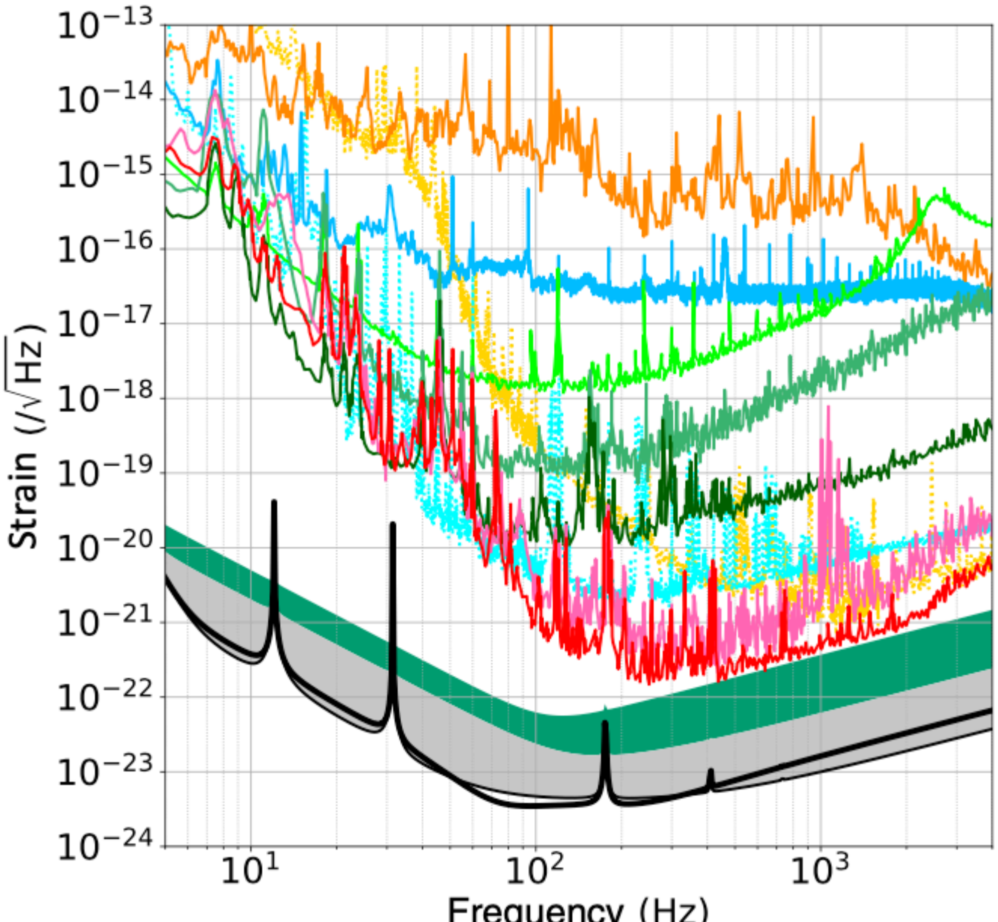
KAGRA collaboration, PTEP ptaa125 (2020)



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2020/3 Joined O3 PRFPMI (@normal temp.)
2020/4 Observation O3GK

FPMI=Fabry-Perot Michelson Interferometer
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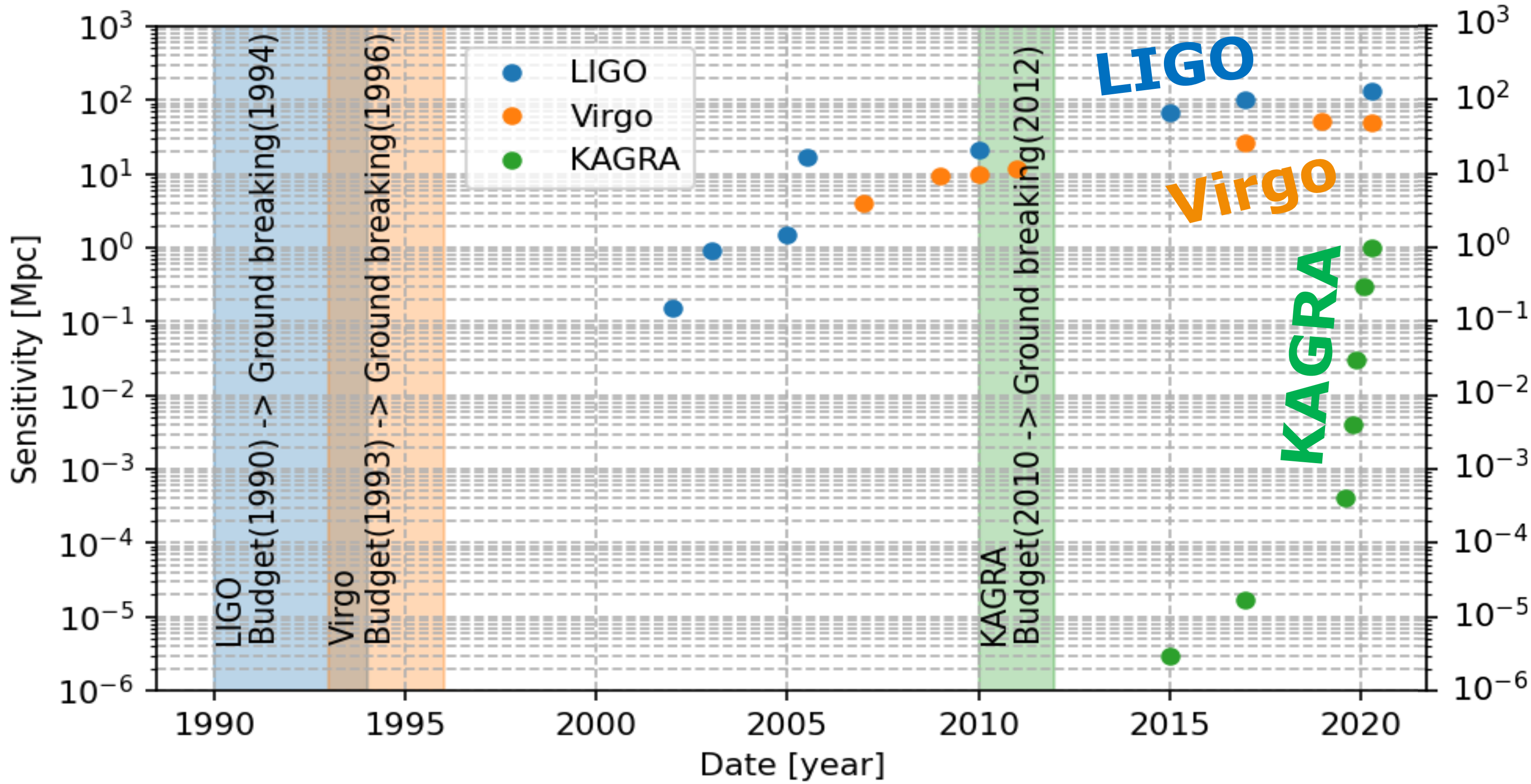
History of KAGRA III

Evolution of the distance to which a binary neutron star (BNS) merger is detectable with S/N> 8: BNS range[Mpc]

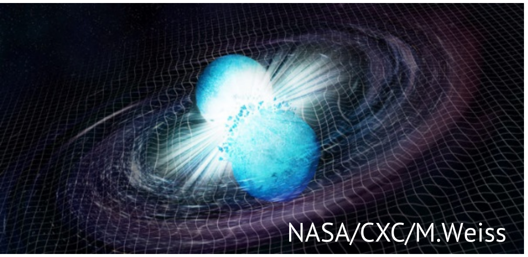


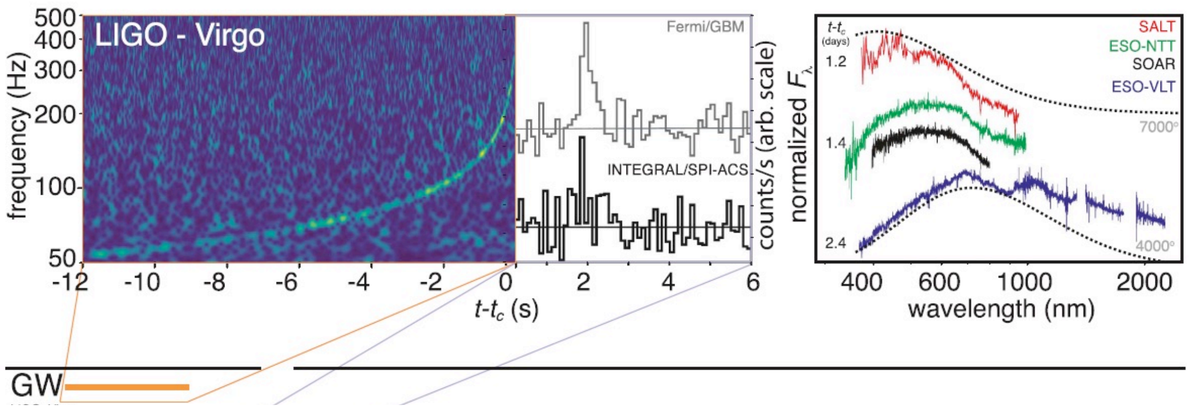
KAGRA started 20 (17) years after LIGO (Virgo).
Its sensitivity has been improving very rapidly since the start of its operation until the start of O3GK.

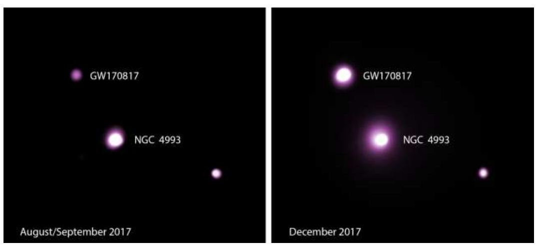
Observing Runs of LIGO, LIGO-Virgo, and LVK

- 2015. 9 - 2016. 1 :   1st Observing Run (O1)
  - LIGO only
  - GW150914   First direct detection of GWs – binary black hole merger

GW170817: Birth of multimessenger astrophysics







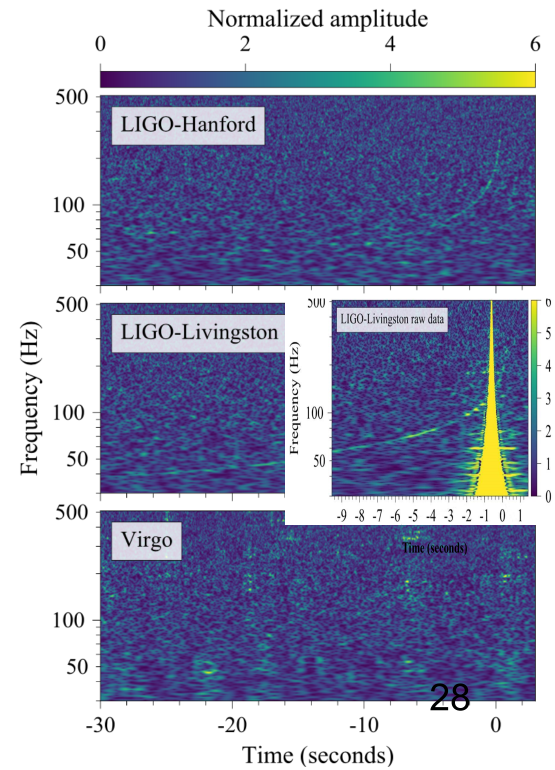
1min 10min 1hour 1day
10days

GW170817: Birth of multimessenger astrophysics

As of August 17, 2017, 6 real-time signal detection pipelines were in operation, namely,

- cWB: Coherent wavelet method
- LALInference oLIB: Burst detection pipeline
- MBTA: Multiband template method
- SPIIR: Summed parallel infinite impulse response
- PyCBC: Compact binary coalescence search
- GstLAL: Compact binary coalescence search

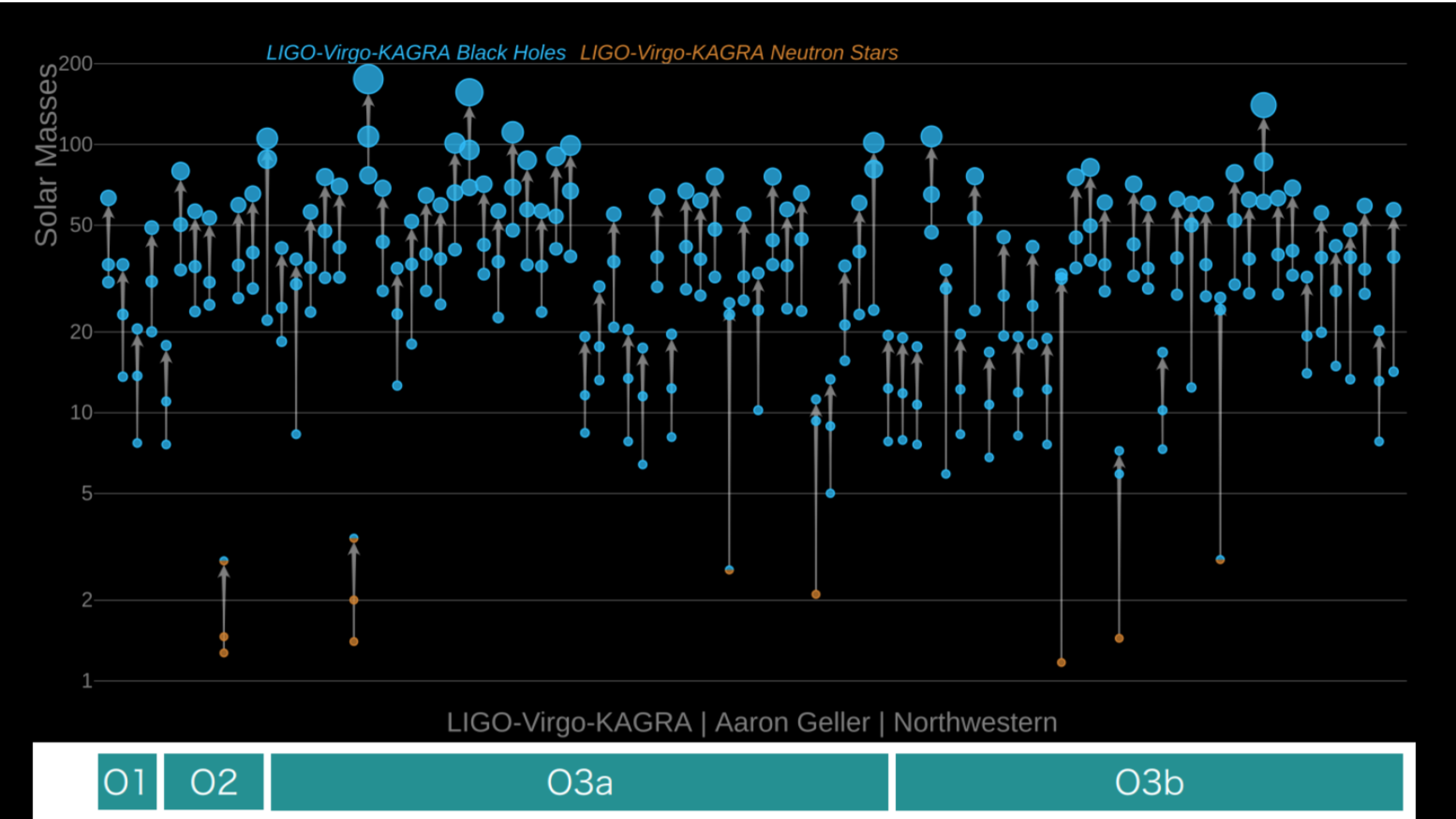
Among them, only GstLAL successfully detected the event! (developed by Kipp Cannon@RESCEU and Chad Hanna et al).



Observing Runs of LIGO, LIGO-Virgo, and LVK

- 2015. 9 - 2016. 1 : 1st Observing Run (O1)
  - LIGO only
  - GW150914 First direct detection of GWs – binary black hole merger
- 2016. 11 - 2017. 8 : 2nd Observing Run (O2),
  - First LIGO only, Virgo joined on August 1st.
  - GW170814 First triple-detector GW detection
  - GW170817 First binary neutron star merger detection (NS-NS)
  - Birth of multi-messenger astronomy with GW
- 2019. 4 - 2020. 3 : 3rd Observing Run (O3 = O3a + O3b)
  - The observation was scheduled until the end of April 2020, but due to Covid-19, it was terminated in March 2020.

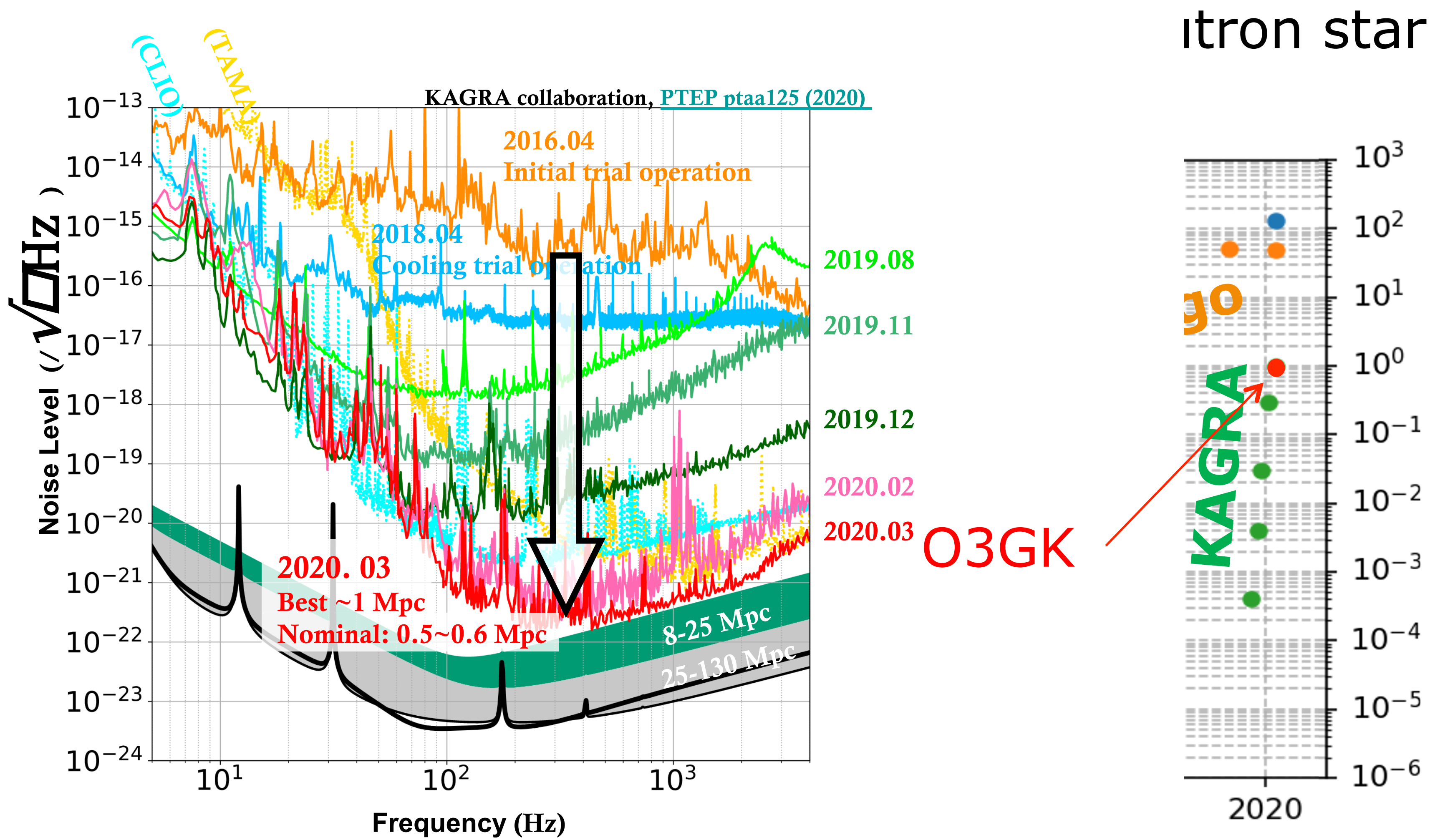
LIGO and Virgo have found 3+8+44+35=90 events so far.



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

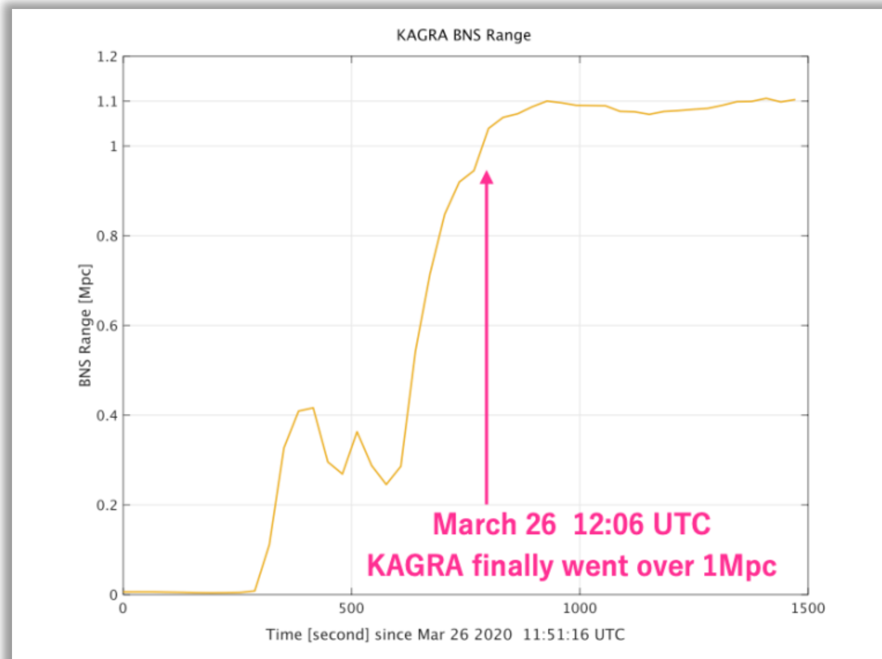
modified by M. Ando

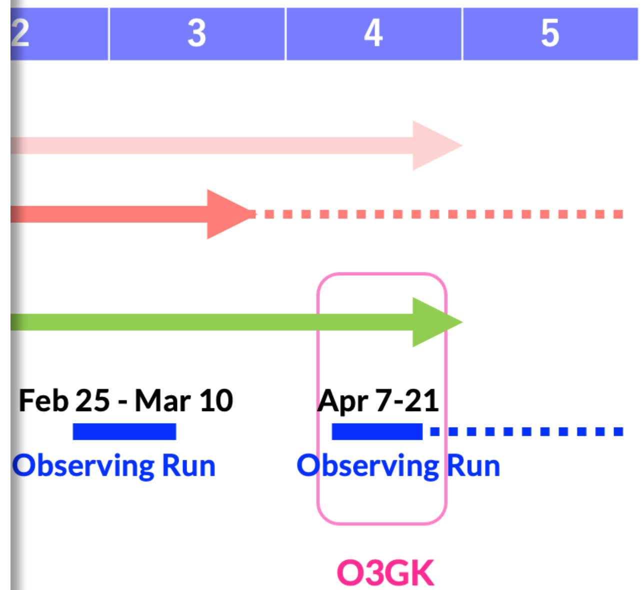
History of KAGRA III



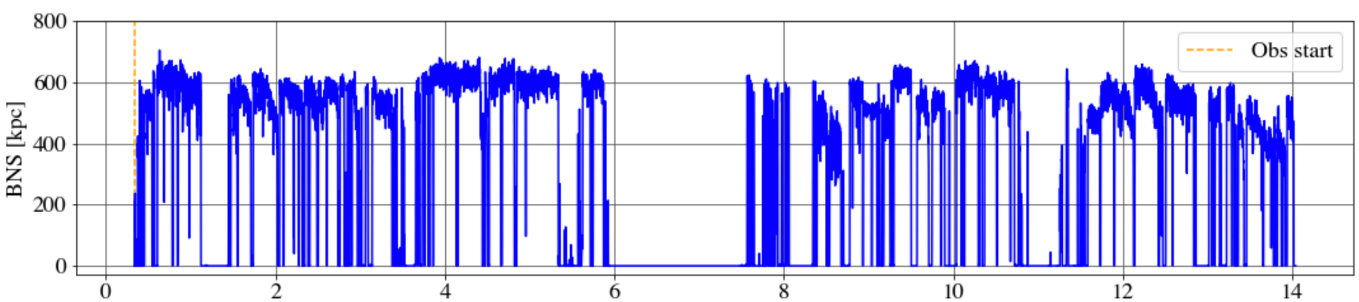
KAGRA started 20 (17) years after LIGO (Virgo).
Its sensitivity has been improving very rapidly since the start of its operation until the start of O3GK.

O3GK Joint observation with GEO600 during the third observation run of LV(K); O3.





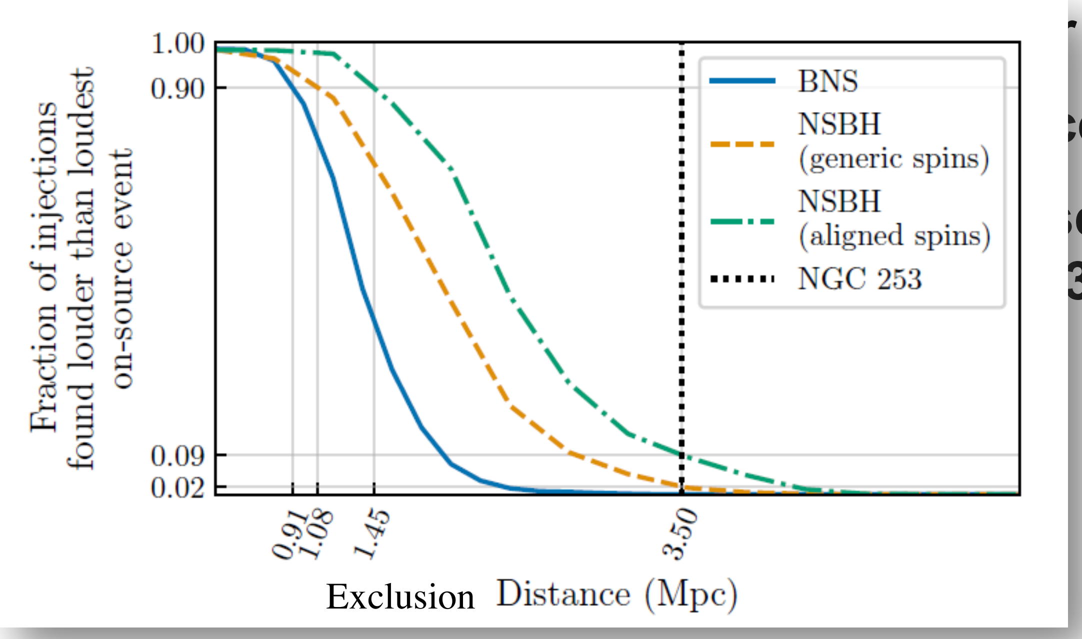
Apr. 7, 2020. 8:00 UTC – Apr. 21, 2020. 0:00 UTC
Average sensitivity in terms of BNS range: 0.6Mpc (Max 1Mpc)



T. Sawada

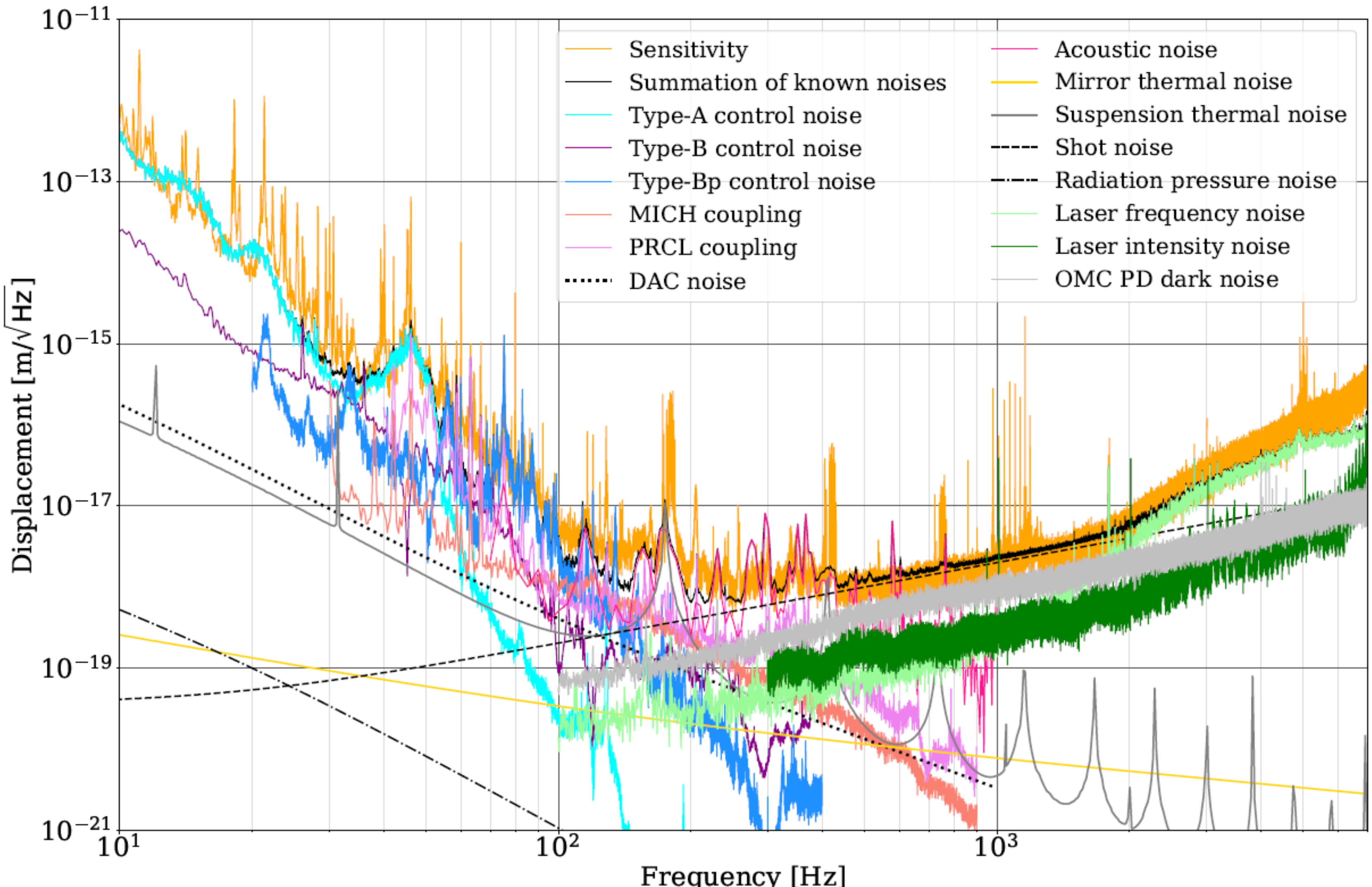
Achievements of O3GK

- **Collaborative work as LVK collaboration**
  - **First full-scale experience of collaborative analysis since KAGRA joined LV (GEO600 is a part of LIGO).**
  - **Building pipelines from acquisition to analysis of data from observation networks, incorporating KAGRA Data-Quality.**
- **Publication of observation results**
  - **Submitte[…] paper.**
  - **Search fo[…]es, etc.**
  - **Coincide[…]erved in the releva[…]3 3.5Mpc).**



Performance of the KAGRA detector during the first joint observation with GEO 600 (O3GK)

arXiv:2203.07011



What noise sources limited the O3GK sensitivity?

Low frequency

Test mass suspension control noises

Coupling from auxiliary degrees of freedom

Scattering light noise due to acoustic noises

Shot noise

Laser frequency fluctuations
Laser intensity fluctuations

High frequency

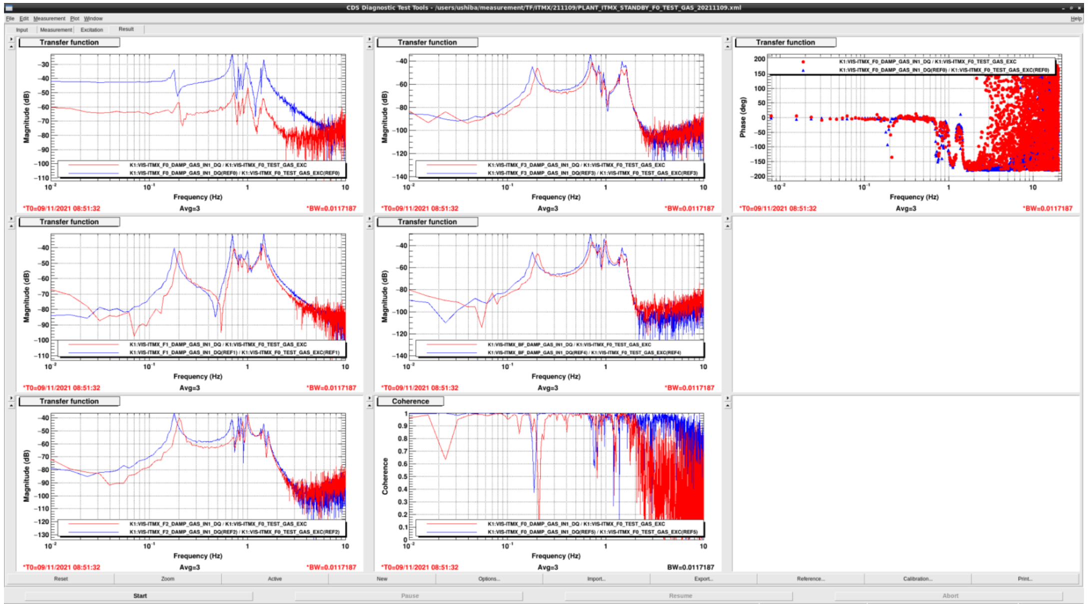
Improvement work in progress toward O4

Low frequency

- Improvement of Vibration Isolation System (VIS)
  - Installation of more accelerometers
  - Installation of optical levers to monitor motion of type-A marionette and platform
  - Replacement of the magnets controlling the mirrors
- Shielding stray light by installing baffles
- Reduction of control noises by filter optimization & tuning
- Removing environmental noises with more sensors and injection tests
- Reduction of shot noise by
  - Replacing SRM
  - Introducing high-power laser (60W; 120W in future)
- Reduction of laser frequency and intensity noises with better alignment using wave-front sensors

High frequency

Improvement of VIS

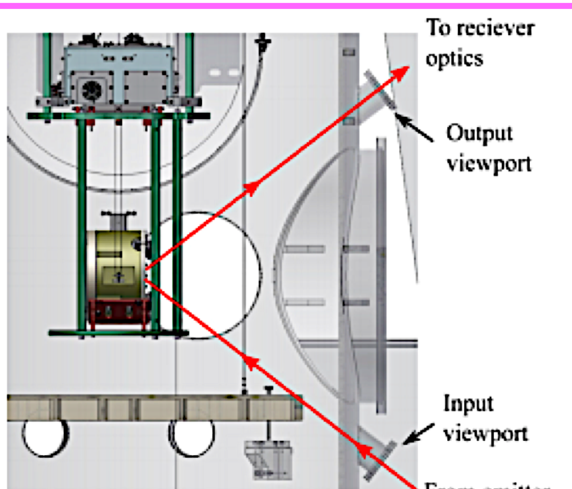


Extensive work on health check and adjustments

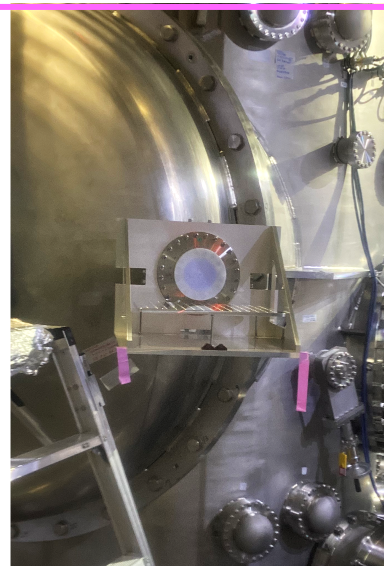
Type-A suspension

Improvement of VIS

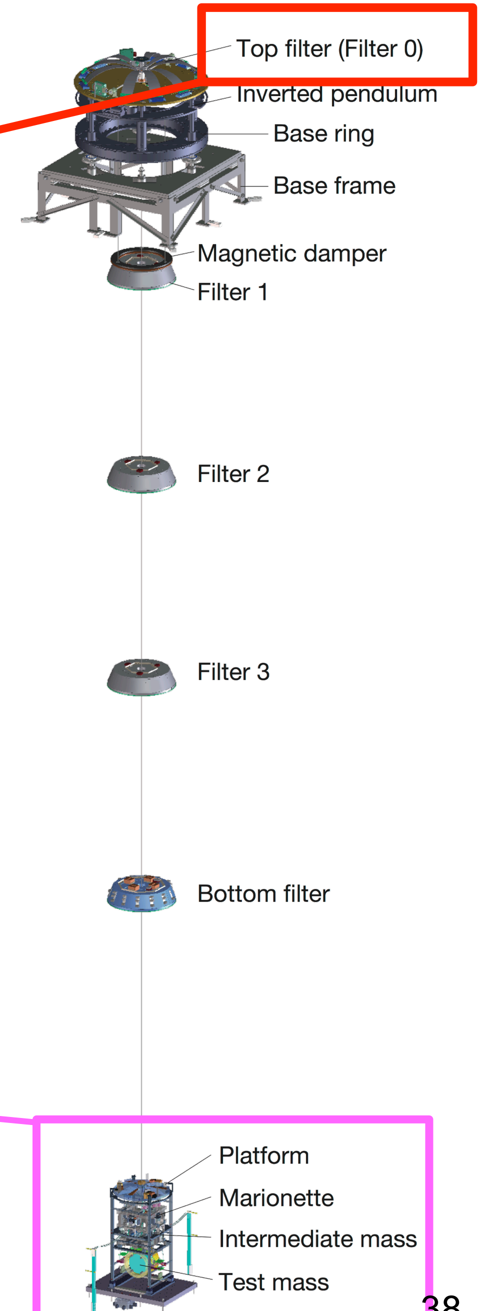
Installation of optical lever for monitoring the motion of Type-A marionette and platform.



Optical Lever の概略図

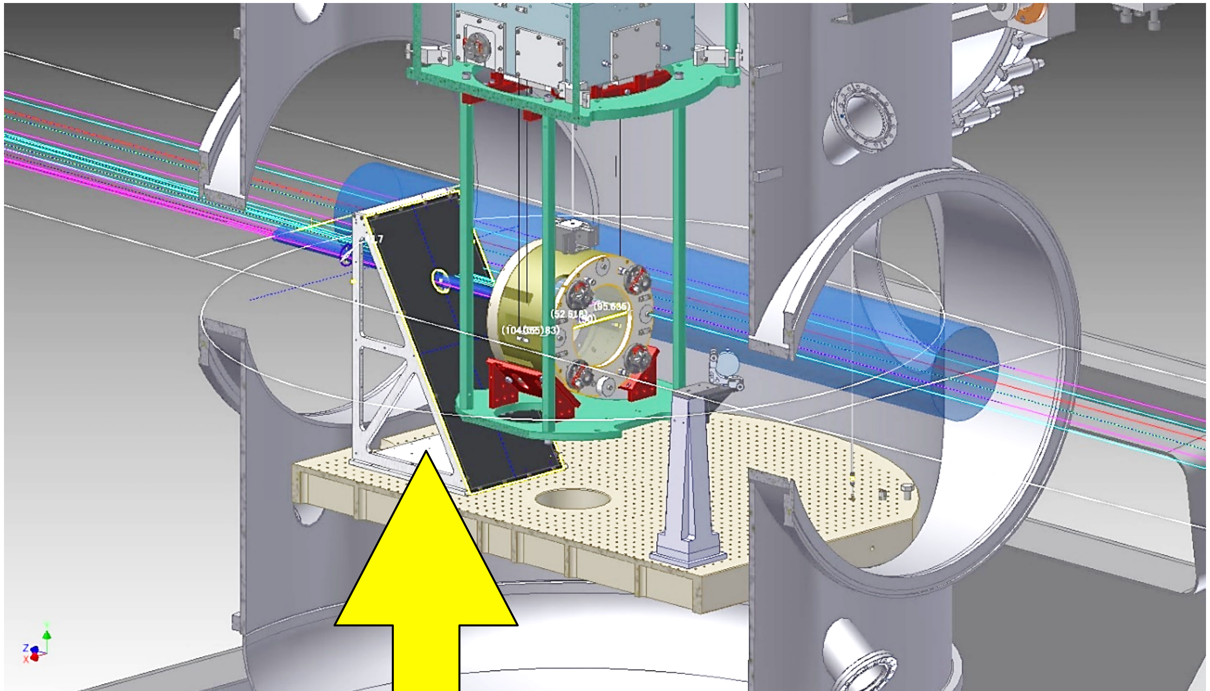


Type-A suspension



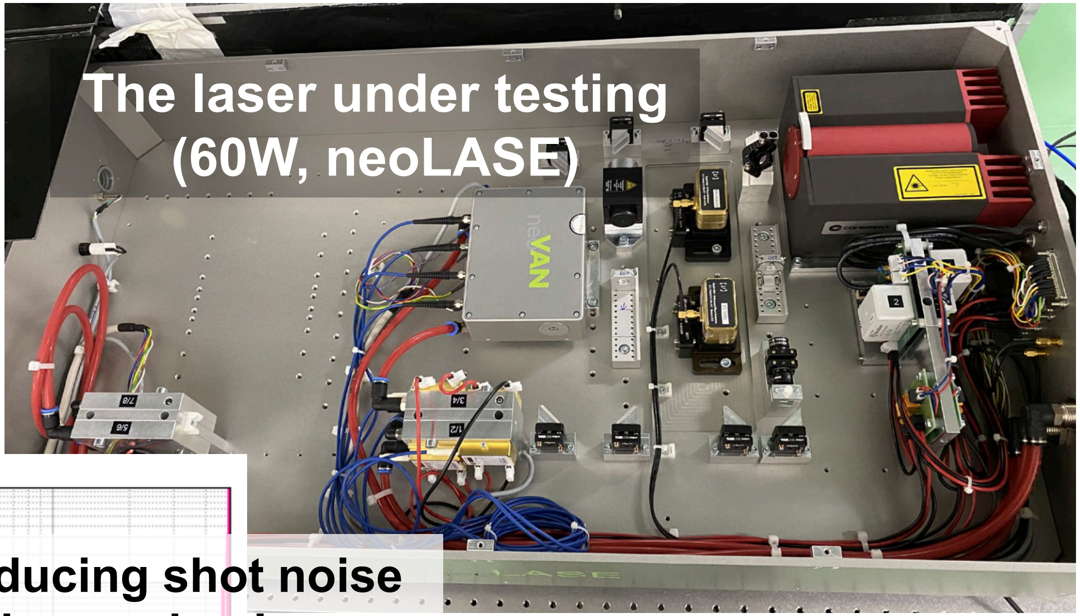
T. Sawada

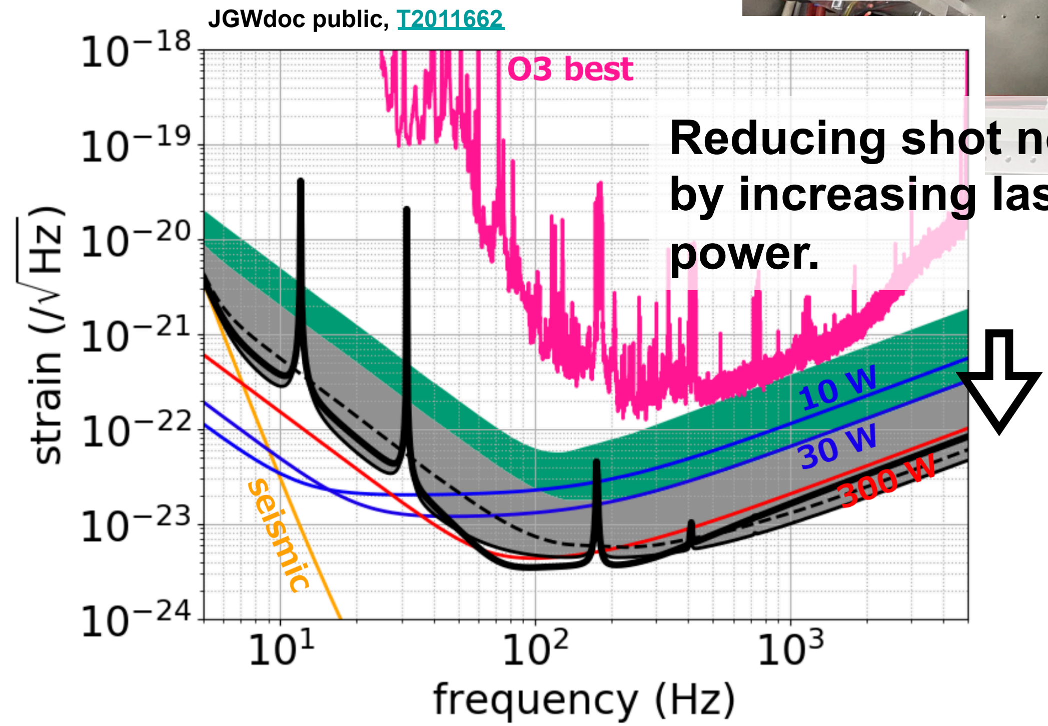
Shielding stray light by installing baffles



at clean room of NAOJ ATC

Introduction of higher power laser to suppress shot noise

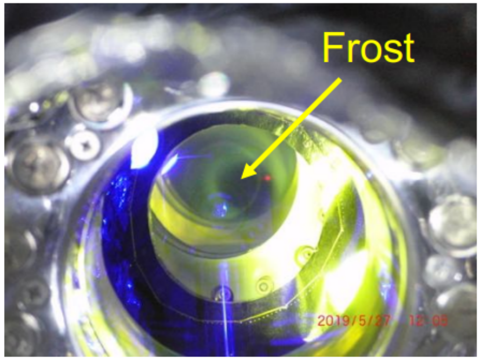


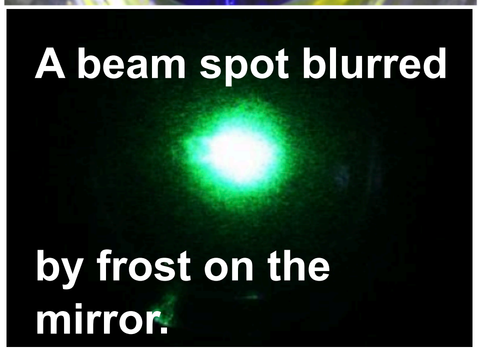


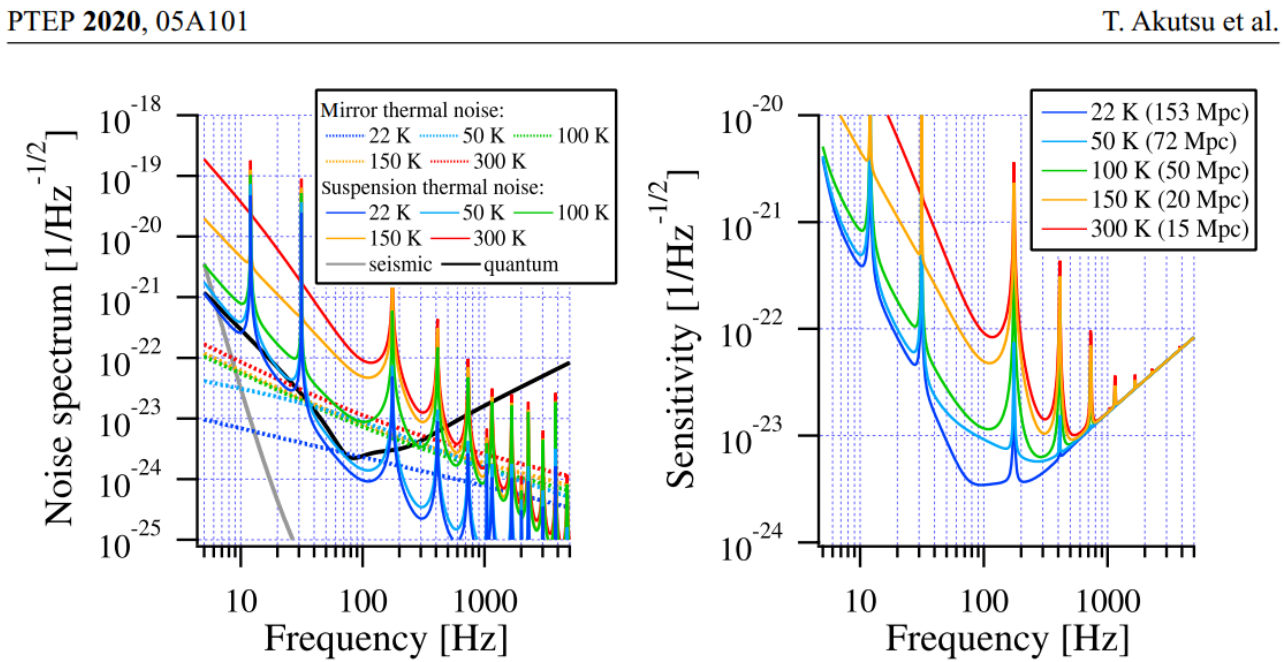
Reducing shot noise by increasing laser power.

T. Sawada

Toward better cooling







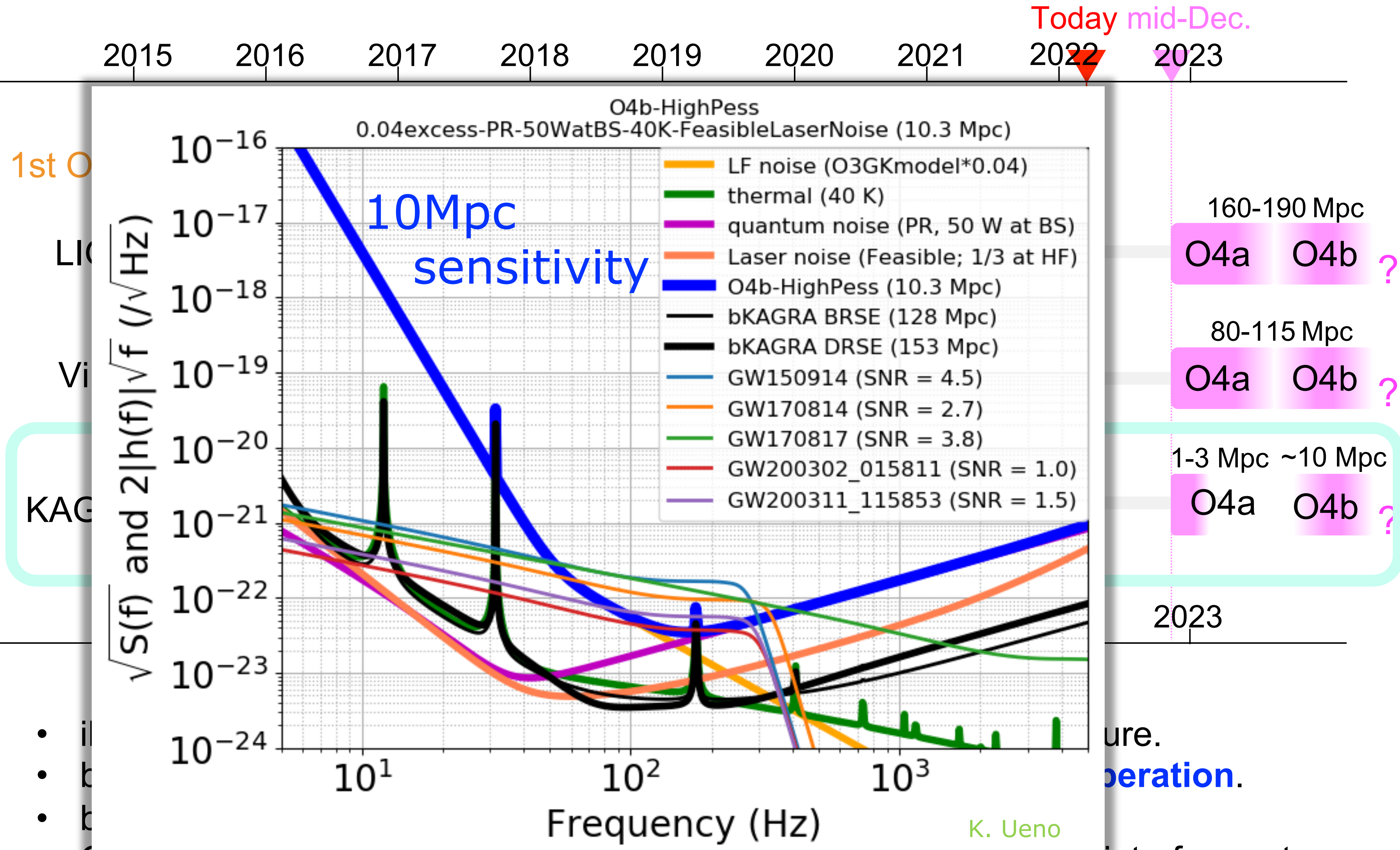
Improvements of cooling equipment and procedures:

- **Installation of defrosting heaters**
- **Absorbing the frost onto the duct shield during cooling**
- **Start cooling after confirmation of sufficient vacuum.**

It takes many weeks to cool down properly.

T. Sawada

Toward first detection



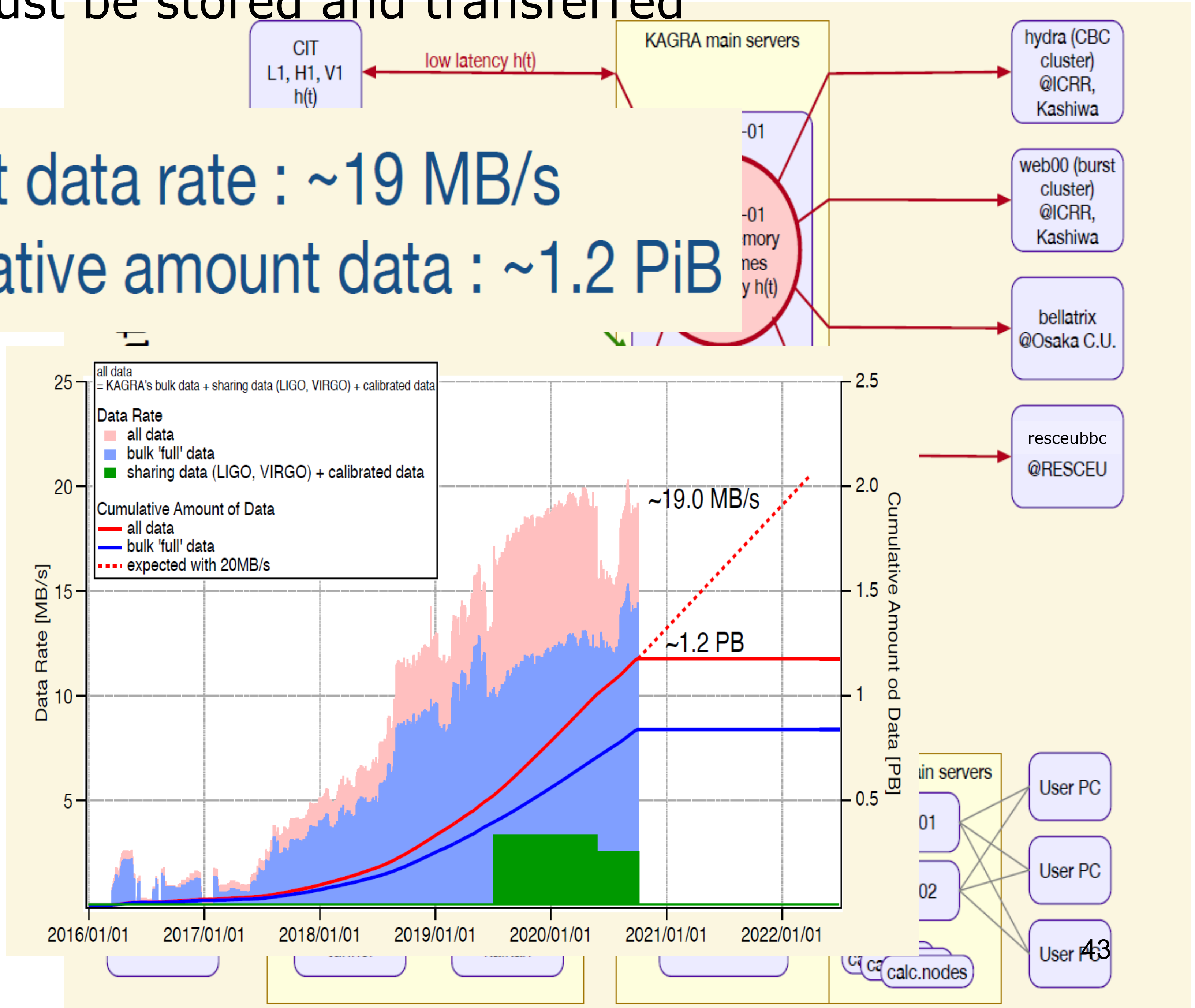
- i … ure.
- b … **peration**.
- b
- O3GK - **Power-Recycling Fabry-Perot** Michelson interferometer at room temperature.

T. Sawada

Data must be stored and transferred

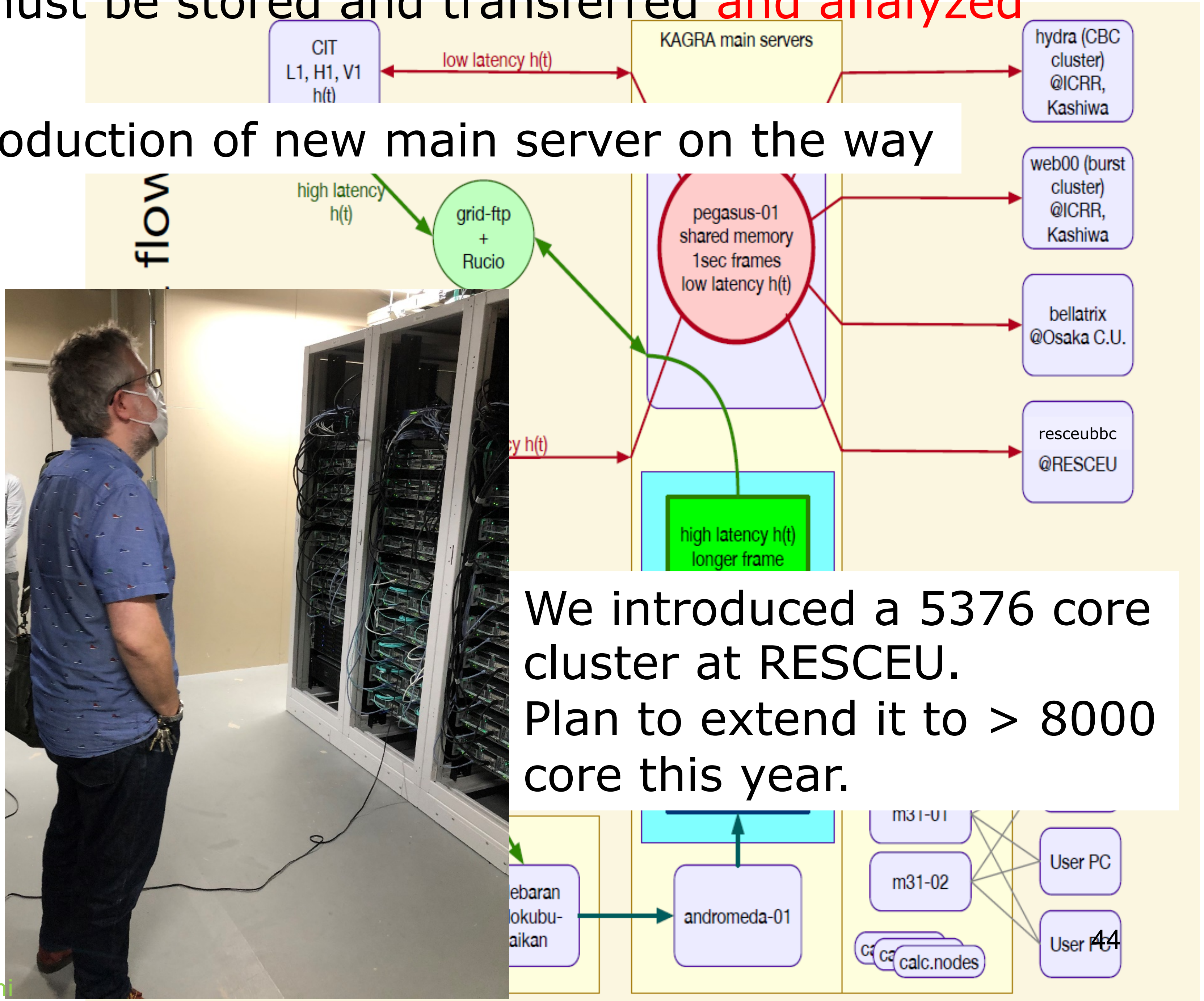
Current data rate : ~19 MB/s

Cumulative amount data : ~1.2 PiB



H. Takahashi

Data must be stored and transferred and analyzed

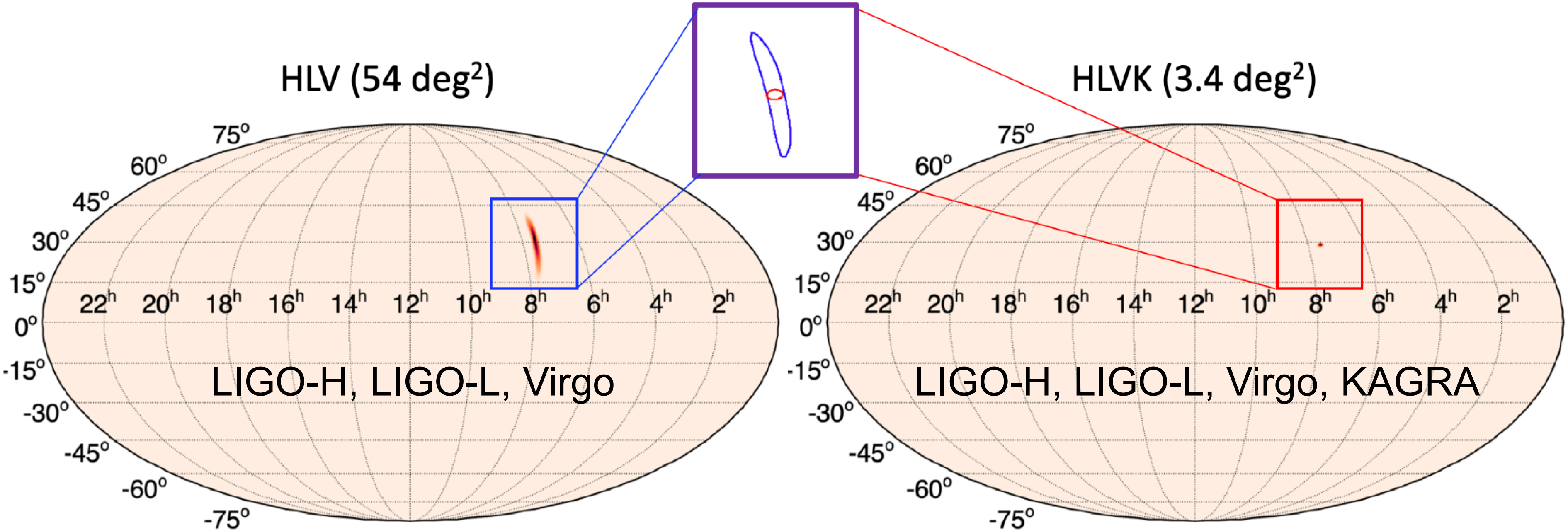


Introduction of new main server on the way

We introduced a 5376 core cluster at RESCEU.
Plan to extend it to > 8000 core this year.

H. Takahashi

Once KAGRA achieves its full sensitivity, it will significantly contribute to sky localization



as well as better measurement of the polarizations of gravitational waves.

Conclusion

KAGRA started 20 years after LIGO, and have been significantly improving its sensitivity toward its first detection of gravitational waves and further contribution to the multimessenger astrophysics and fundamental physics.