KAGRA Perspective

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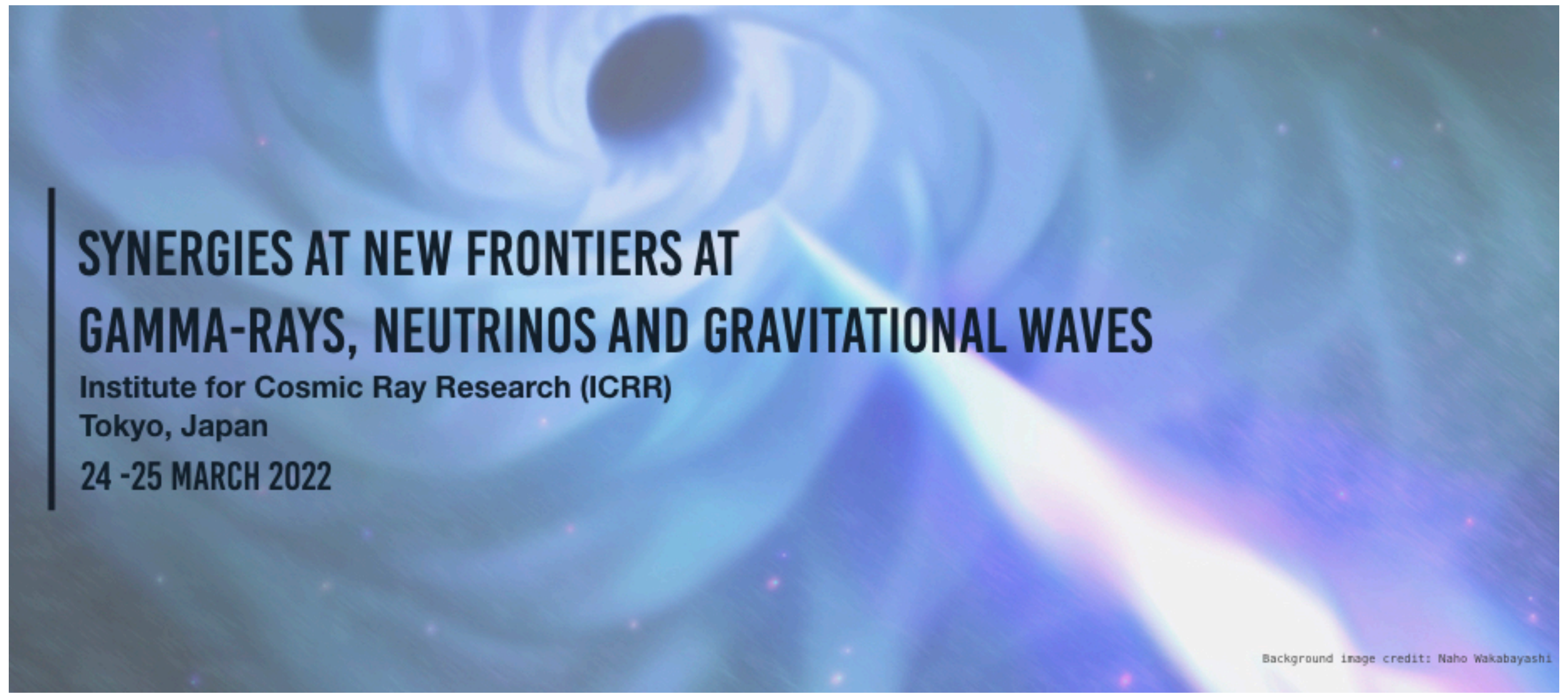


SYNERGIES AT NEW FRONTIERS AT
GAMMA-RAYS, NEUTRINOS AND GRAVITATIONAL WAVES
Institute for Cosmic Ray Research (ICRR)
Tokyo, Japan
24 -25 MARCH 2022

Background image credit: Naho Wakabayashi

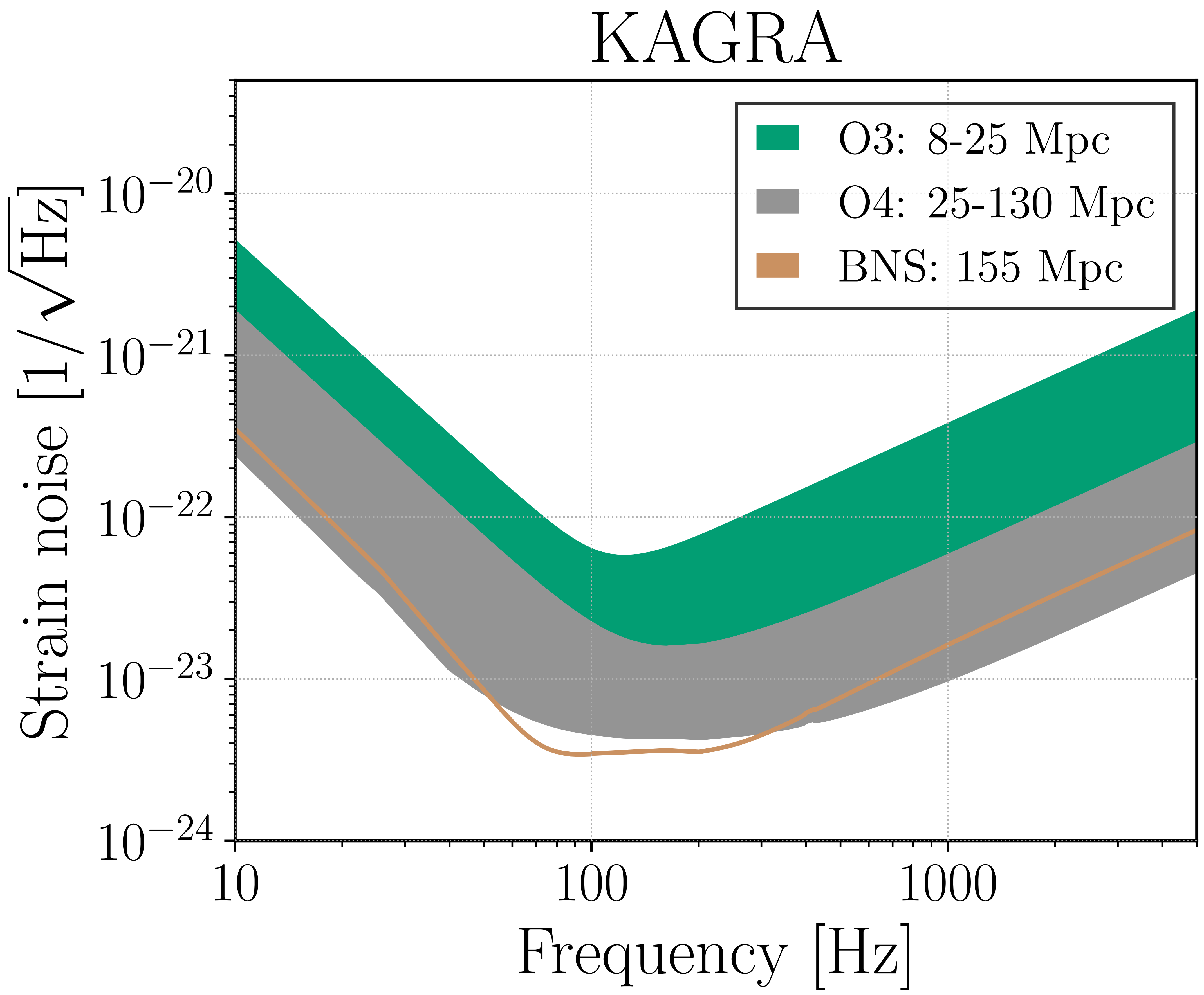
https://indico.icrr.u-tokyo.ac.jp/event/694/overview

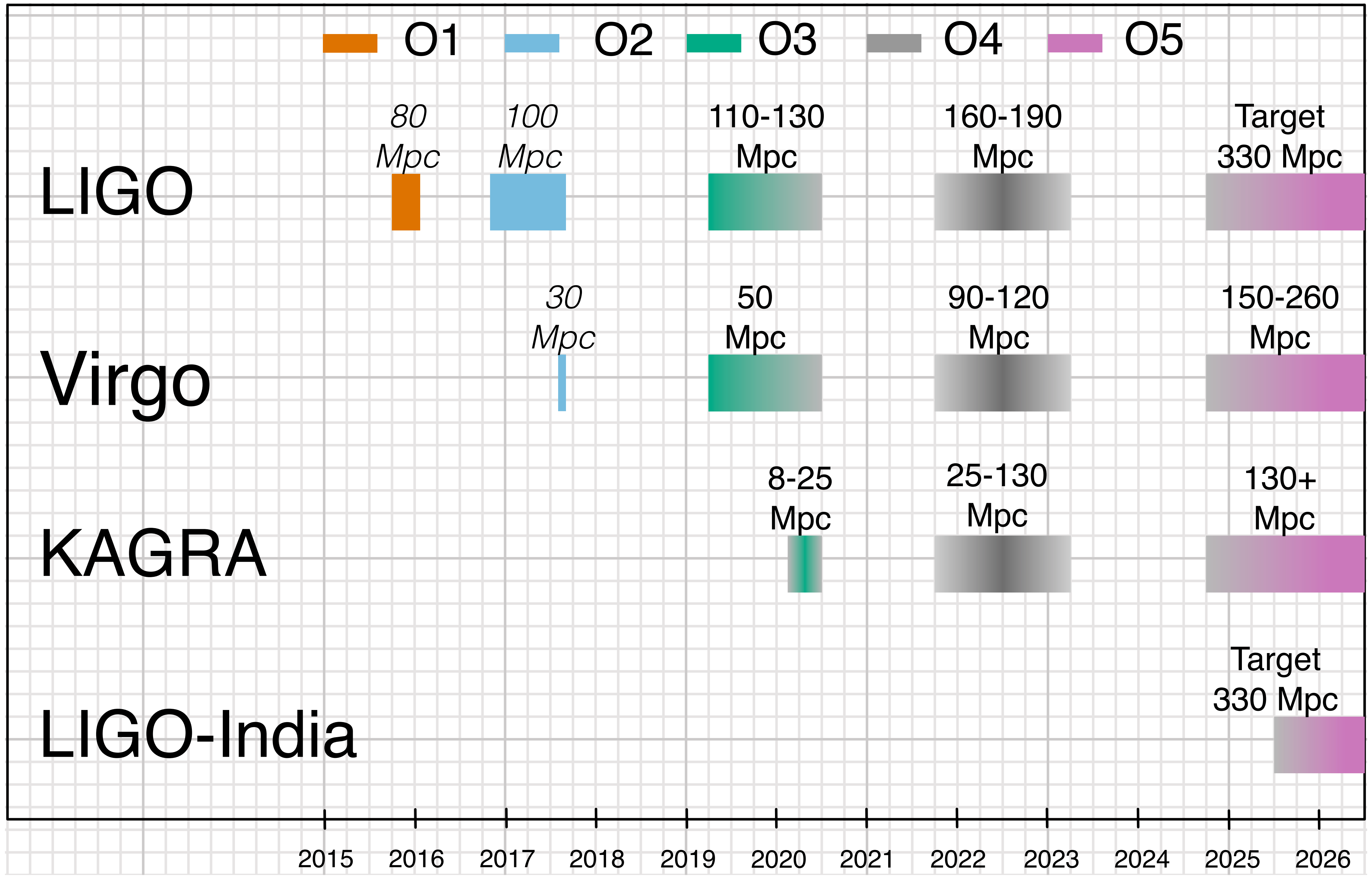
Contents

- Observation plan of gravitational wave detectors (LVK)
- O4 and O5
- After O5
- Mid-2030s

Observation plan of gravitatinal wave detectors (LVK)

- KAGAR, LIGO, and VIRGO makes a document which shows observing scenarios over the next several years.
  - “Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA”
  - https://arxiv.org/abs/1304.0670
  - Last revised 24 Nov 2020 (this version, v11)

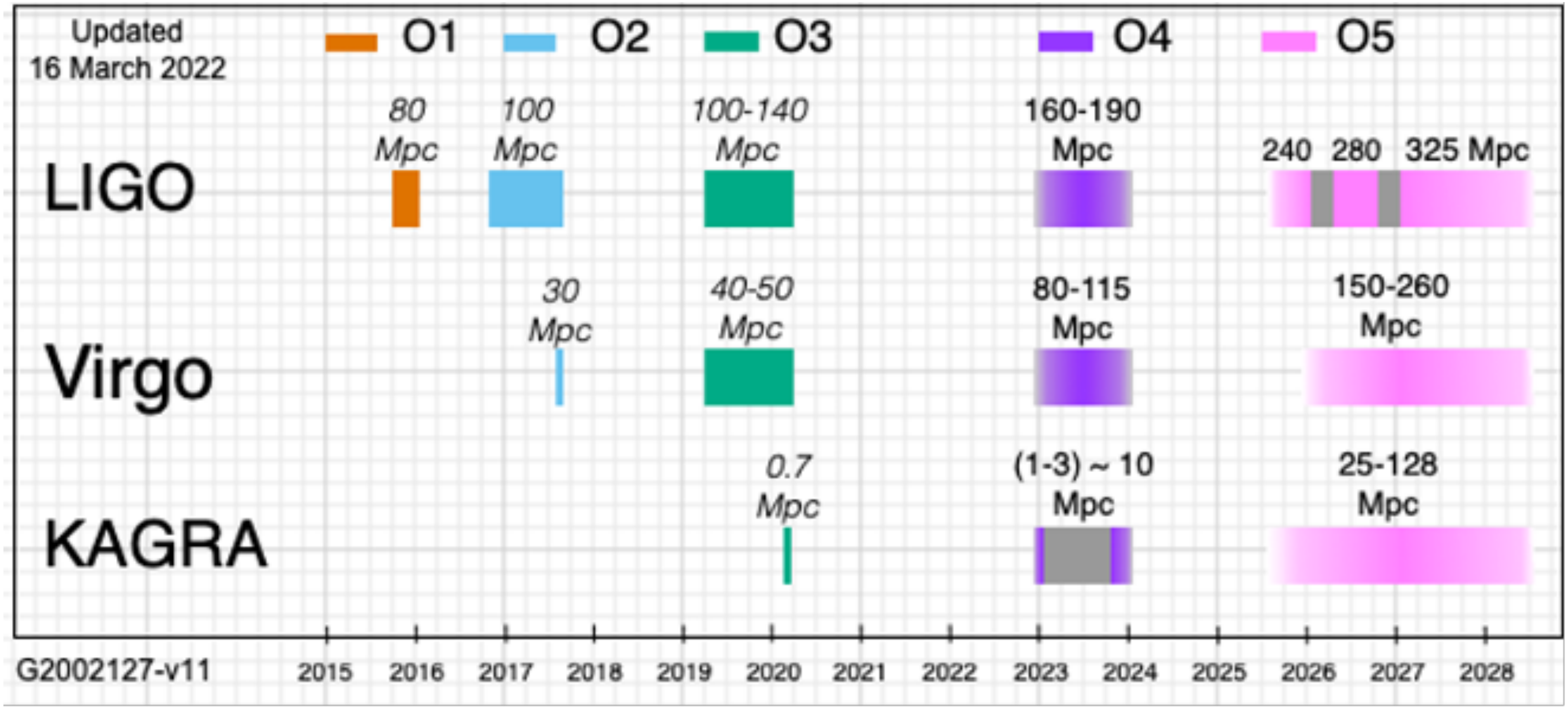




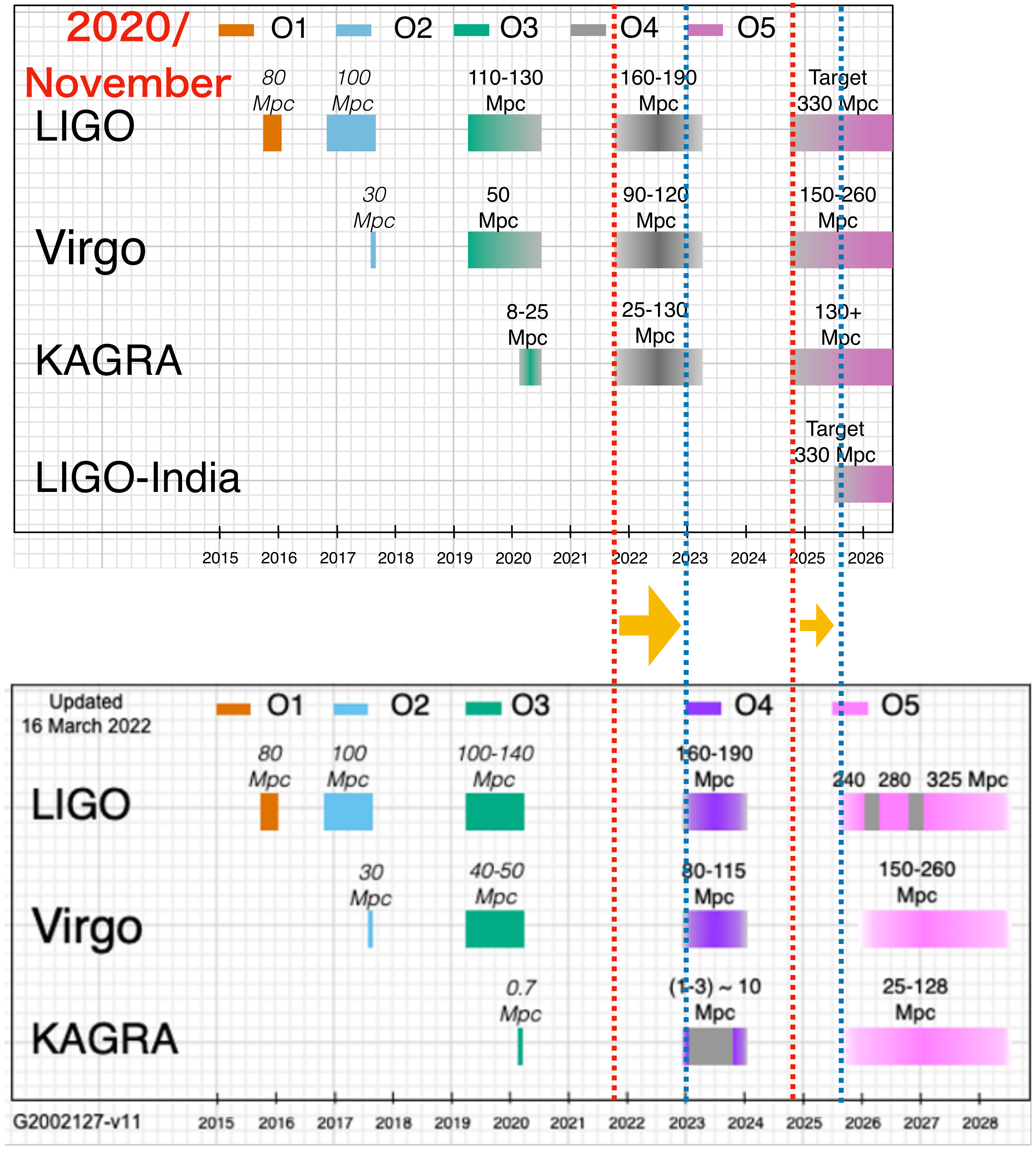
The scenario paper shows the expected sensitivity curves of each detector and observation schedule. Updates are being made according to the current situation.

https://arxiv.org/abs/1304.0670

The latest scenario

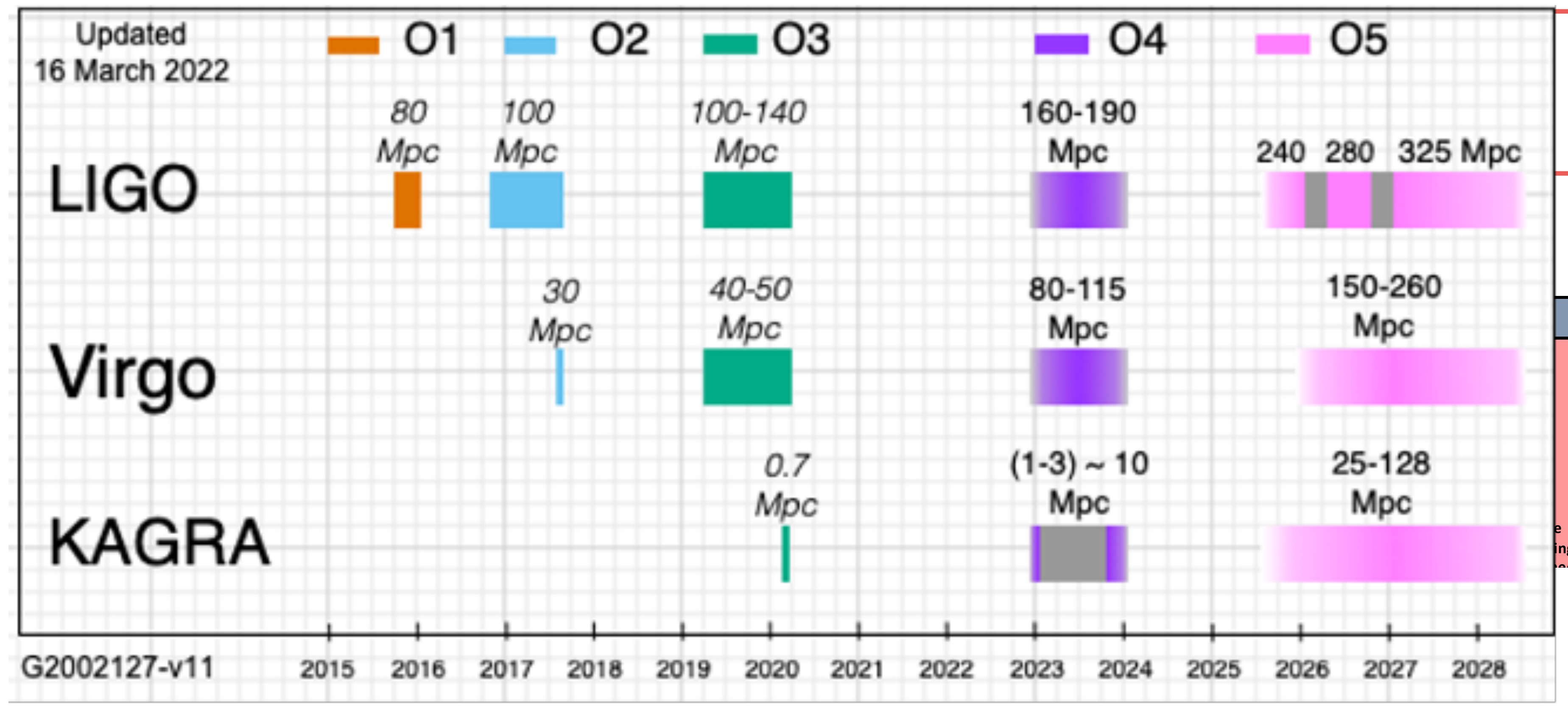


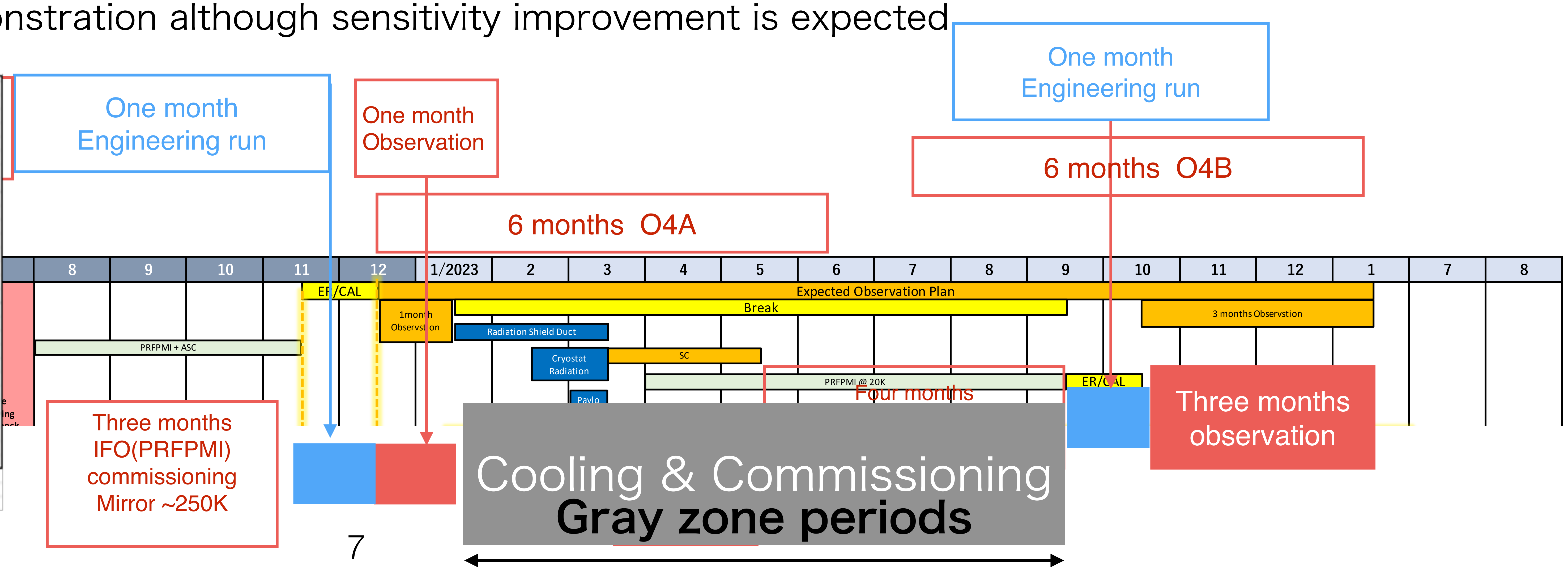
- Differences
  - O4
    - O4 start: Late 2021 -> Late 2022 (1Year delay)
      - COVID-19
      - LIGO(LLO) was hugely damaged due to a hurricane in 2021.
    - O4 length: 1Year (Same)
    - The start date and length of the observation are still discussion items. The next update will be presented in May.
  - O5
    - O5 start: Late 2024 -> Mid 2025 or Early 2026 (1 or 1.5 Year delay)
      - Delay of O4
      - VIRGO needs longer intervals for 2 years to replace test masses.
      - Since KAGRA will also replace test masses during O4 and O5, longer intervals may be necessary as well as VIRGO.
    - O5 length: 1.5 Year -> longer than 2 Year
    - Uncertainty is large. Many updates will be done in the future.
  - KAGRA
    - What is the gray zone in O4?
    - Sensitivities
  - LIGO-India
    - Now it is under construction. It is unclear when LIGO-India will join observations.



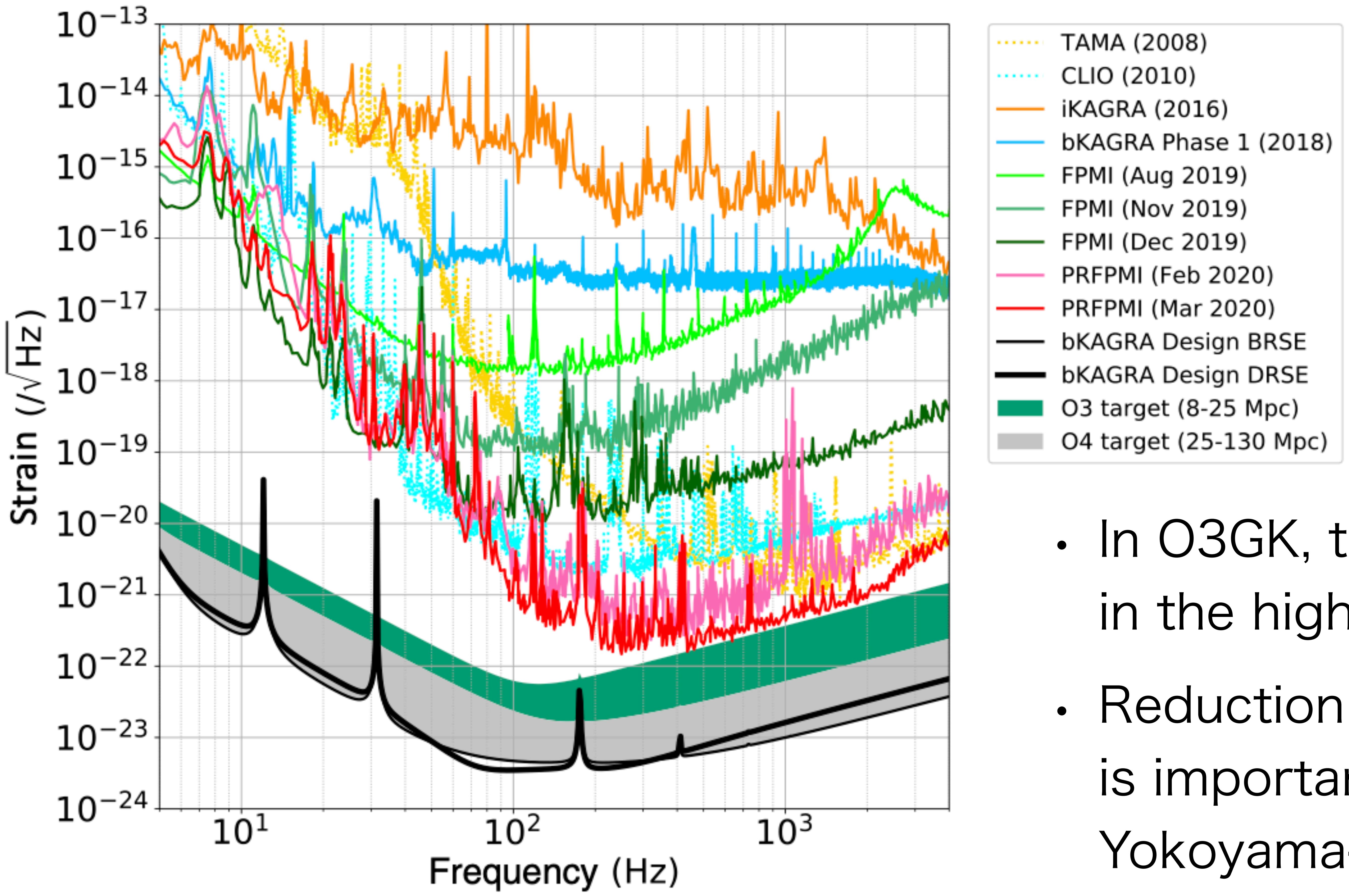
KAGRA’s plan in O4

- The current plan of O4:
    - Starting in mid-December 2022
    - O4A(6 months)+ Break(1 month)+ O4B(6 months)
- KAGRA’s plan in O4
    - Join O4 at beginning of O4A. The target sensitivity is 1Mpc at least (similar to O3GK).
    - After O4A KAGRA operation (One month), KAGRA has a longer commissioning break for cooling mirrors.
    - Resume the observation in O4B and we will observe for 3 months at least.
        - We expect a sensitivity of 10Mpc at this time. -> Chance for the 1st detection of KAGRA.
- Interferometer (IFO) configuration: PRFPMI (same as in O3GK)
- Test mass mirrors
    - O4A: ~250K (Partial operation of cryocoolers)
    - O4B: ~20K (Full operation of cryocoolers)
    - This is the first trial of full cryocoolers operation. An important challenge for KAGRA.
    - The main purpose of cooling is a technical demonstration although sensitivity improvement is expected.

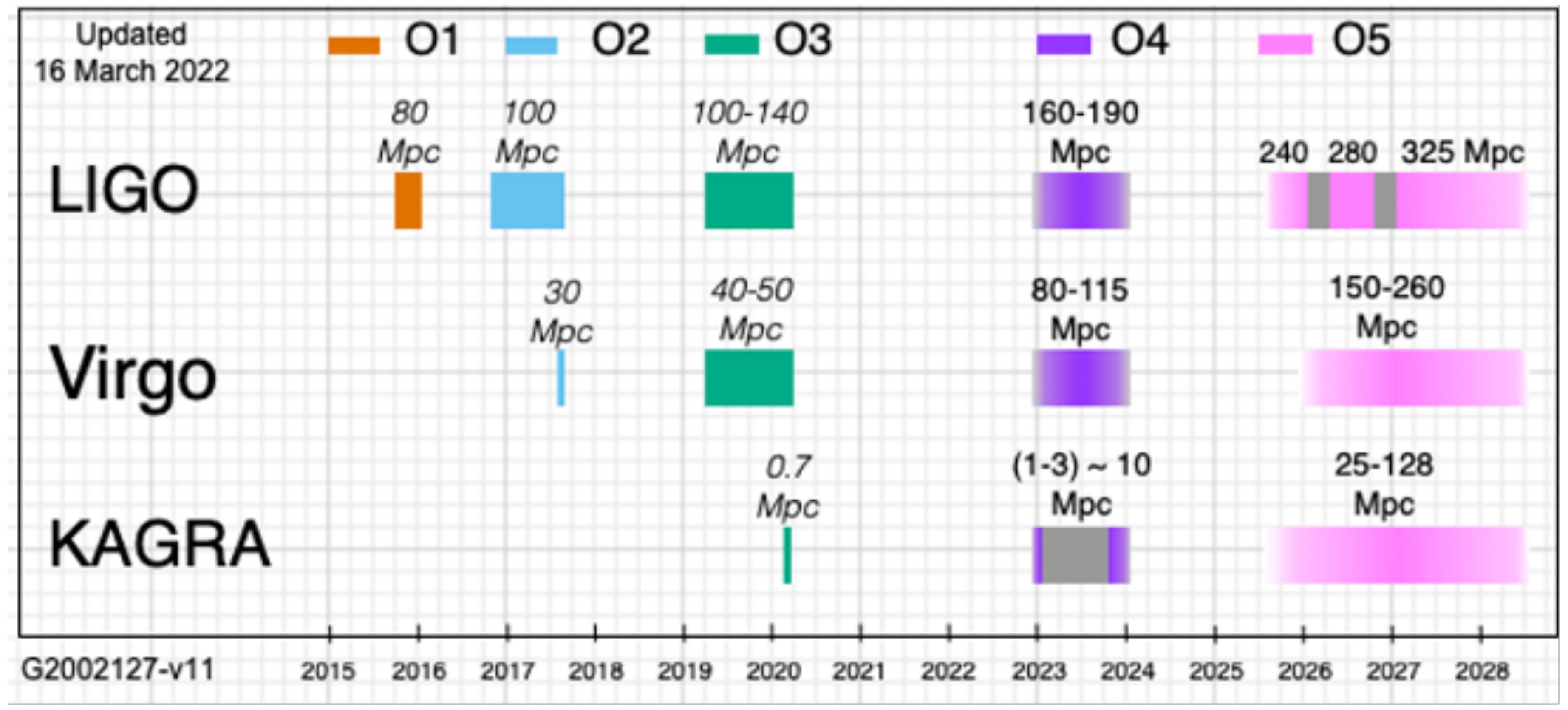




KAGRA sensitivity

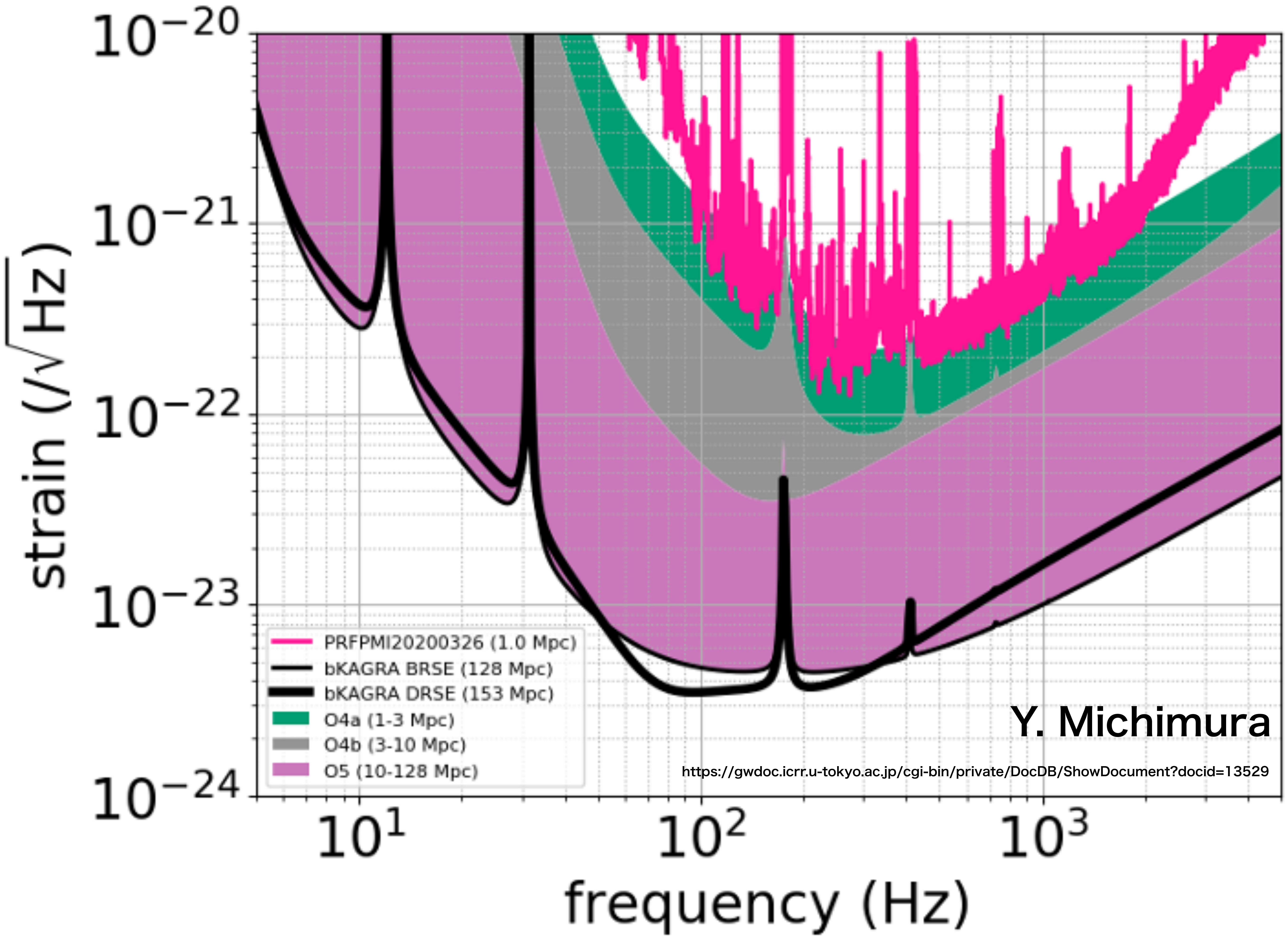


KAGRA sensitivity curves compared with target sensitivities (old version)



- In O3GK, the sensitivity reached a part of the O3 target in the high-frequency region.
- Reduction of the noise floor in the low-frequency region is important and we carried out many things as in the Yokoyama-sensei's talk.
- O4 target is reaching O3 target (Green area).
- O5 target is realizing O4 target (Gray area).

KAGRA sensitivity



Y. Michimura

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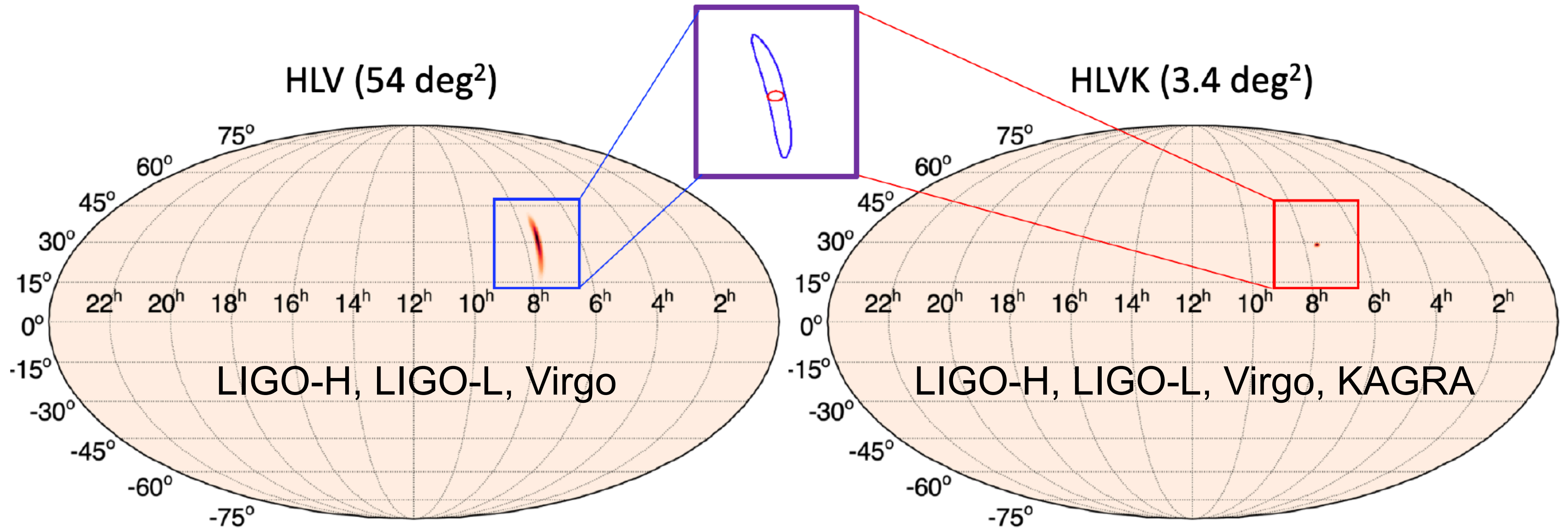
KAGRA sensitivity curves compared with target sensitivities

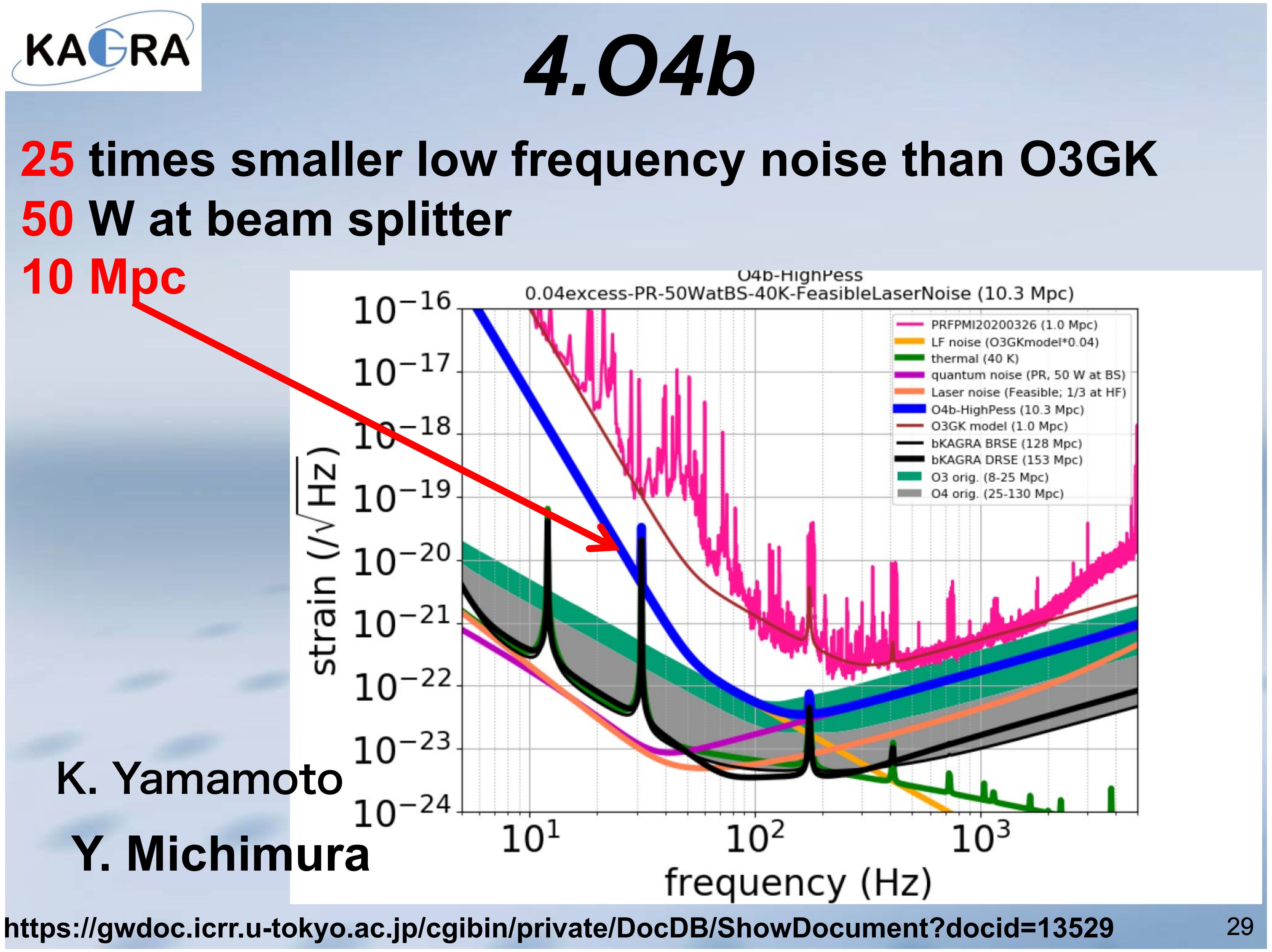
Once KAGRA achieves its full sensitivity, it will significantly contribute to sky localization



Yokoyama-sensei’s slide

- In O4A, reproduce O3.
- In O4B, Better sensitivity after cooling.
- In O5, the design sensitivity will be the target. KAGRA can contribute to better sky localization and multi-messenger astronomy.

To reach 10Mpc in O4B



KAGRA

4.O4b

25 times smaller low frequency noise than O3GK

50 W at beam splitter

10 Mpc

K. Yamamoto

Y. Michimura

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29

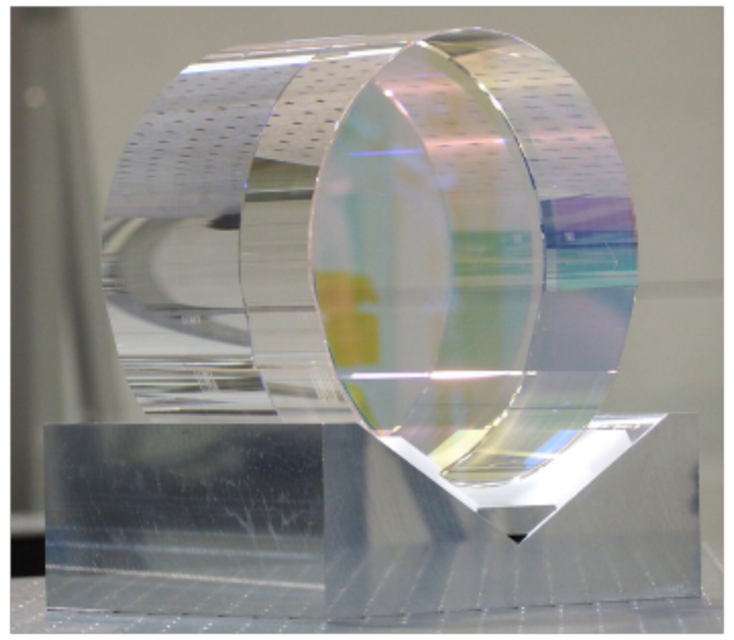
10Mpc case

- Laser power at BS: 50W (~same as O3GK)
- PRFPMI (~same as O3GK)
- Mirror temperature: ~20K
- Reduction of low-frequency noise floor: 1/25
  - Contents: Suspenstion contorol noise, acoustic noise, and so on

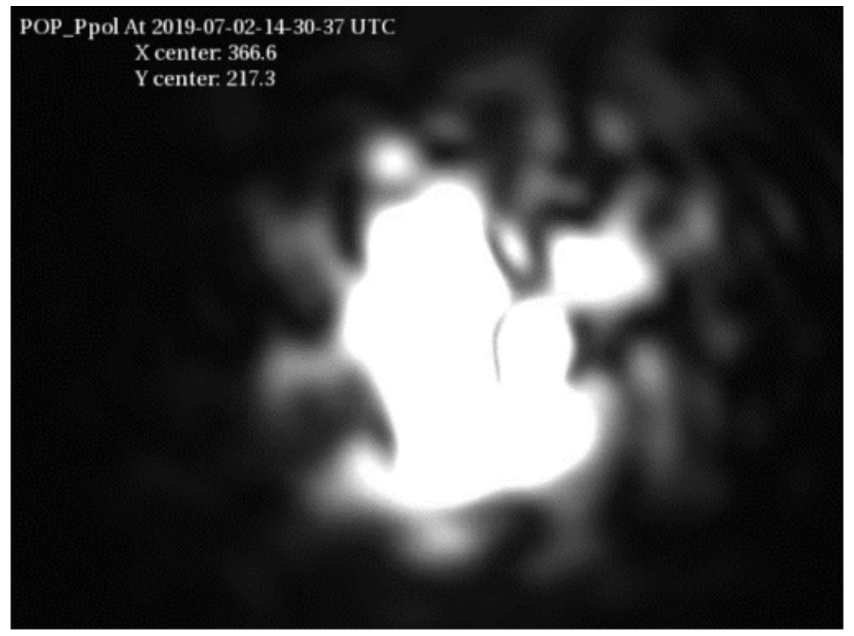
Inorder to obtain the better sensitivity, reduction of fundamental noises (thermal noise, quantum noise, and so on) and of technical noises are necessary.

Toward O5-1

- Replacements of the test masses (Without this, observation range may be limited by 80Mpc)
  - Developments of new sapphire mirrors for the front test masses are ongoing.
  - Birefringence problem.
    - Birefringence is the natural nature of sapphire.
    - A problem is birefringence is inhomogeneous in the test masses.
    - Unwanted laser power loss might happen.
    - Difficult to evaluate noises caused by this problem -> Simulation is ongoing.
    - Annealing is thought to be a key technique to reduce inhomogeneously.
  - Reflective index mismatch between the front test masses.
    - Because we couldn't make a reflective coating at the same time.
    - This problem causes higher laser frequency and intensity noise than design values.
- Installation of high power laser (120W)
  - Reduce the shot noise and improve the sensitivity in the high-frequency region.



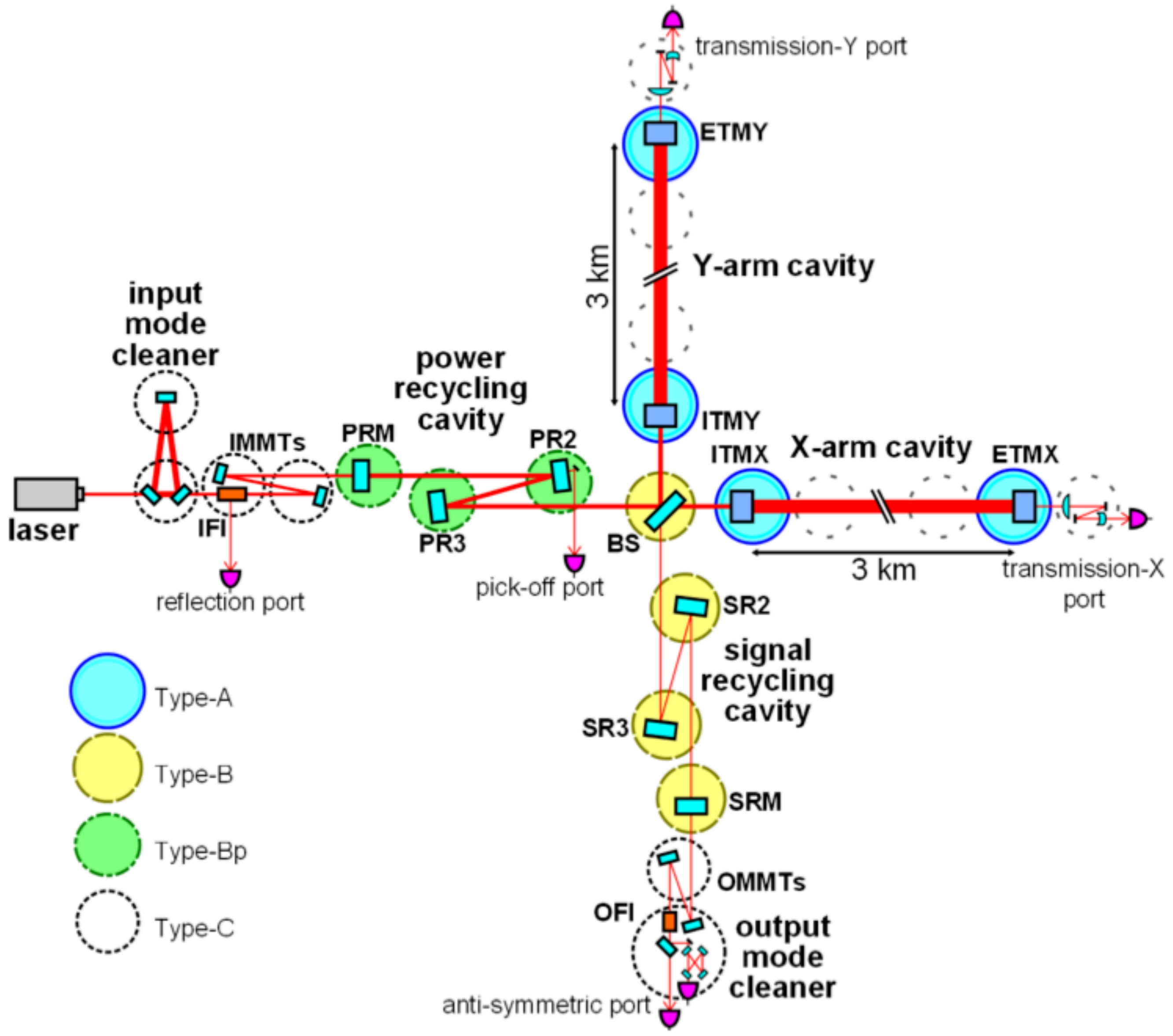
Sapphire mirror
ϕ220X150, 23kg



Unwanted reflection beam caused by birefringence

Toward O5-2

- Operate dual recycling
  - KAGRA employs power recycling technique and signal recycling technique.
  - Signal recycling has not been used so far and will not be used in O4.
  - Difficulties of controls. Not enough time for commissioning.
  - Improve the sensitivity in the high-frequency region.

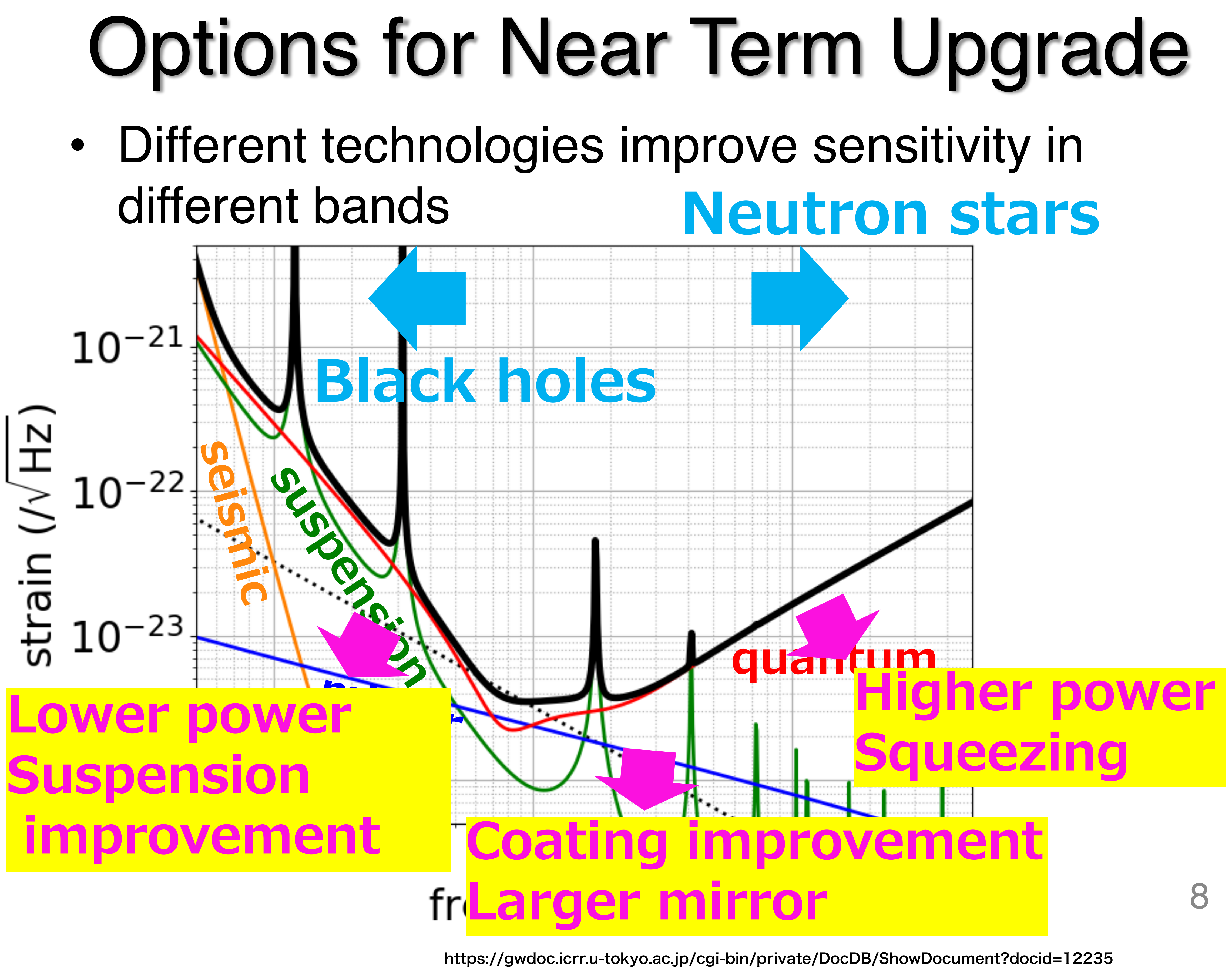


KAGRA interferometer

- Installation of squeezing techniques
  - The frequency-dependent squeezing (FDQ) technique can reduce quantum noises in all the frequency band.
  - LIGO and VIRGO introduce FDQ toward O4.
  - Japanese GW group proved the technique and the results have been published. (We have the technology to make it.)
    - Y. Zhao, et al., Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors. *Phys. Rev. Lett.* **124**, 171101 (2020).
  - The budget is a problem for KAGRA.

After O5

- We were discussing possible upgrade plans.
  - Not changing the current facility.
- The discussion has been published.
  - Prospects for improving the sensitivity of the cryogenic gravitational wave detector KAGRA
  - Y. Michimura et al., PHYSICAL REVIEW D 102, 022008 (2020)



Options for Near Term Upgrade

- Different technologies improve sensitivity in different bands

8

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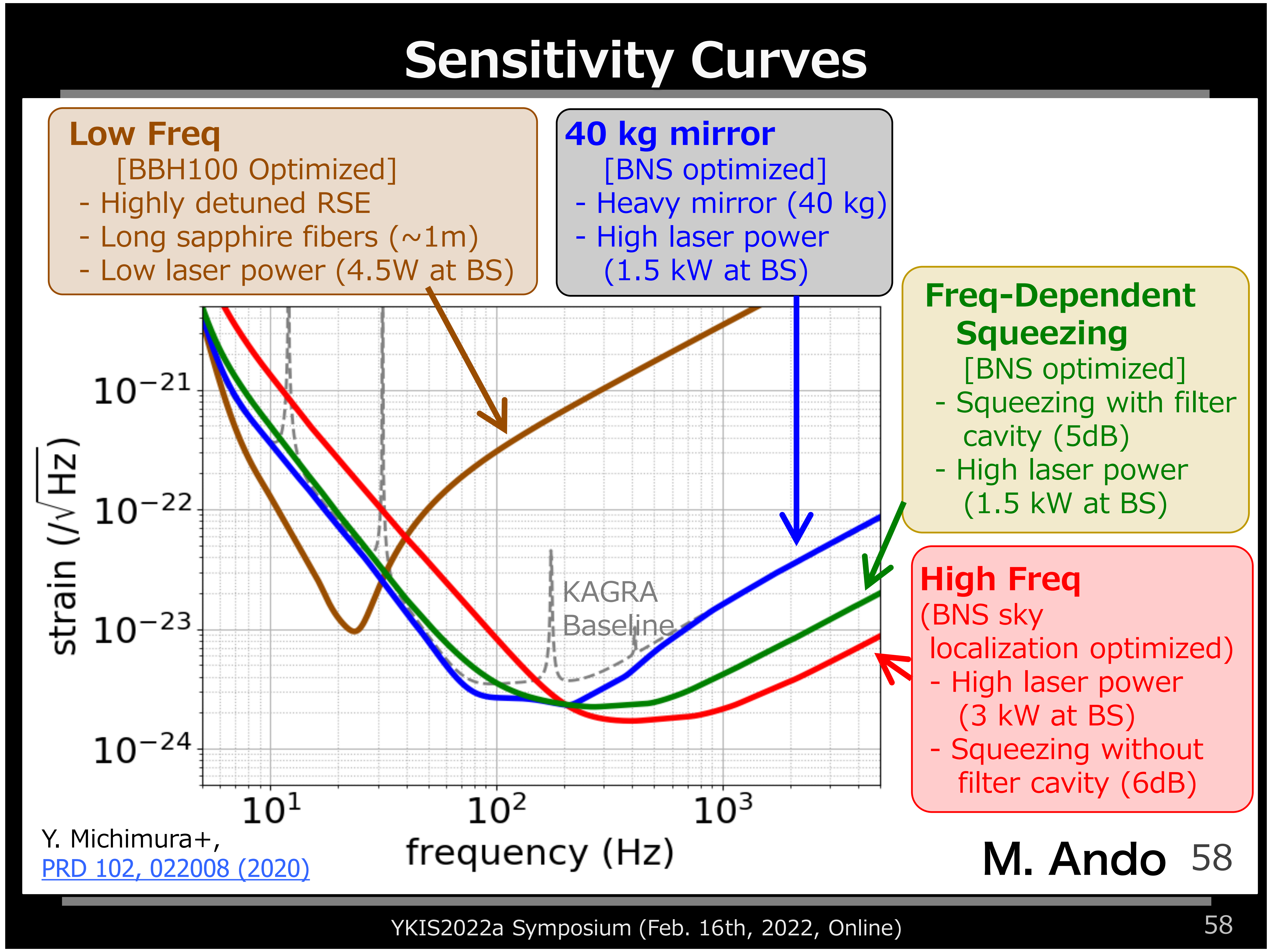
4 plans +1



Sensitivity Curves

Low Freq
[BBH100 Optimized]
- Highly detuned RSE
- Long sapphire fibers (~1m)
- Low laser power (4.5W at BS)

40 kg mirror
[BNS optimized]
- Heavy mirror (40 kg)
- High laser power (1.5 kW at BS)

Freq-Dependent Squeezing
[BNS optimized]
- Squeezing with filter cavity (5dB)
- High laser power (1.5 kW at BS)

High Freq
(BNS sky localization optimized)
- High laser power (3 kW at BS)
- Squeezing without filter cavity (6dB)

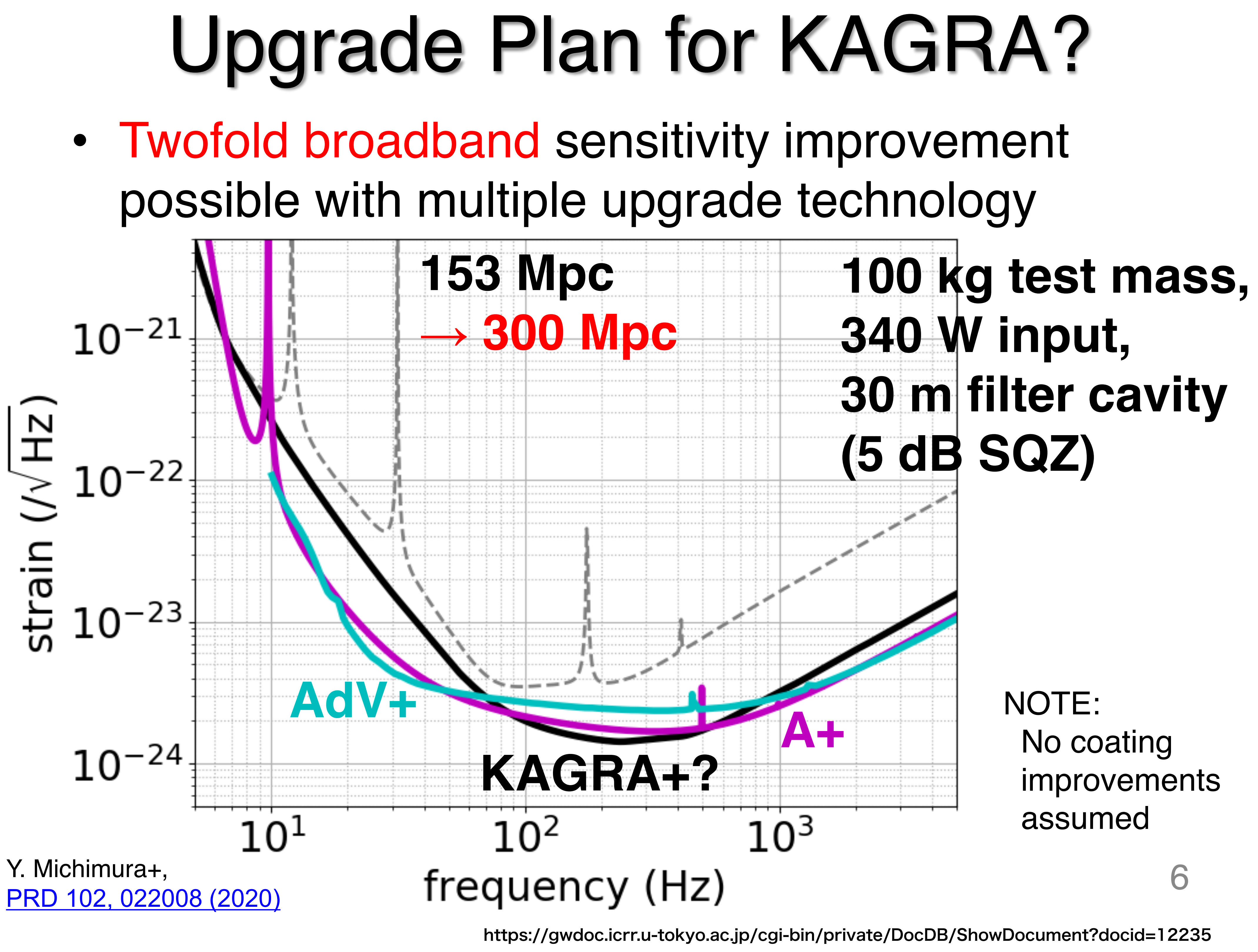
Y. Michimura+,
PRD 102, 022008 (2020)

M. Ando 58

YKIS2022a Symposium (Feb. 16th, 2022, Online) 58

Four ideas of the future

ref: 50W@BS@O3GK



Upgrade Plan for KAGRA?

- Twofold broadband sensitivity improvement possible with multiple upgrade technology

NOTE:
No coating improvements assumed

Y. Michimura+,
PRD 102, 022008 (2020)

6

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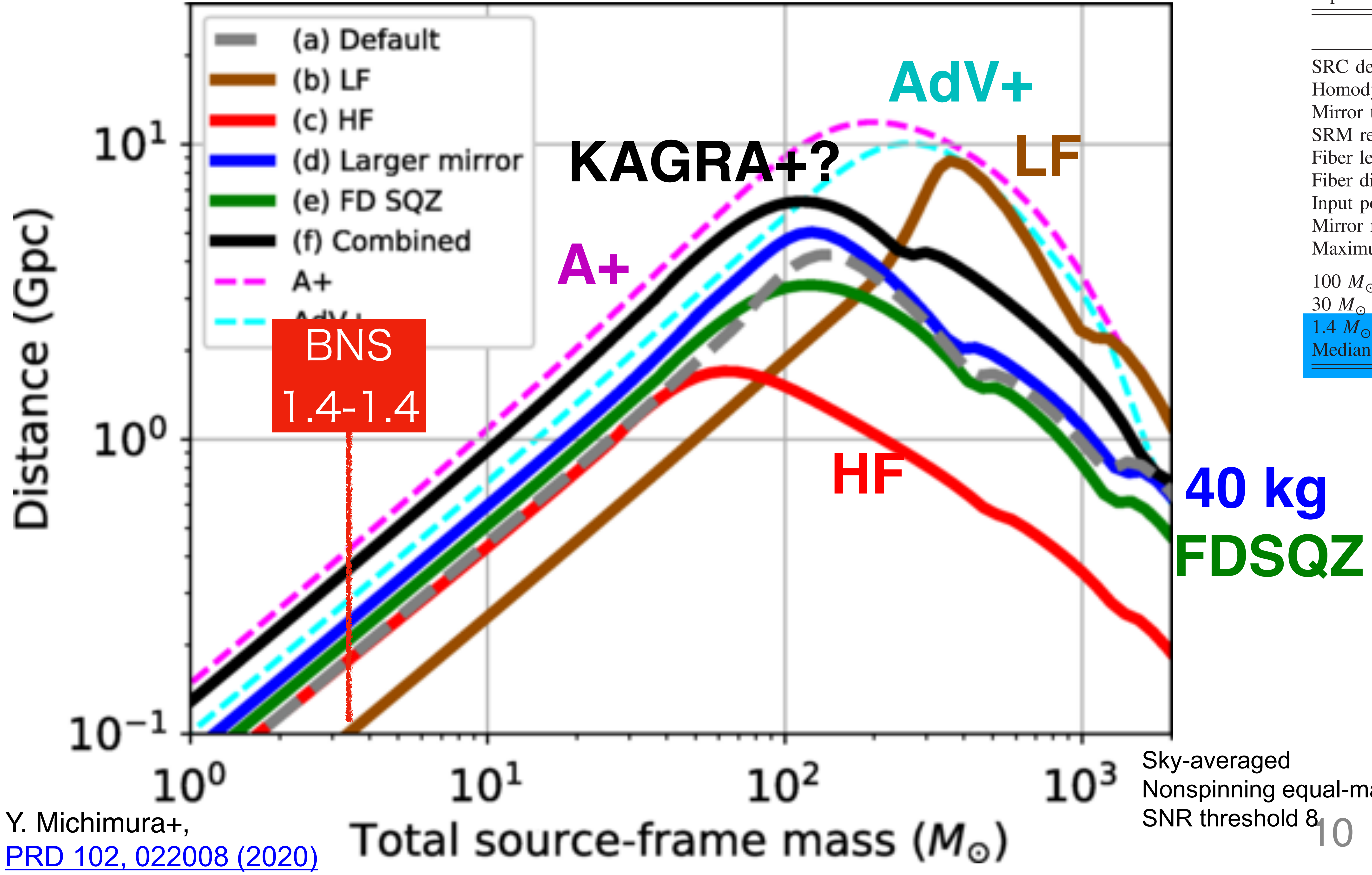
More aggressive plan

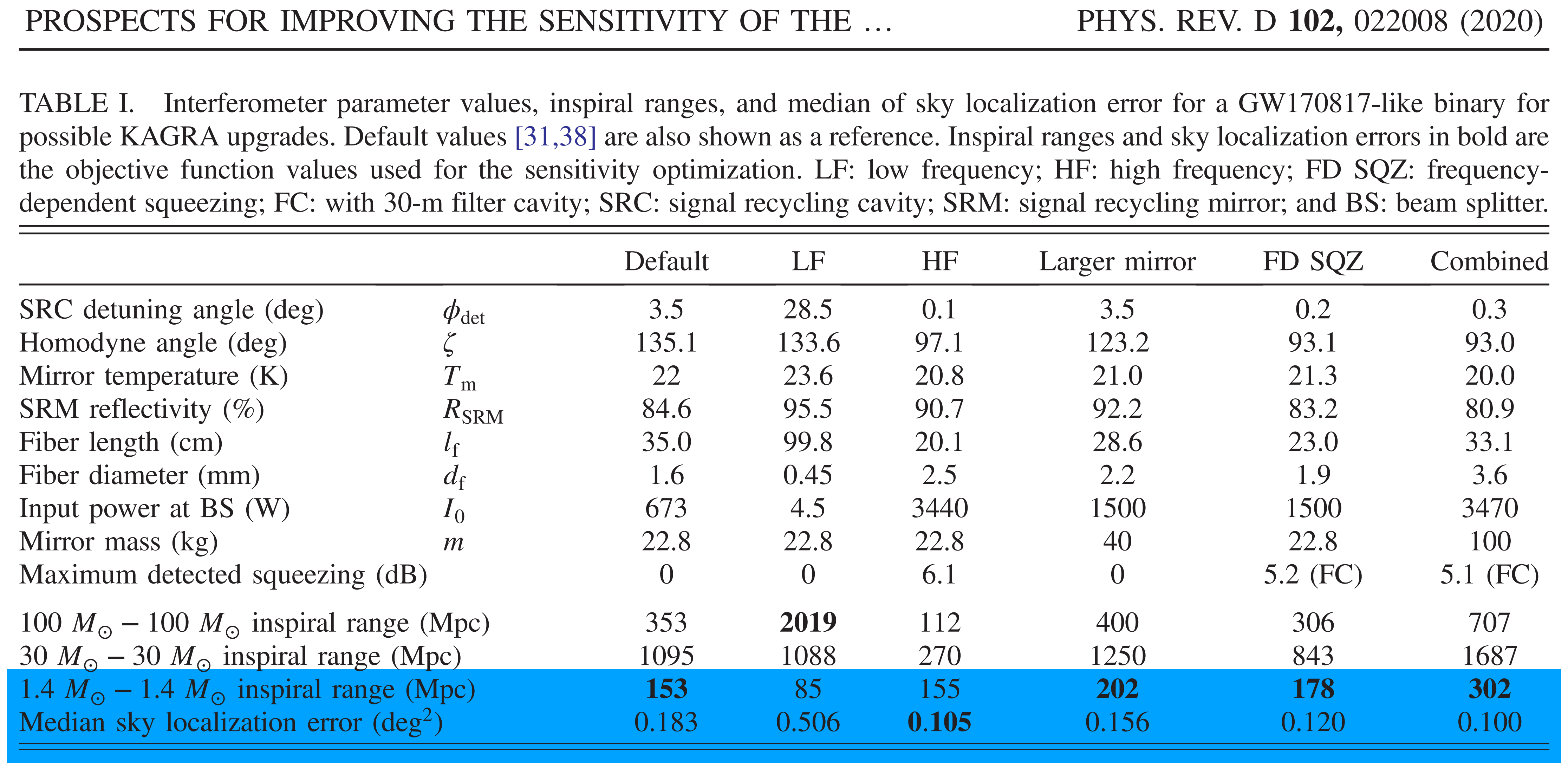
Detection Ranges

- Hard to beat A+ with horizon distance



Y. Michimura+,
[PRD 102, 022008 (2020)](#)

Sky-averaged
Nonspinning equal-mass
SNR threshold 8



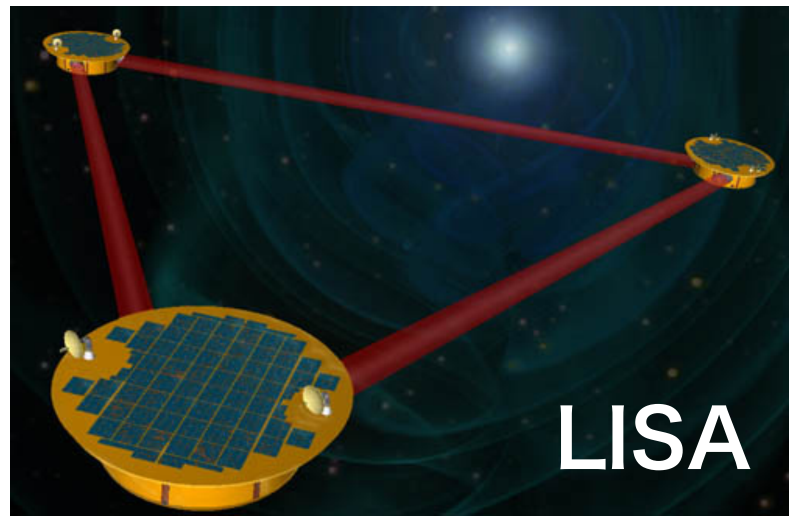
PROSPECTS FOR IMPROVING THE SENSITIVITY OF THE … PHYS. REV. D **102,** 022008 (2020)

TABLE I. Interferometer parameter values, inspiral ranges, and median of sky localization error for a GW170817-like binary for possible KAGRA upgrades. Default values [31,38] are also shown as a reference. Inspiral ranges and sky localization errors in bold are the objective function values used for the sensitivity optimization. LF: low frequency; HF: high frequency; FD SQZ: frequency-dependent squeezing; FC: with 30-m filter cavity; SRC: signal recycling cavity; SRM: signal recycling mirror; and BS: beam splitter.

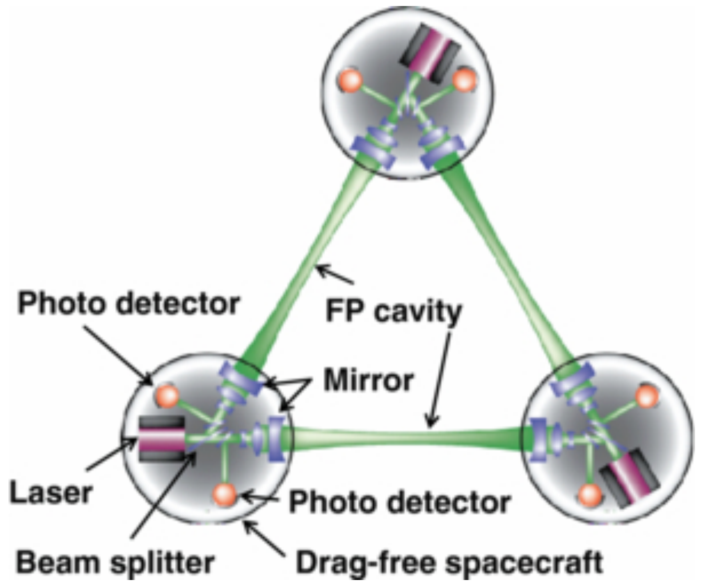
		Default	LF	HF	Larger mirror	FD SQZ	Combined
SRC detuning angle (deg)	$\phi_{\rm det}$	3.5	28.5	0.1	3.5	0.2	0.3
Homodyne angle (deg)	ζ	135.1	133.6	97.1	123.2	93.1	93.0
Mirror temperature (K)	$T_{\rm m}$	22	23.6	20.8	21.0	21.3	20.0
SRM reflectivity (%)	$R_{\rm SRM}$	84.6	95.5	90.7	92.2	83.2	80.9
Fiber length (cm)	$l_{\rm f}$	35.0	99.8	20.1	28.6	23.0	33.1
Fiber diameter (mm)	$d_{\rm f}$	1.6	0.45	2.5	2.2	1.9	3.6
Input power at BS (W)	I_0	673	4.5	3440	1500	1500	3470
Mirror mass (kg)	m	22.8	22.8	22.8	40	22.8	100
Maximum detected squeezing (dB)		0	0	6.1	0	5.2 (FC)	5.1 (FC)
$100\,M_\odot - 100\,M_\odot$ inspiral range (Mpc)		353	**2019**	112	400	306	707
$30\,M_\odot - 30\,M_\odot$ inspiral range (Mpc)		1095	1088	270	1250	843	1687
$1.4\,M_\odot - 1.4\,M_\odot$ inspiral range (Mpc)		**153**	85	155	**202**	**178**	**302**
Median sky localization error (deg^2)		0.183	0.506	**0.105**	0.156	0.120	0.100

For the multi-messenger astronomy and BNS observations, we can expect some improvement from all the upgrade plans except for LF.

mid-2030s
3rd generation interferometers and space interferometers



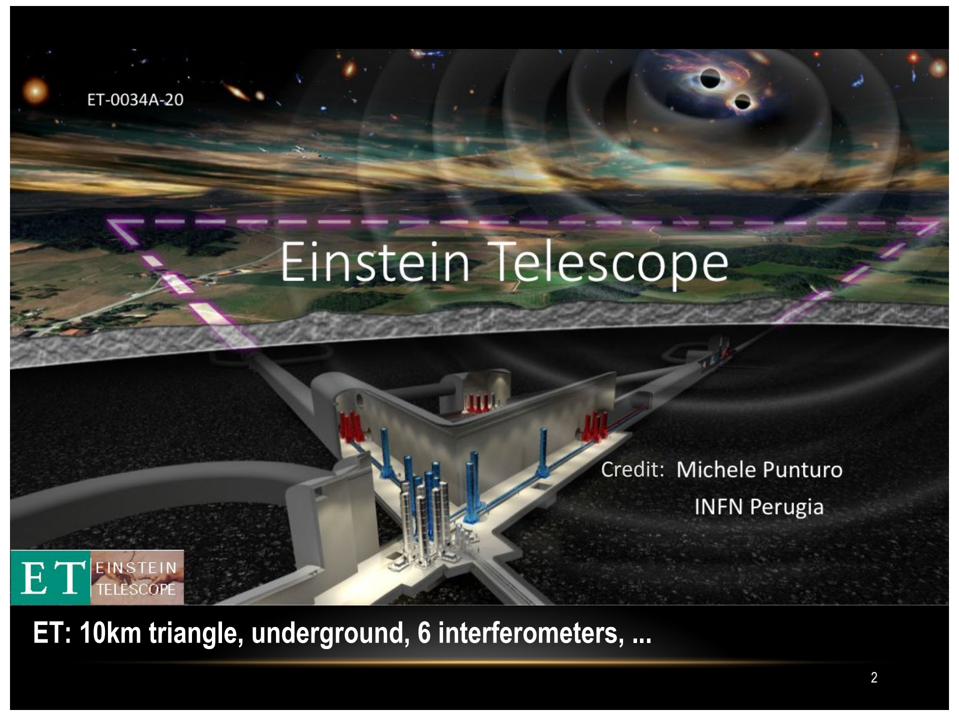
http://lisa.nasa.gov

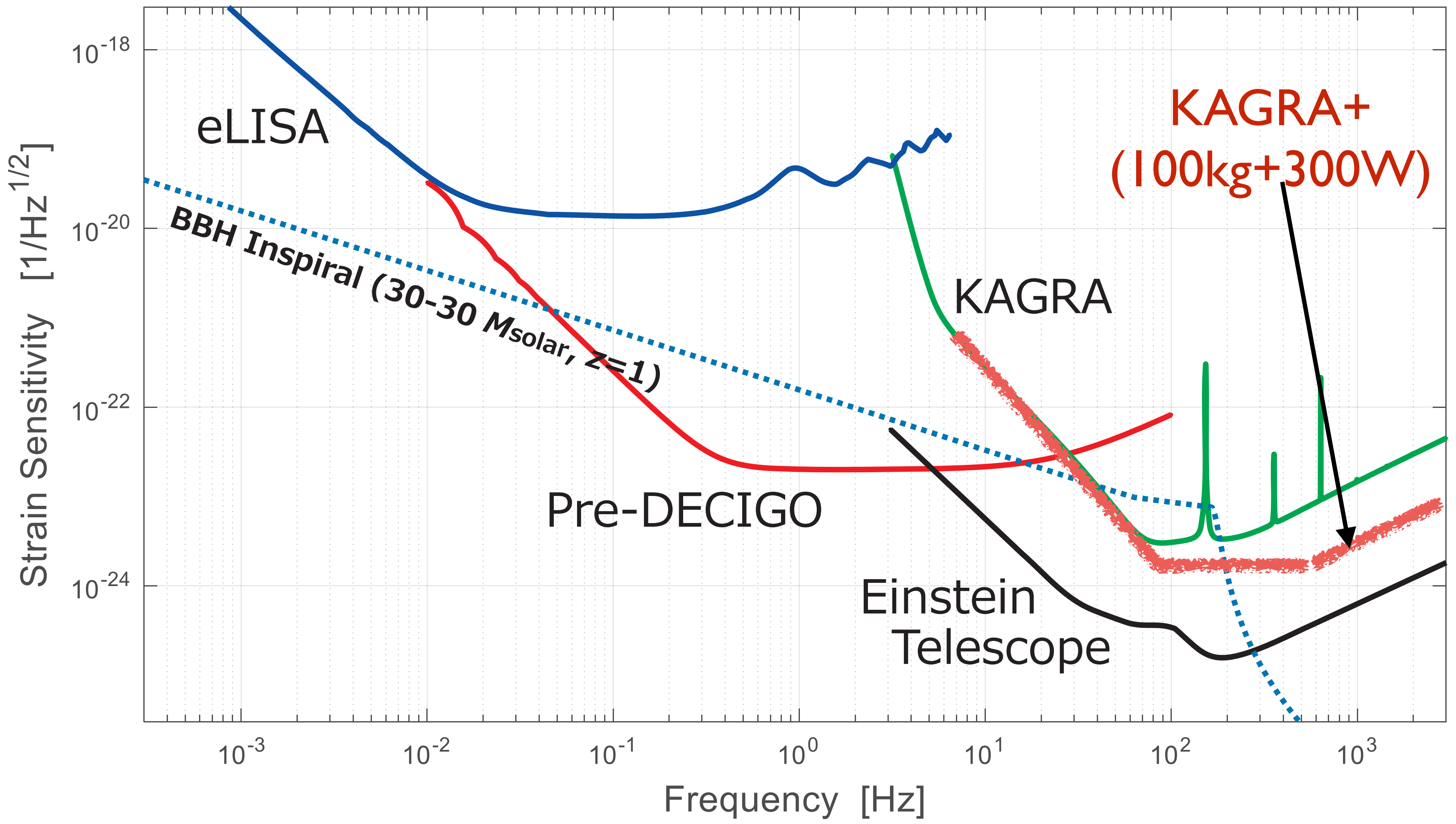


DECIGO

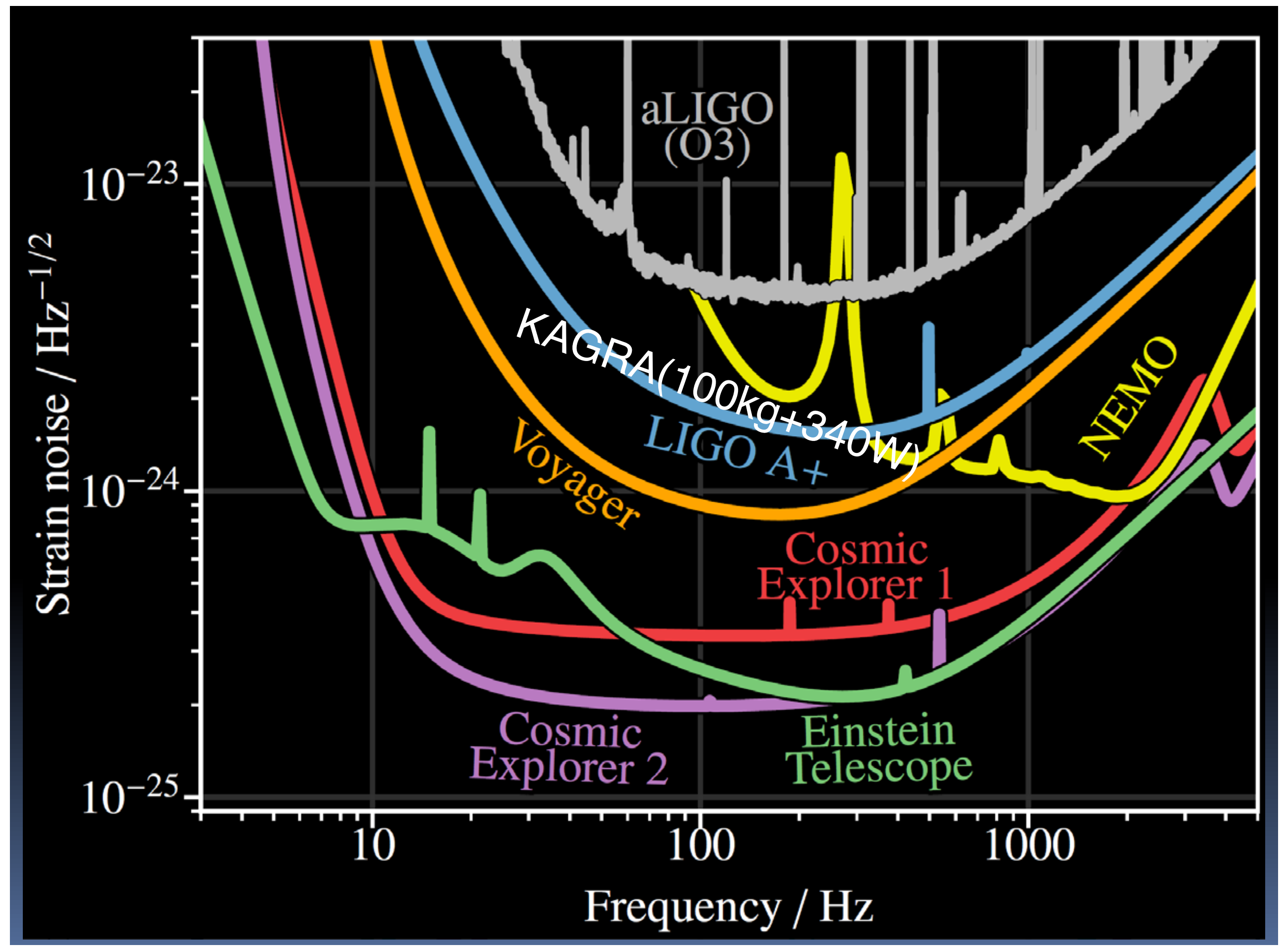
Class. Quantum Grav. 28 (2011) 094011 (12pp)

- Gravitational-wave astronomy will enter a new era since the mid-2030s.
  - eLISA: Space IFO (2.5×10^9 m), Scheduled to be launched in 2034.
  - Pre-DECIGO: Space IFO (1,000 km).
  - Einstein Telescope (10km, Cryogenic, Underground): Scheduled to be 2034
  - Cosmic Explorer I&II (Max40km, Cryogenic): Observations scheduled to start in 2036&2045.
  - Voyager(4km, Cryogenic, Silicon Mirror): Introduced low temperatures to LIGO's facilities
  - NEMO(4km, Cryogenic): Specializing in high-frequency sensitivity. Proposed by an Australian group
- KAGRA is a facility with 3km, cryogenic and underground site. Upgrade similar to Voyager or Nemo may be possible. It is also possible to specialize in low frequencies.





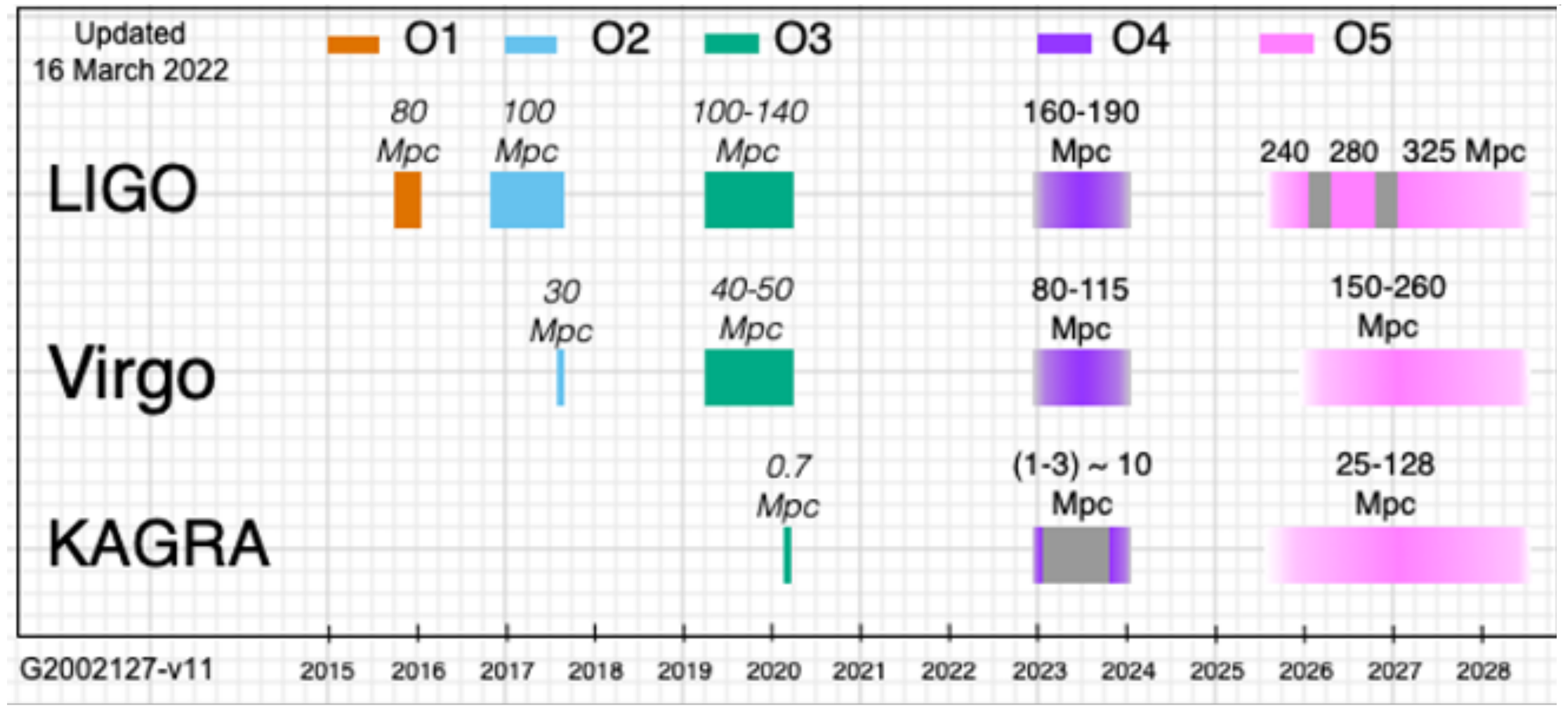
Sensitivity curves with space interferometers

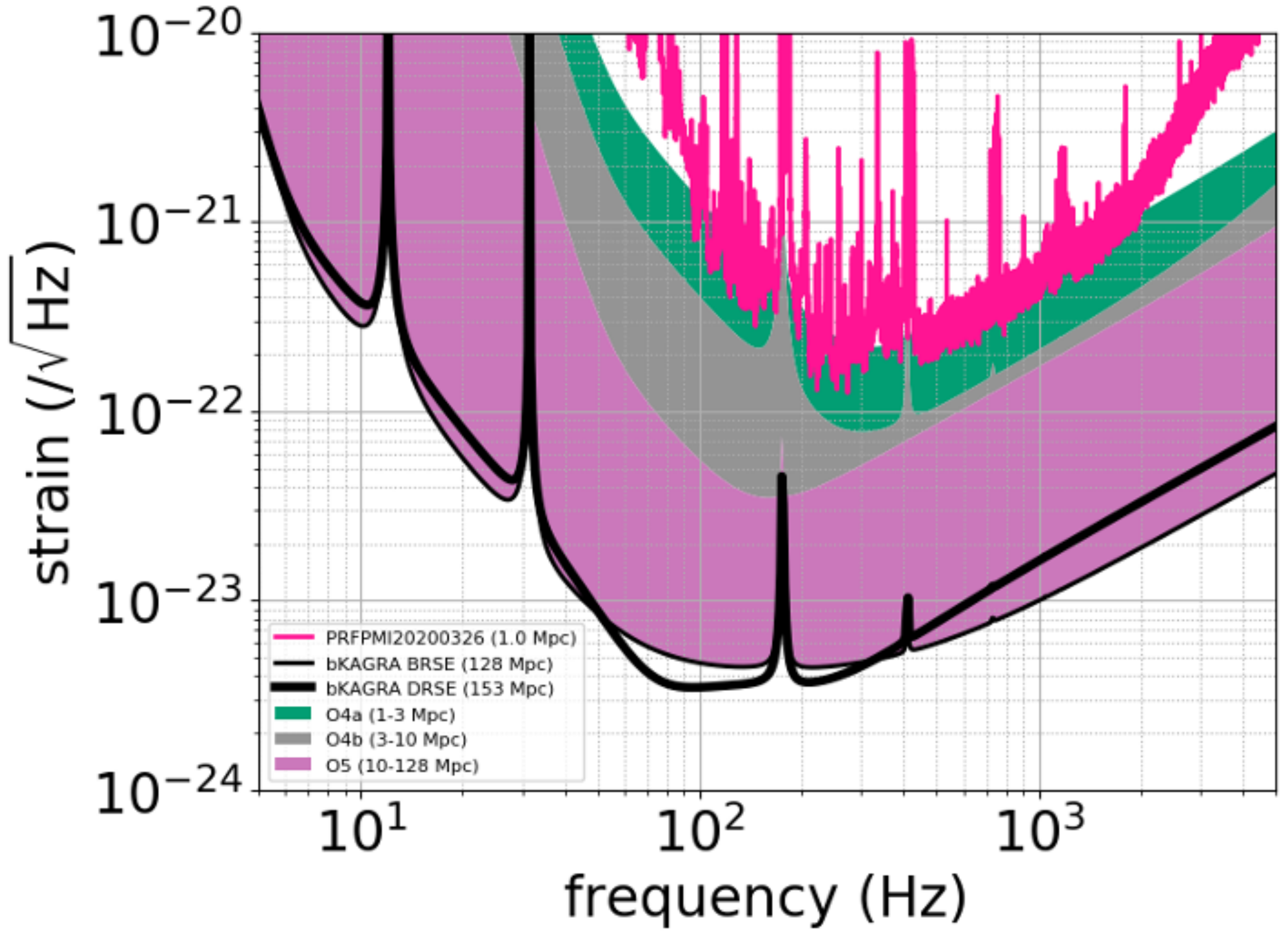


Sensitivity curve with the 3rd generation IFOs
KAGRA+(100kg, 340W) is similar to LIGO A+

Summary

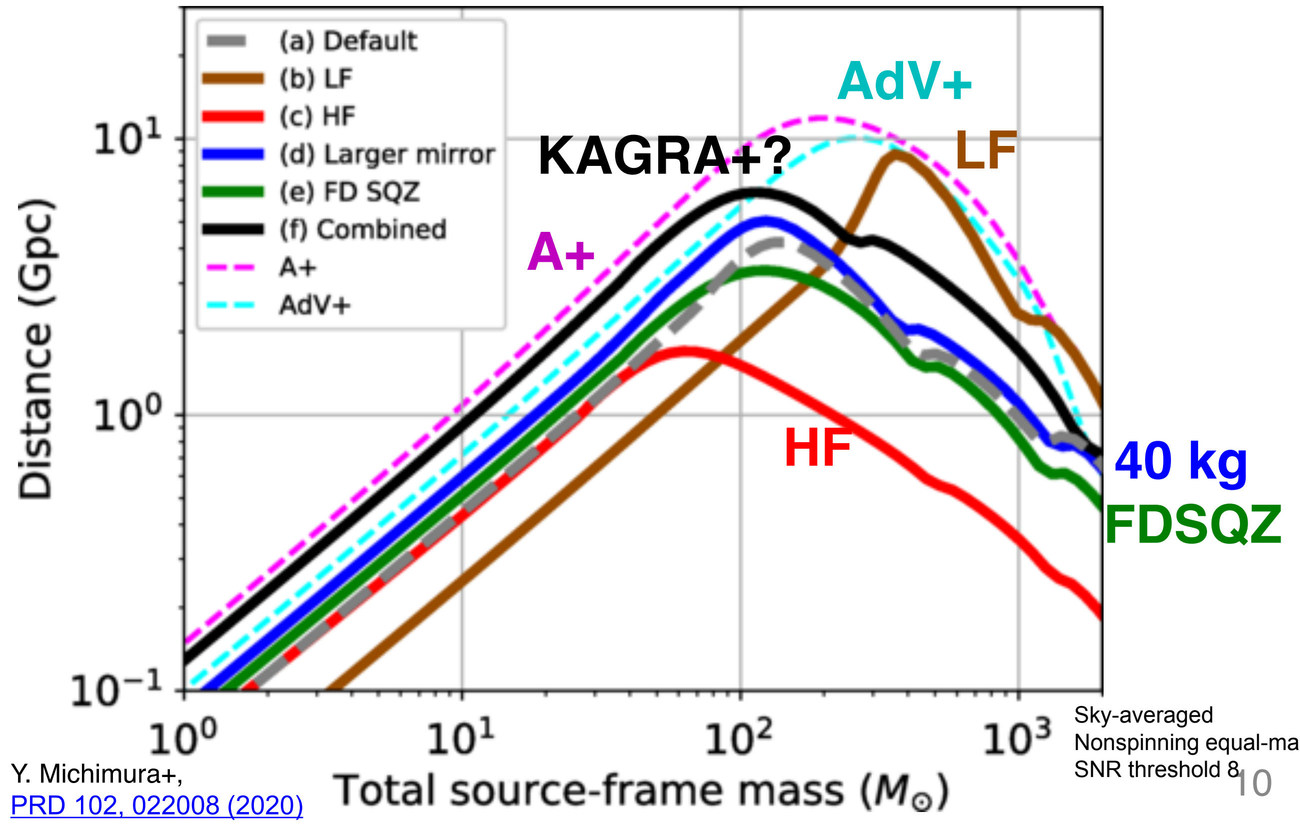
- The latest observation scenario has been shown.
- The full cryogenic operation will be carried out in O4.
- We expect the 1st detection of KAGRA in O4.
- KAGRA's contribution to Sky localization can be expected from O5.
- There are many ideas for updating KAGRA after O5.
- Gravitational-wave astronomy will enter a new era since the mid-2030s.





Detection Ranges

- Hard to beat A+ with horizon distance



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Sky-averaged
Nonspinning equal-mass
SNR threshold 8

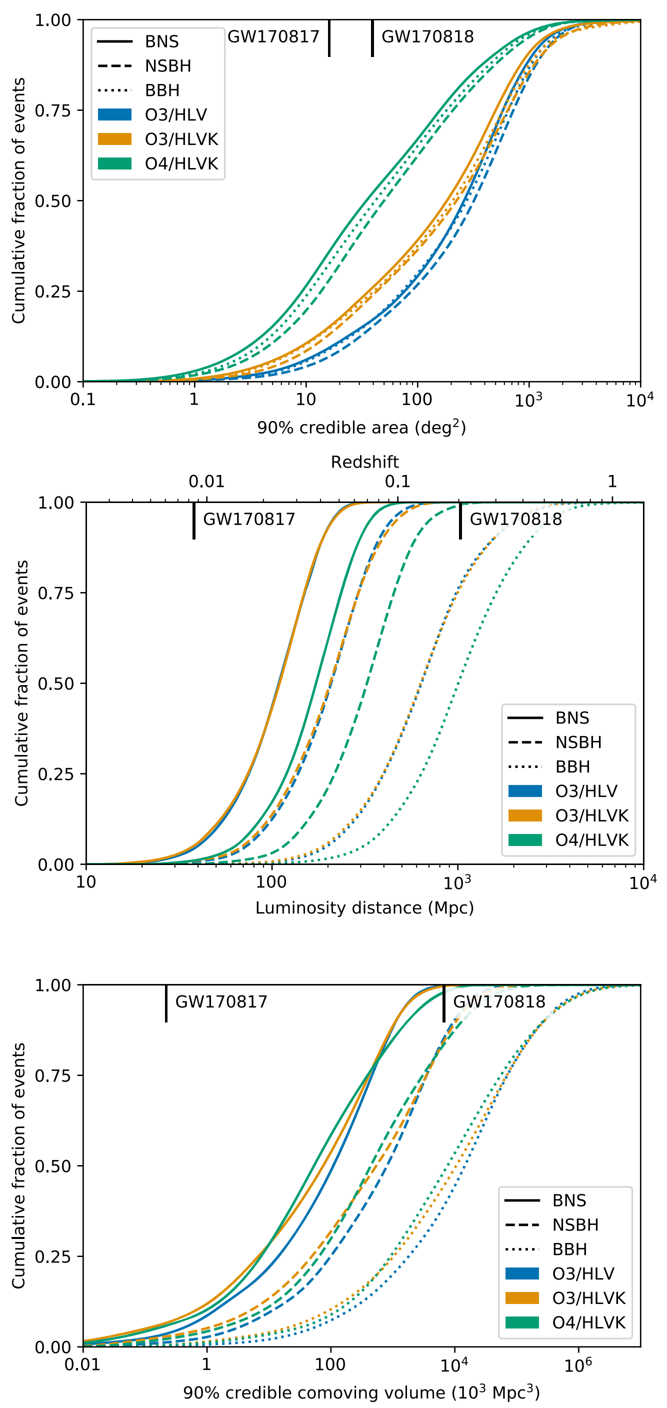


Fig. 6 Anticipated GW sky localization for CBC signals during the third and fourth runs (for O3, see Sect. 5.1 and for O4, see Sect. 5.2). For O3, the detector sensitivities were taken to be representative of the first 3 months of observations for aLIGO Hanford and Livingston, and AdV, and the highest expected O3 sensitivity for KAGRA (see Fig. 1). For O4, the detector sensitivities were taken to be the target sensitivities for aLIGO and AdV, and the mid of the interval expected for KAGRA during O4. Top: The plot shows the cumulative fractions of events with sky-localization area smaller than the abscissa value. Central: The plot shows the cumulative fractions of events with luminosity distance smaller than the abscissa value. Bottom: The plot shows the cumulative fractions of events with comoving volume smaller than the abscissa value. Sky-localization area (comoving volume) is given as the 90% credible region, the smallest area (comoving volume) enclosing 90% of the total posterior probability. Results are obtained using the low-latency BAYESTAR pipeline (Singer and Price 2016). The simulation accounts for an independent 70% duty cycle for each detector, and the different sensitivity of each sub-network or network of detectors. For O3, all the combinations of sub-networks of two operating detectors and the three detector network (HLV) are included in the blue lines. All the combinations of sub-networks of two and three operating detectors, and the four detector network (HLVK) are included in the orange lines for O3 and in the green lines for O4. The O3 HLV and the O3 HLVK curves in the central panel are very similar due to the modest contribution by KAGRA to the network SNR. Solid lines represent BNSs, dashed lines NSBHs, dotted lines BBHs. As a comparison, the plots show the area, distance and volume of GW170817 and GW170818, which are the best localized BNS and BBH signals during O1 and O2

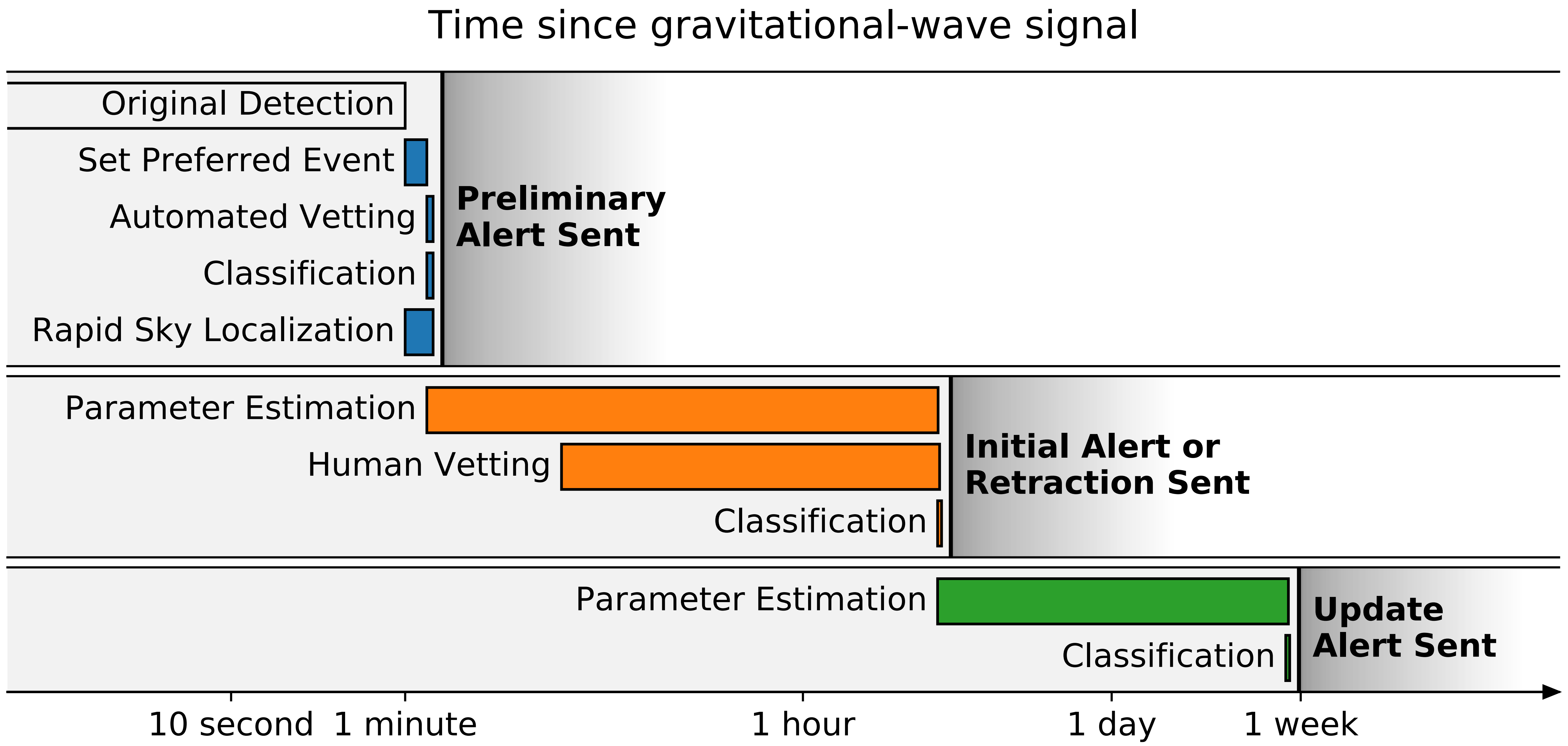
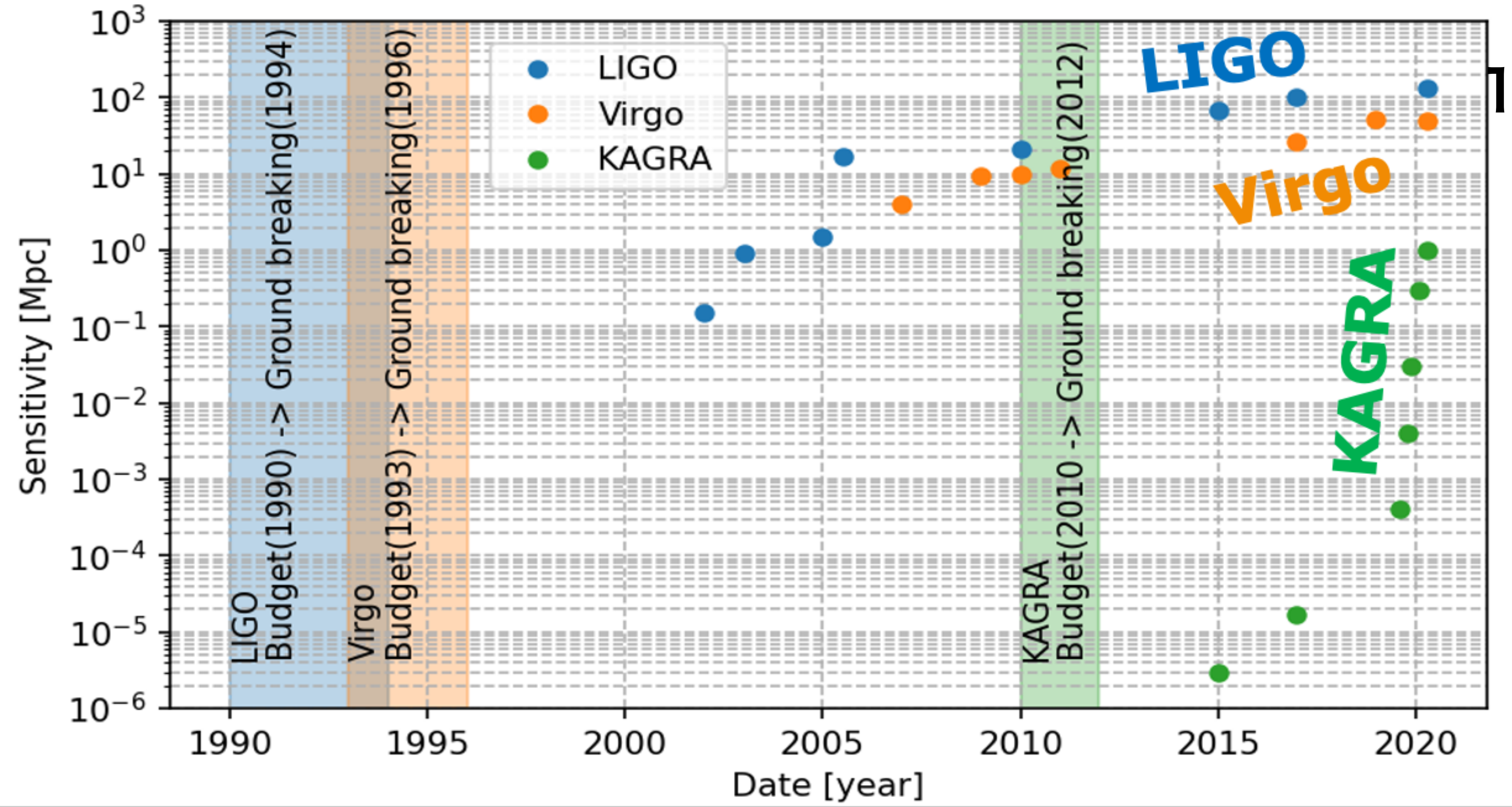


Fig. 8 Alert timeline. The *Preliminary GCN Notice* is sent autonomously within 1–10 min after the GW candidate trigger time. Some preliminary alerts may be retracted after human inspection for data quality, instrumental conditions, and pipeline behavior. The human vetted *Initial GCN Notice* or *Retraction GCN Notice* and associated *GCN Circular* are distributed within a few hours for BNS or NSBH sources and within 1 day for BBH. Update notices and circulars are sent whenever the estimate of the parameters of the signal significantly improves. Image adapted from the LIGO/Virgo Public Alerts User Guide (see footnote 17)

https://arxiv.org/abs/1304.0670

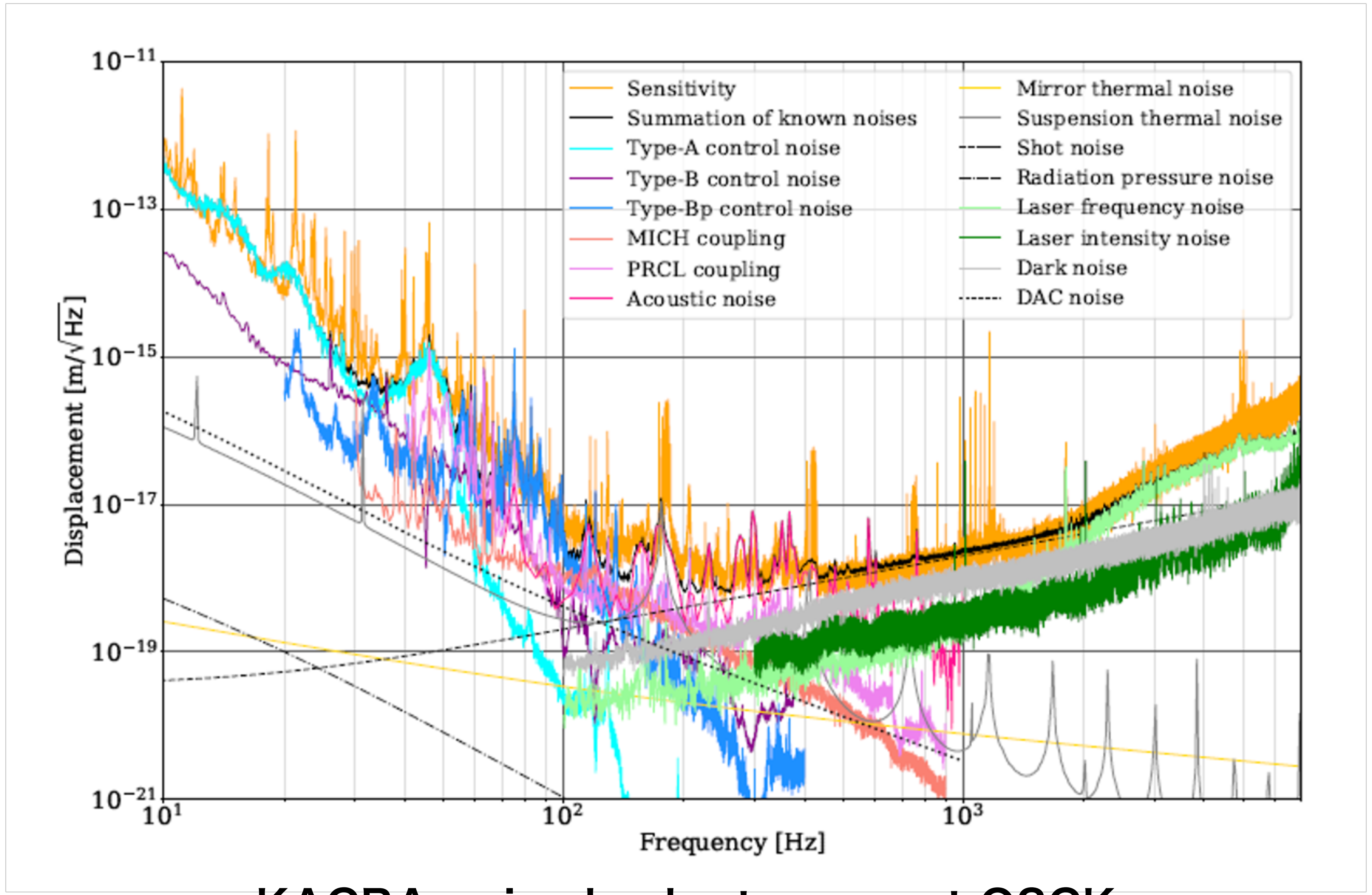


100Mpc

1Mpc

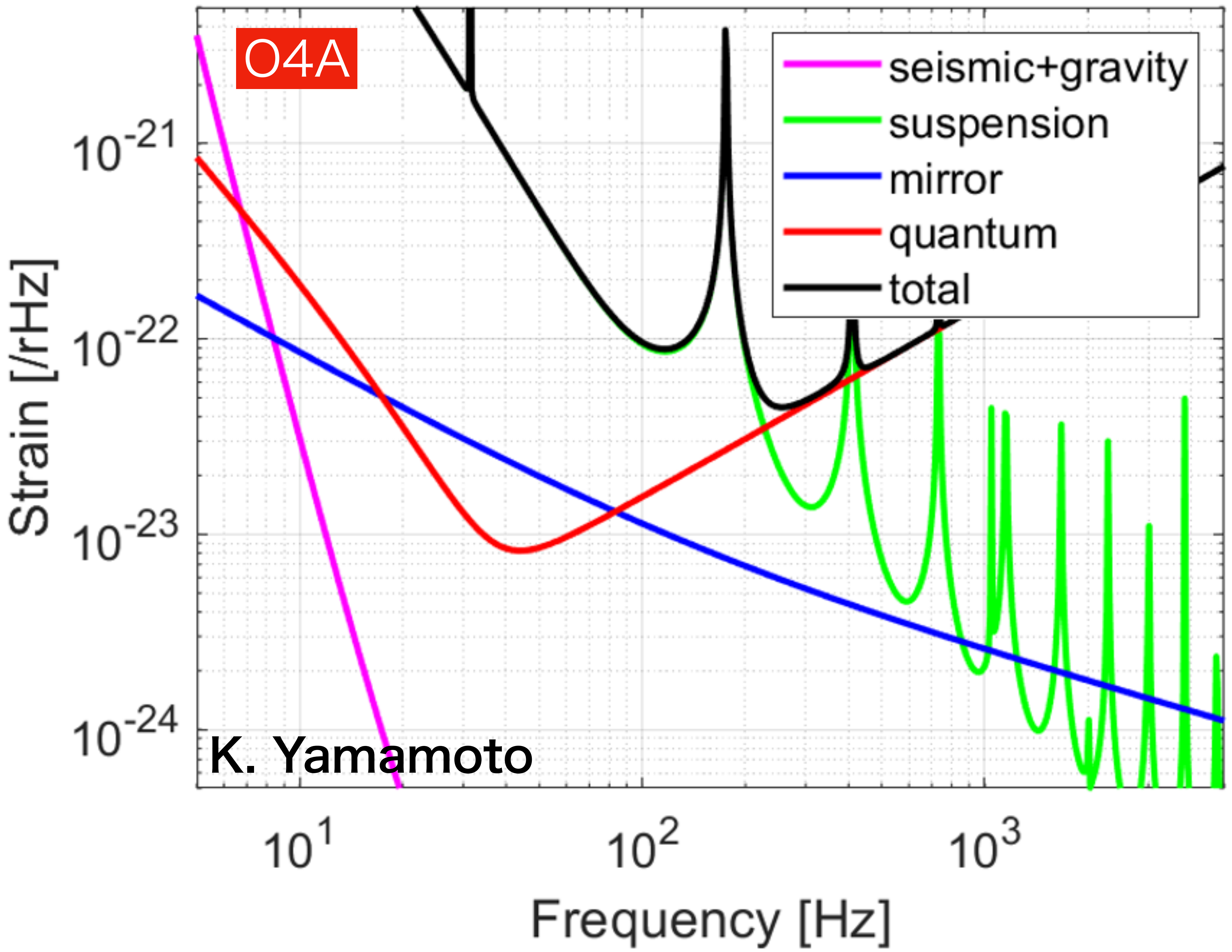
Evolution of the distance to which a binary neutron star (BNS) merger is detectable with S/N> 8: BNS range[Mpc]

Yokoyama sensei's presentation

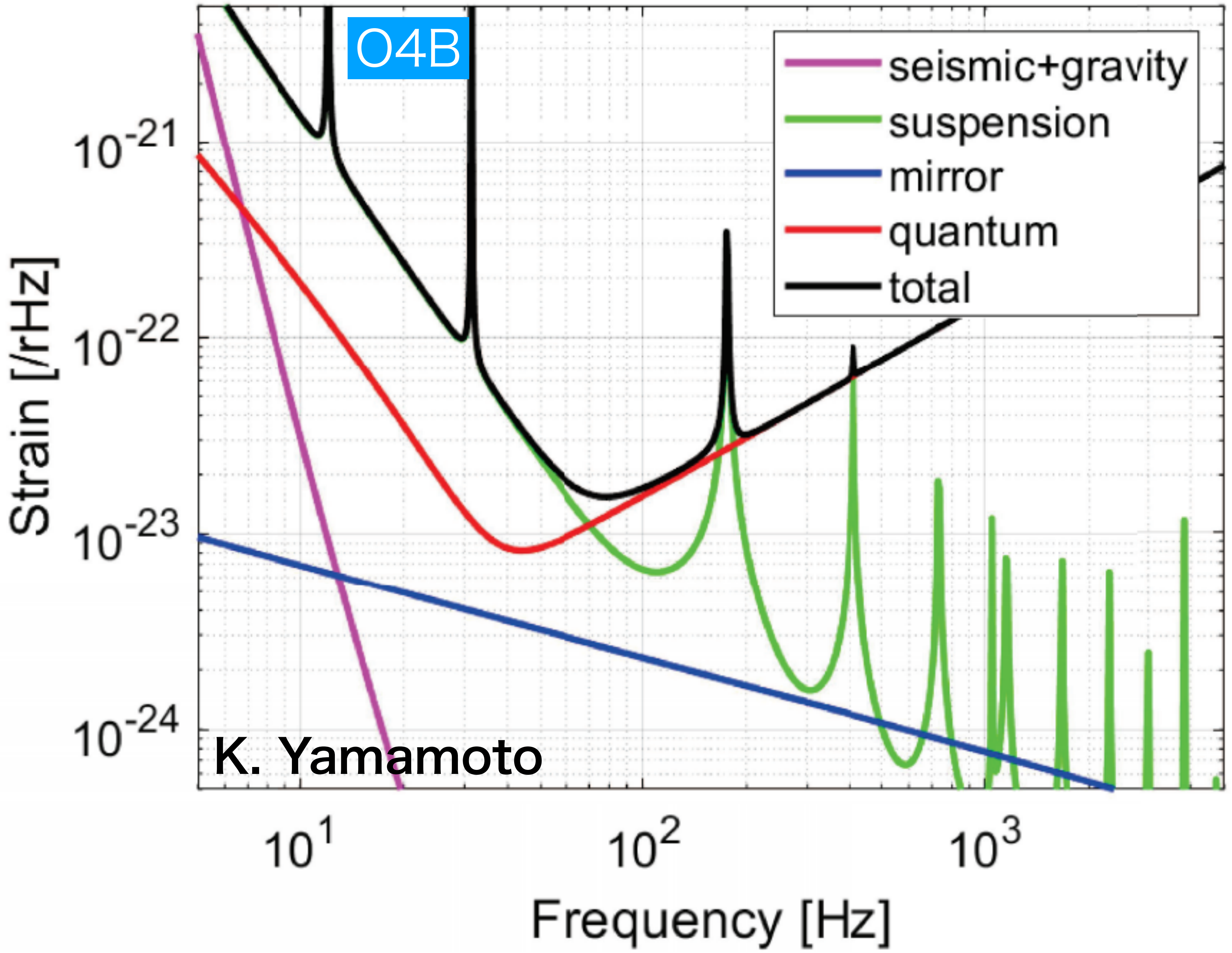


KAGRA noise budget curve at O3GK
https://arxiv.org/abs/2203.07011

Fundamental noises in O4



- Mirror temperature: 250K ~ 300K
- Laser power at BS: 58W (same as O3GK)
- PRFPMI
- Observation range limit: 6Mpc
- Target: 1Mpc

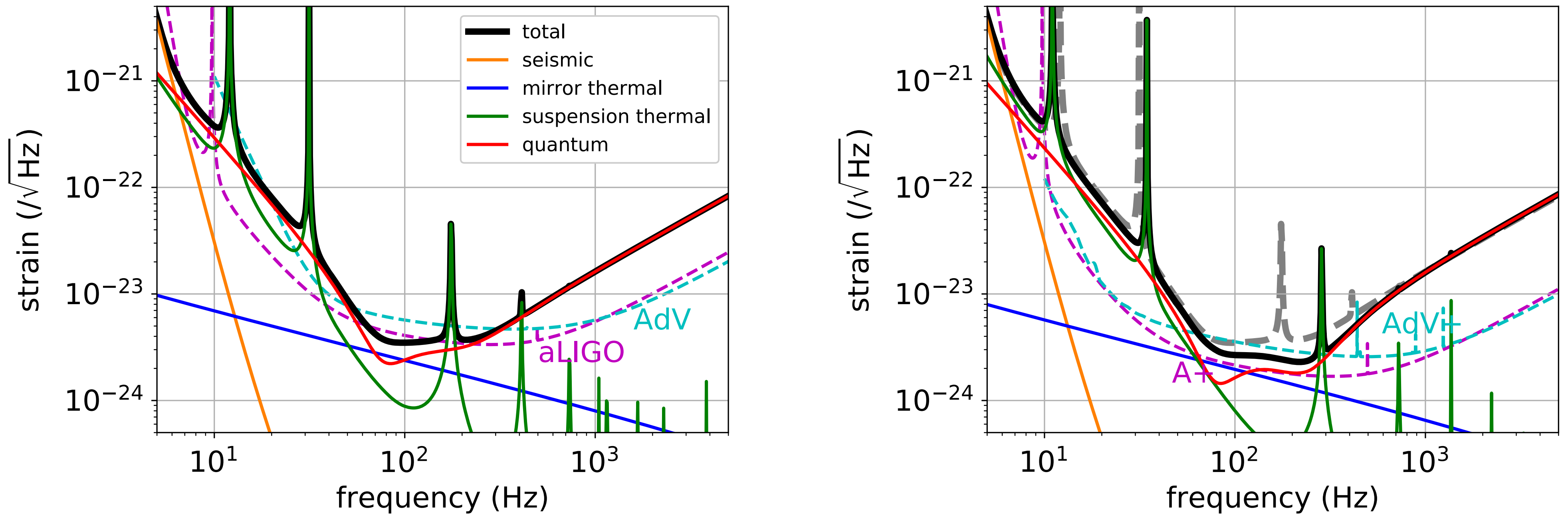


- Mirror temperature: ~20K
- Laser power at BS: 58W
- PRFPMI
- Observation range limit: 35Mpc
- Target: 10Mpc

Details of 2021 Version

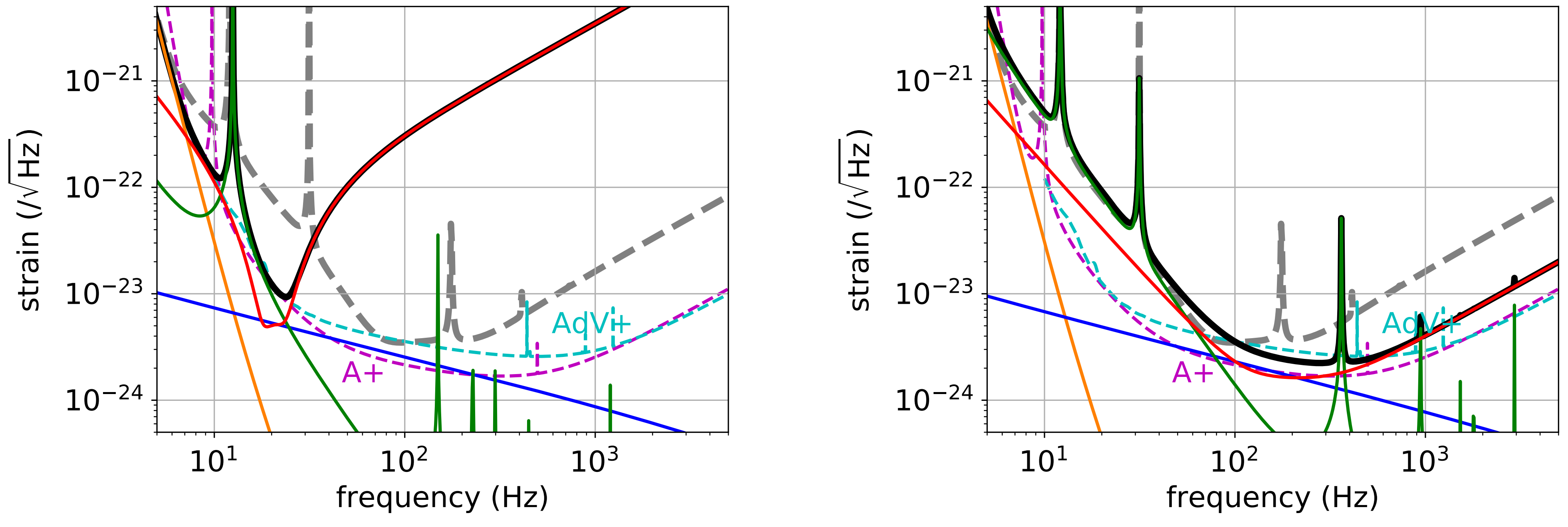
- O5 high same as BRSE (conventional readout) in JGW-T1707038

	Mirror temp.	Power at BS	SRM reflectivity	Detuning angle	Homodyne angle	Excess noises
O3GK best	~250 K	30-50 W	70 % tilted	90 deg (PRFPMI)	90 deg (conventional)	LFnoise Pess. laser noise
O4a low	300 K	50 W	70 % tilted	90 deg (PRFPMI)	90 deg	LFnoise Pess. laser noise
O4a high / O4b low	300 K	50 W	0 %	90 deg (PRFPMI)	90 deg	0.3*LFnoise Feasible laser noise
O4b high / O5 low (10 Mpc)	40 K	50 W	0 %	90 deg (PRFPMI)	90 deg	0.04*LFnoise Feasible laser noise
O4b high / O5 low (25 Mpc)	40 K	300 W	0 %	90 deg (PRFPMI)	90 deg	0.013*LFnoise Feasible laser noise
O5 high	22 K	673 W	85 %	90 deg (BRSE)	90 deg (conventional)	no excess
Design	22 K	673 W	85 %	86.5 deg (DRSE)	135.1 deg	no excess



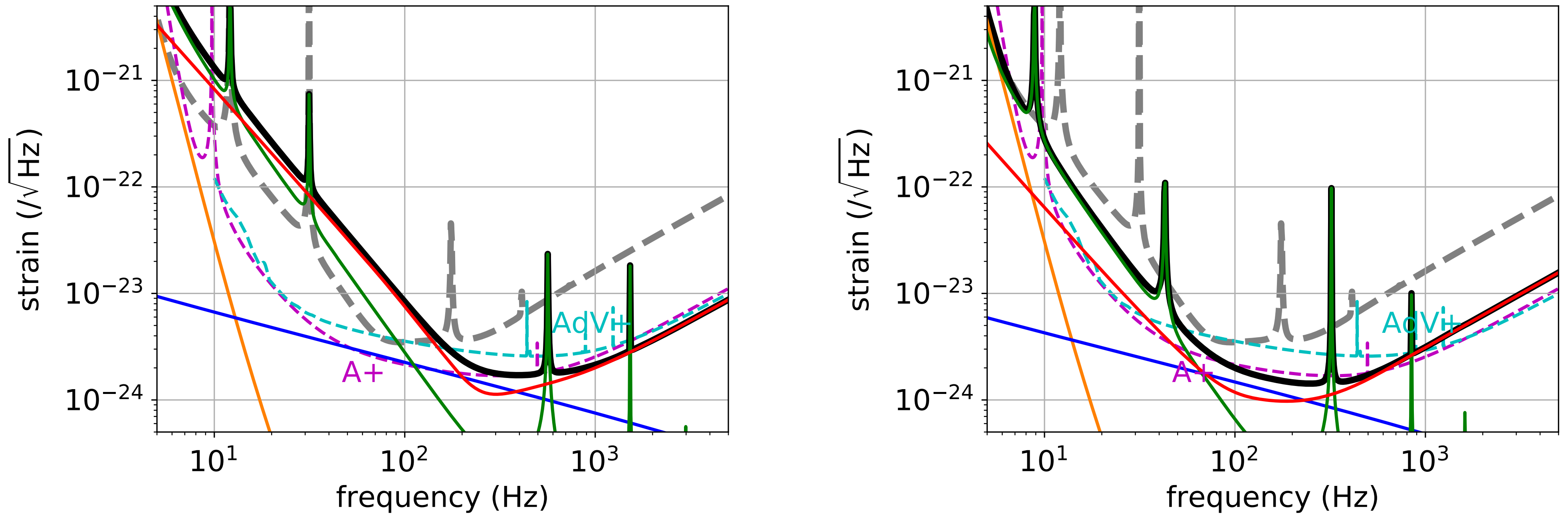
(a) Default

(d) Larger mirror



(b) Low frequency

(e) Frequency dependent squeezing



(c) High frequency

(f) Combined

FIG. 1. Sensitivity curves for the default KAGRA and possible upgrades calculated with the parameters shown in Table I. Sensitivity curves for Advanced LIGO (aLIGO) and Advanced Virgo (AdV) are also shown for comparison in (a). For other plots, sensitivity curves for the upgrades A+ and AdV+, and default KAGRA are shown. Sensitivity curve data for Advanced LIGO and A+ are taken from Refs. [22,37], and those for Advanced Virgo and AdV+ are extracted from Ref. [26].

TABLE I. Interferometer parameter values, inspiral ranges, and median of sky localization error for a GW170817-like binary for possible KAGRA upgrades. Default values [31,38] are also shown as a reference. Inspiral ranges and sky localization errors in bold are the objective function values used for the sensitivity optimization. LF: low frequency; HF: high frequency; FD SQZ: frequency-dependent squeezing; FC: with 30-m filter cavity; SRC: signal recycling cavity; SRM: signal recycling mirror; and BS: beam splitter.

		Default	LF	HF	Larger mirror	FD SQZ	Combined
SRC detuning angle (deg)	$\phi_{\rm det}$	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)	$T_{\rm m}$	22	23.6	20.8	21.0	21.3	20.0
SRM reflectivity (%)	$R_{\rm SRM}$	84.6	95.5	90.7	92.2	83.2	80.9
Fiber length (cm)	$l_{\rm f}$	35.0	99.8	20.1	28.6	23.0	33.1
Fiber diameter (mm)	$d_{\rm f}$	1.6	0.45	2.5	2.2	1.9	3.6
Input power at BS (W)	I_0	673	4.5	3440	1500	1500	3470
Mirror mass (kg)	m	22.8	22.8	22.8	40	22.8	100
Maximum detected squeezing (dB)		0	0	6.1	0	5.2 (FC)	5.1 (FC)
$100\ M_\odot - 100\ M_\odot$ inspiral range (Mpc)		353	**2019**	112	400	306	707
$30\ M_\odot - 30\ M_\odot$ inspiral range (Mpc)		1095	1088	270	1250	843	1687
$1.4\ M_\odot - 1.4\ M_\odot$ inspiral range (Mpc)		**153**	85	155	**202**	**178**	**302**
Median sky localization error (deg^2)		0.183	0.506	**0.105**	0.156	0.120	0.100

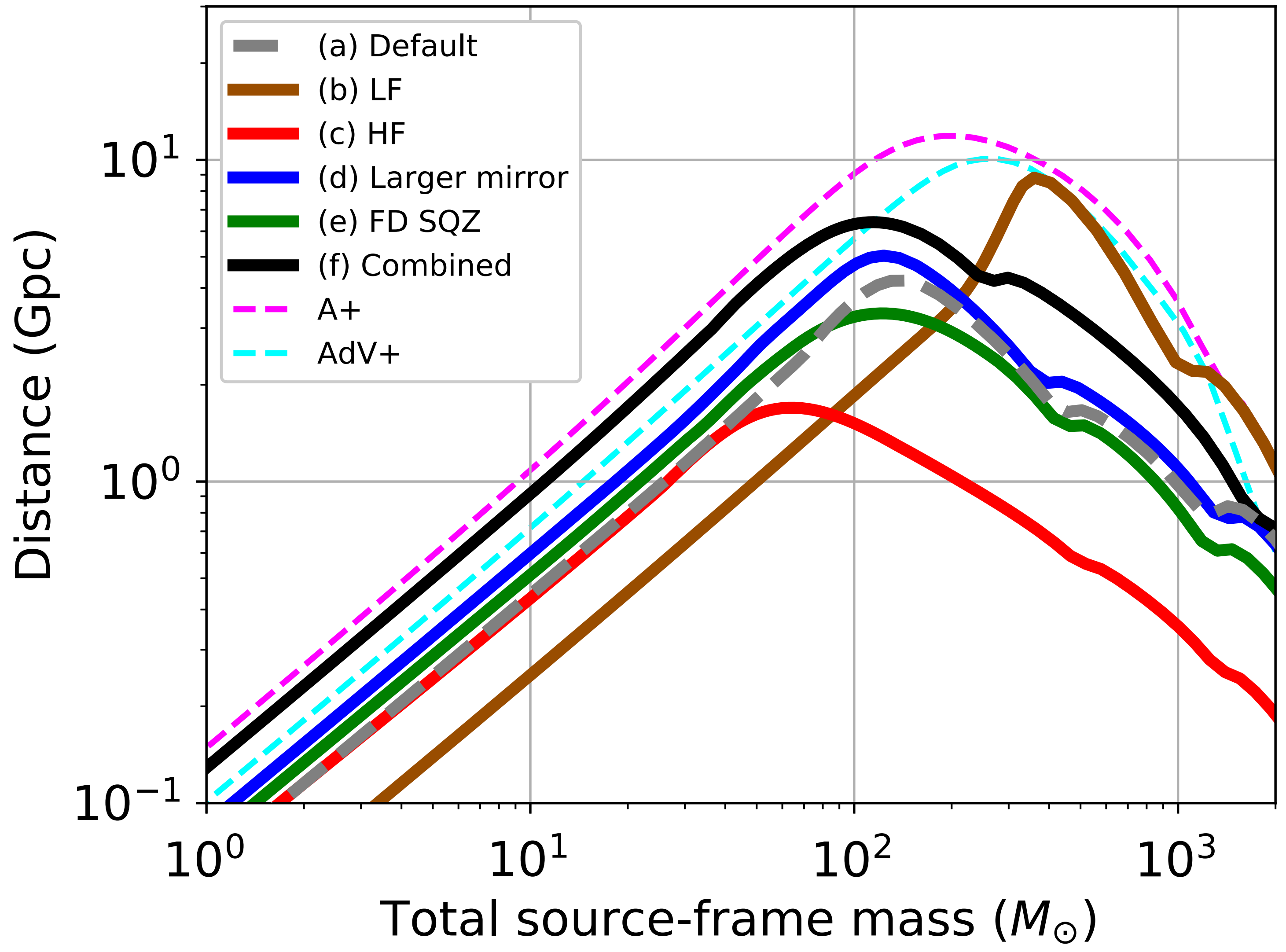
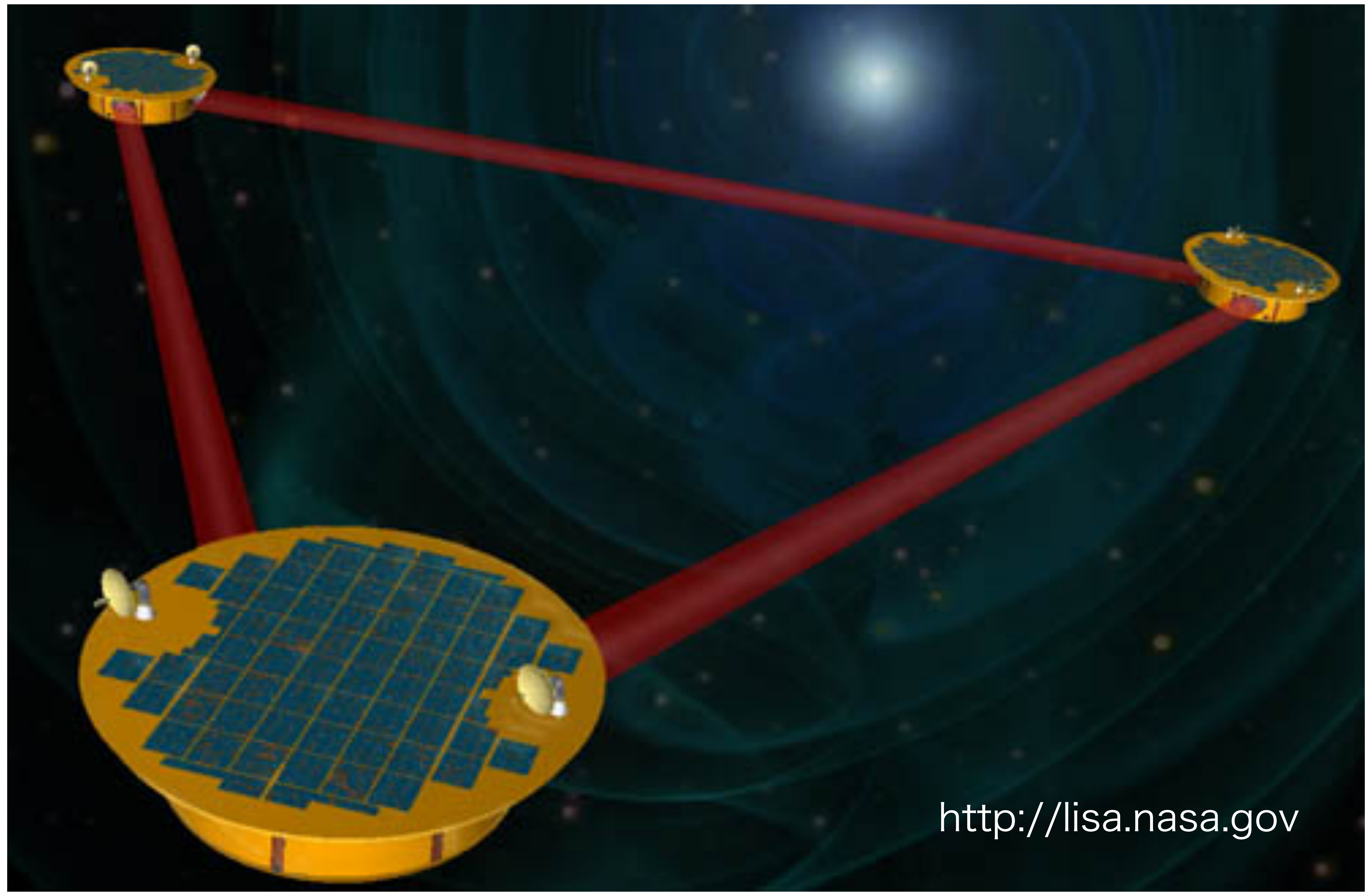


FIG. 2. The detection ranges of possible KAGRA upgrades for nonspinning equal-mass binaries. The redshift corrected, sky averaged distance at which gravitational waves can be detected with a signal-to-noise ratio of more than 8 is shown for each upgrade.

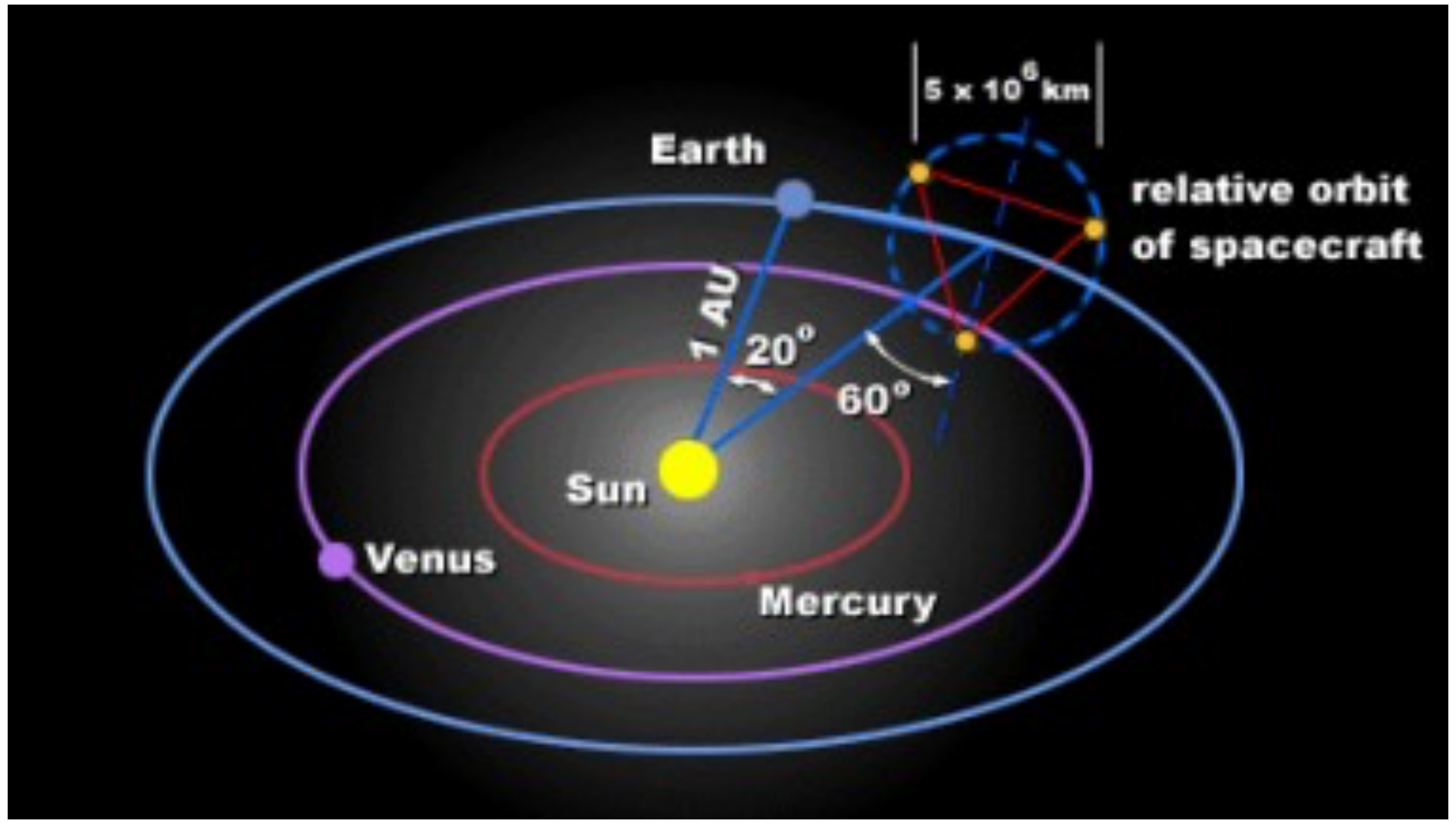
Space Interferometer -LISA-

Laser Interferometer Space Antenna (LISA)

- Triangular constellation of three space craft in heliocentric orbit.
- Inter distance: 2.5×10^9 m.
- Target GW: SMBH binaries, Compact objects captured by SMBH.
- Frequency: 0.03 mHz - 0.1Hz
- Lunch in 2034 is planned.
- Prototype experiment successfully completed -> LISA pathfinder



http://lisa.nasa.gov



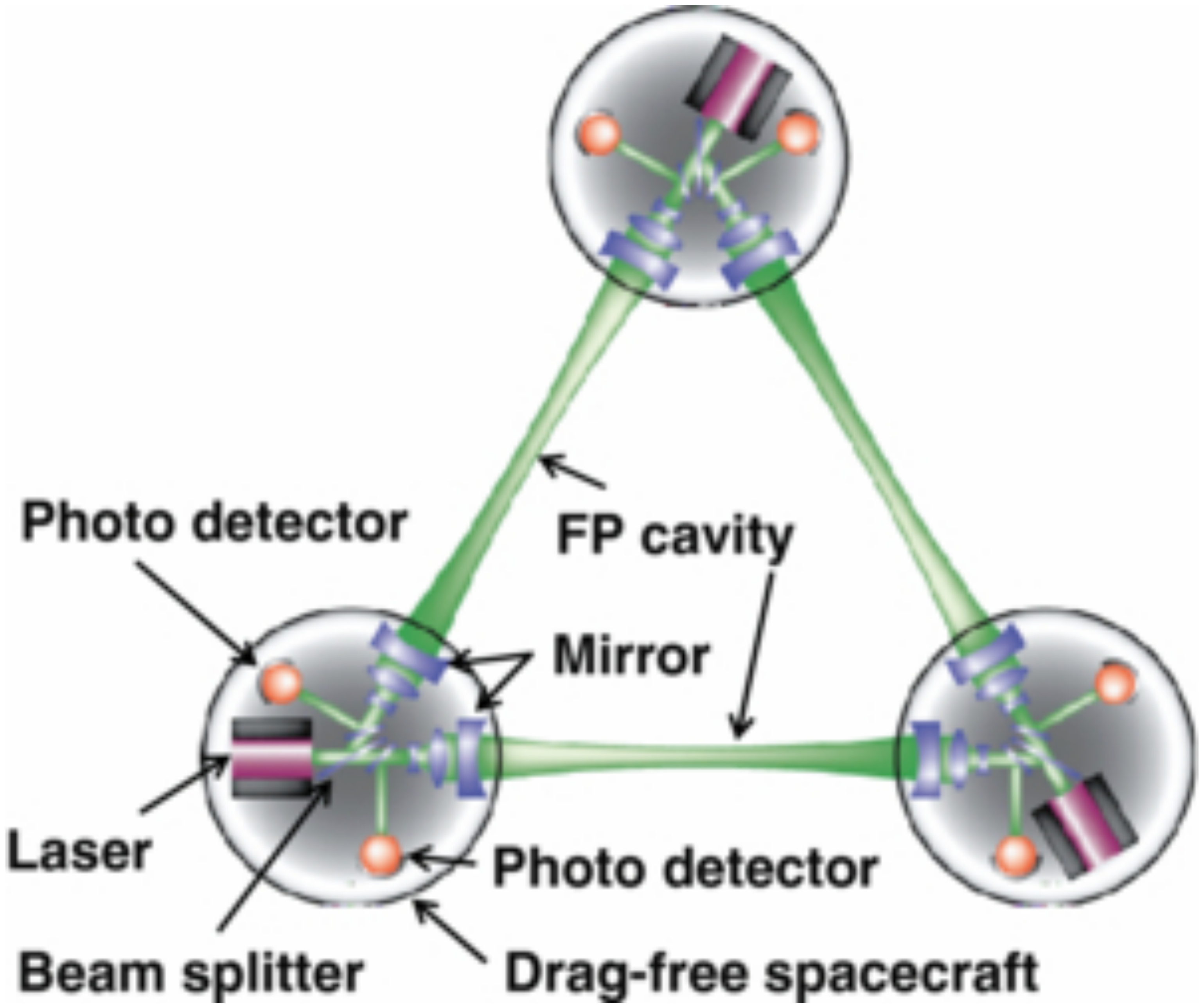
Laser Interferometer Space Antenna (LISA)

- 三角形を形成する3機の宇宙船を太陽光天気道場に展開。
- 宇宙船間の距離: 2.5×10^9 m.
- 対象となる重力波: SMBH binaries、SMBHに落下する恒星サイズの天体
- 周波数: 0.03 mHz - 0.1Hz
- 2034年に打ち上げの予定。
- プロトタイプ実験が成功裏に完了 →LISA pathfinder

Space Interferometer -DECIGO-

DECi-hertz Interferometer Gravitational wave Observatory (DECIGO)

- 4 sets of triangular constellation of three space craft in heliocentric orbit.
- Inter distance: 1,000 km.
- Target GW: Inspiral phase of compact binaries, Cosmological GW background.
- Frequency: 0.1 Hz - 10Hz



DECi-hertz Interferometer Gravitational wave Observatory (DECIGO)

- 4組の三角形を形成する宇宙船を太陽光天気道場に展開。
- 宇宙船間の距離: 1,000 km.
- 対象となる重力波: コンパクト星連星のinspiral phase, 宇宙論的重力波背景輻射。
- 周波数: 0.1 Hz - 10Hz

http://tamago.mtk.nao.ac.jp/decigo/index_E.html

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