ICRR Seminar @ ICRR Kashiwa

June 18, 2019

Current status and future prospects of KAGRA gravitational wave telescope

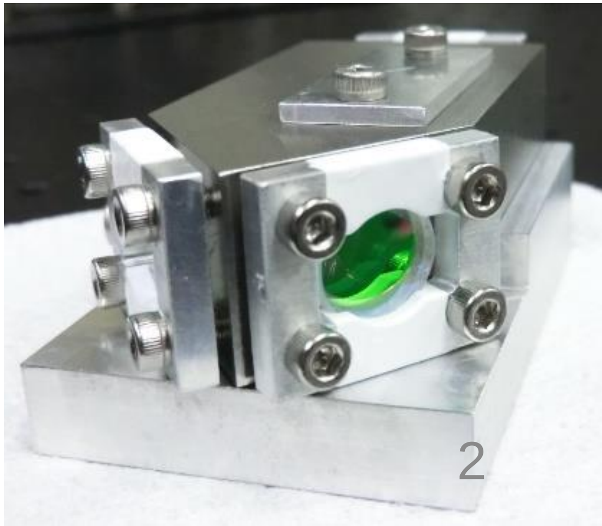
Yuta Michimura

Department of Physics, University of Tokyo

Self Introduction

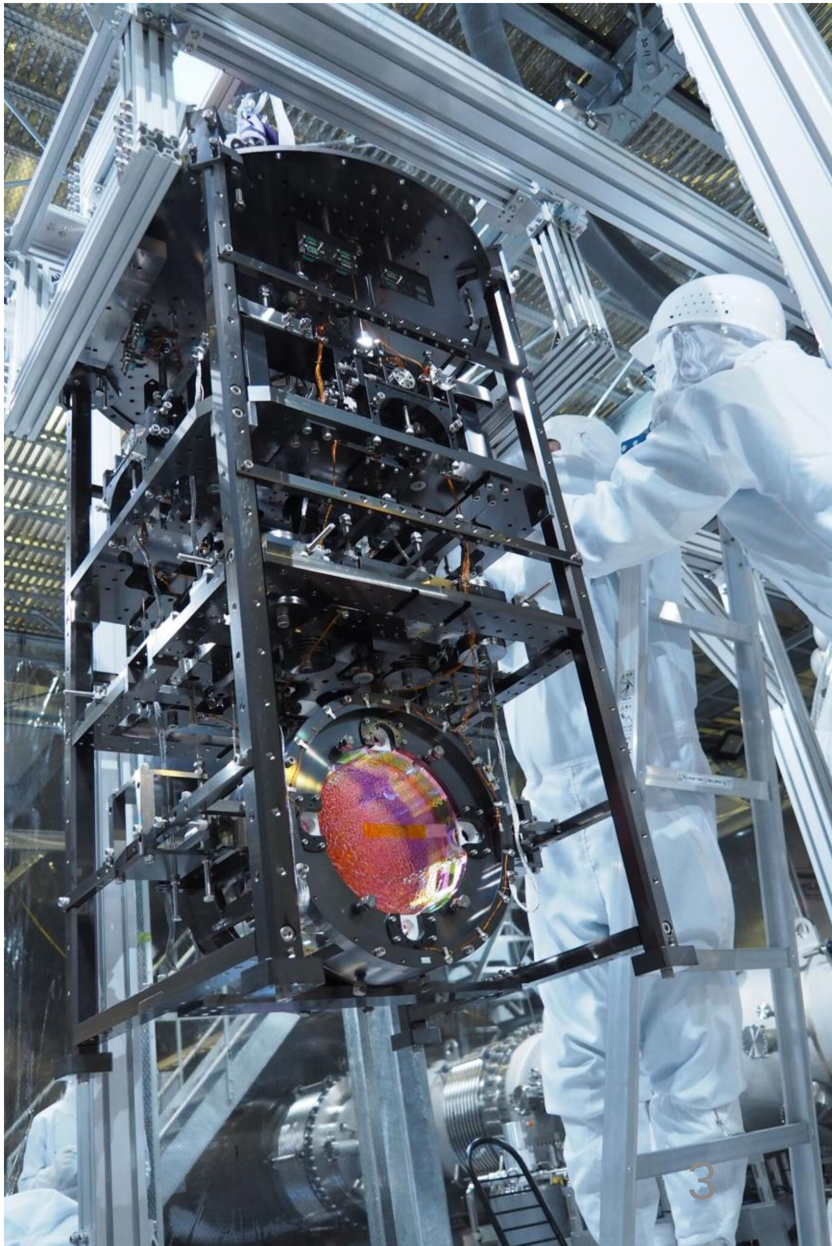
- Yuta Michimura (道村 唯太)
- Interferometric gravitational wave telescope
  - KAGRA
    (Interferometer design and controls)
  - DECIGO
- Test of fundamental physics with laser interferometry
  - Lorentz invariance
  - Macroscopic quantum mechanics
  - Axion search

  etc…



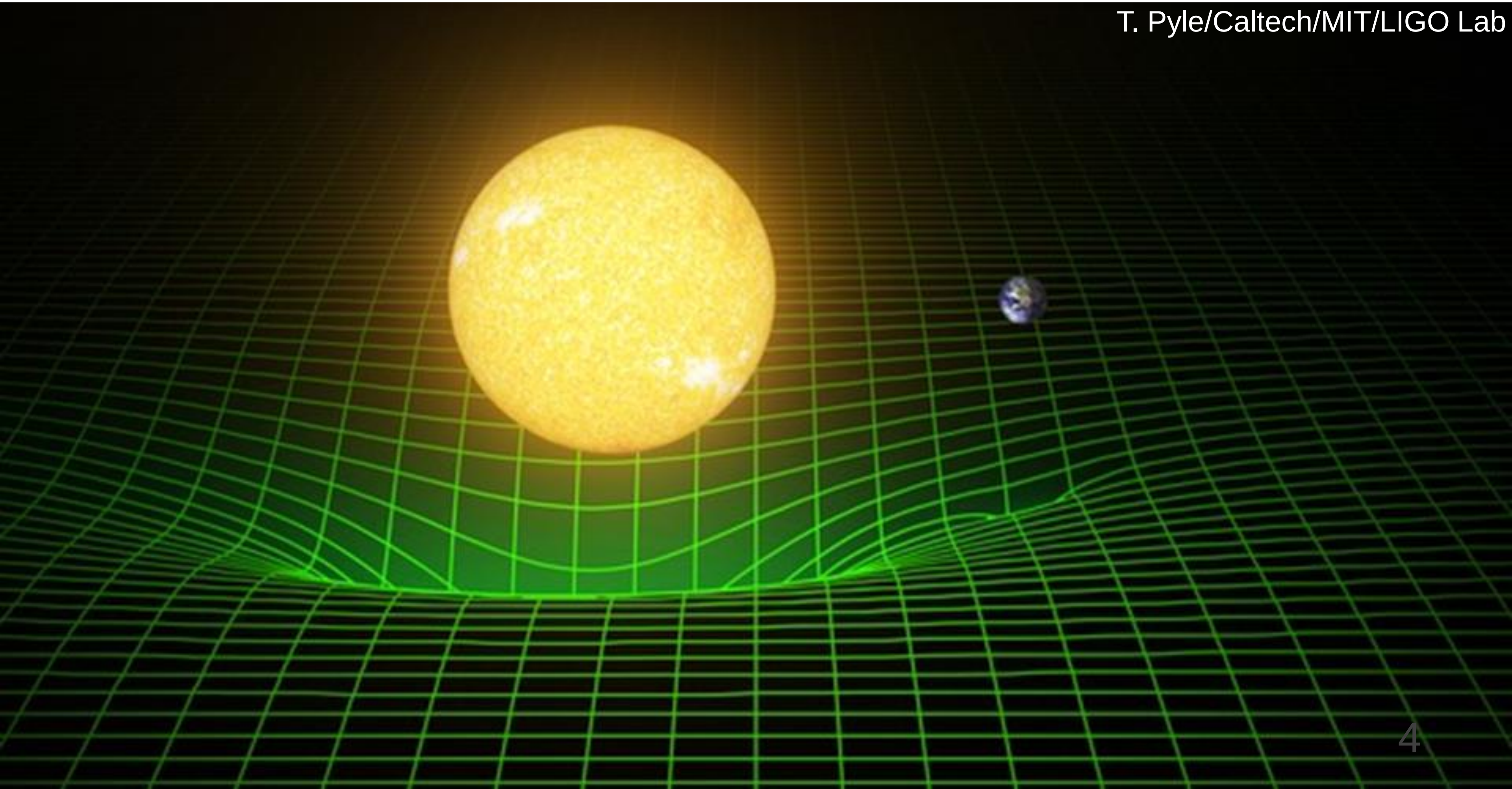
Outline

- Introduction
  - Gravitational waves
  - Interferometric detection
  - Observing runs
- Status of KAGRA
  - Project overview
  - Installation and test runs
- Future Prospects
  - KAGRA upgrade plans
  - Next generation
- Summary



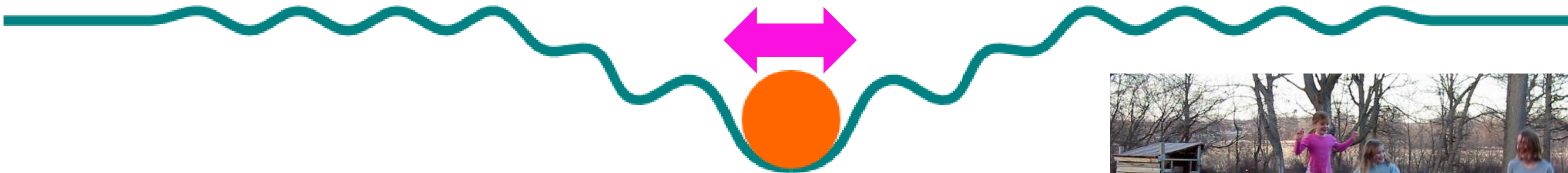
Gravity in General Relativity

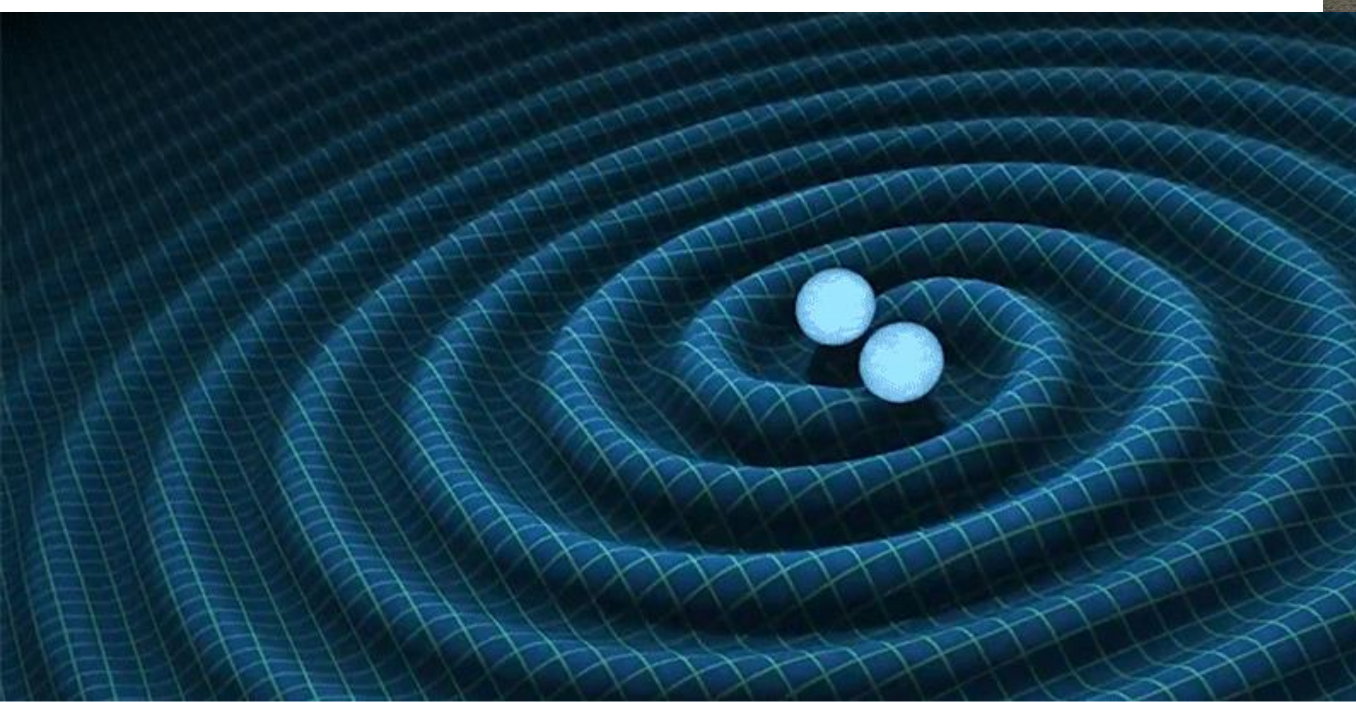
- space-time bends with presence of mass
- bending affects motion of objects → gravity



Gravitational Waves

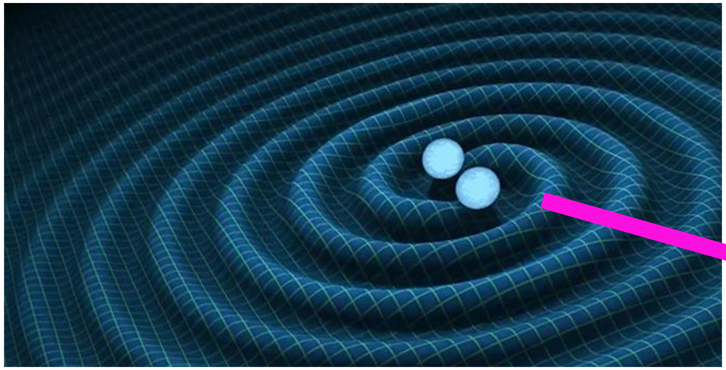
- ripples in space-time created by motion of objects

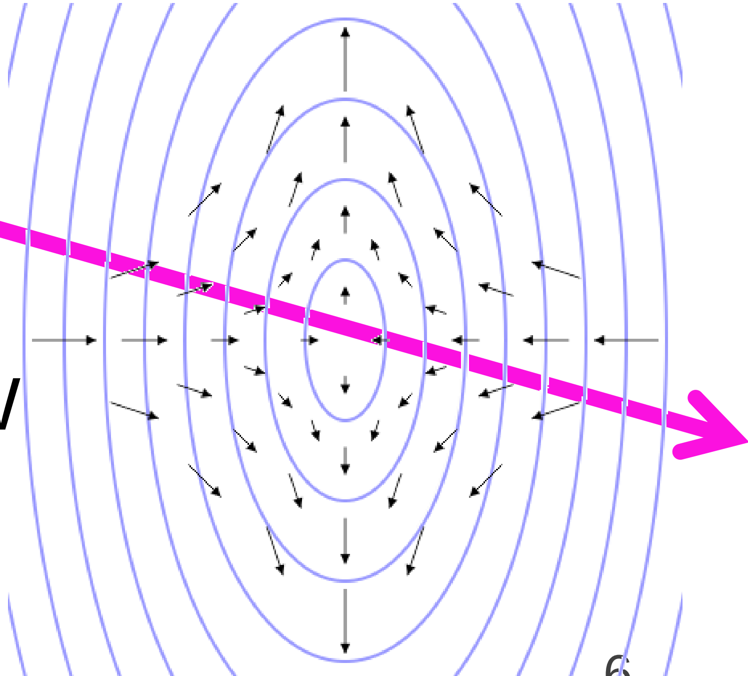




Characteristics of GWs

- propagates at the speed of light
- quadrupole radiation (+ mode and x mode)
- high transmissivity ↔ very weak interaction

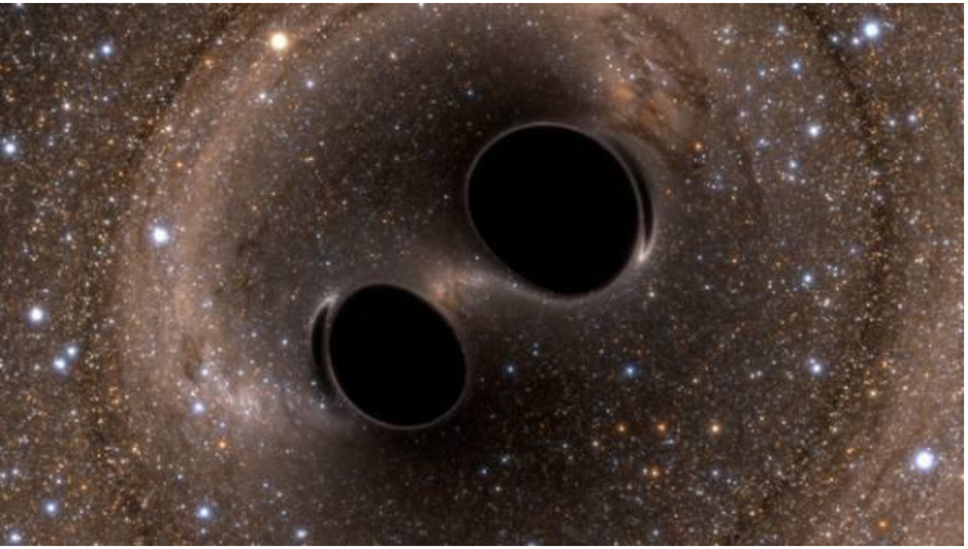




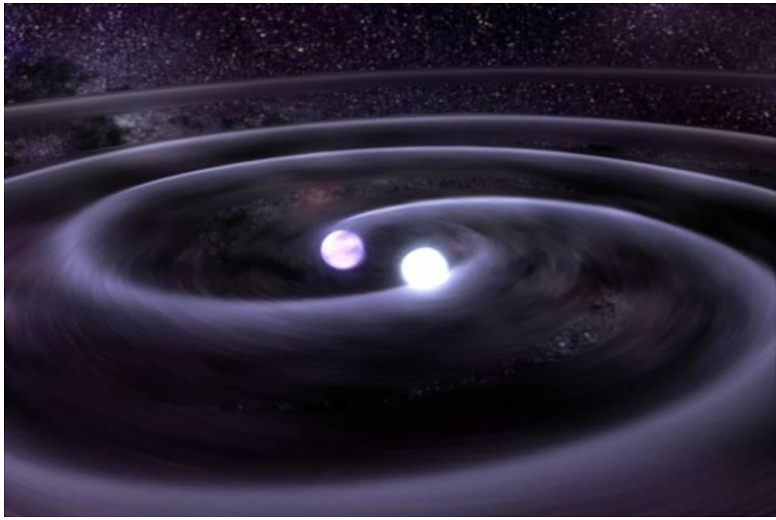
- large mass and large acceleration creates large GW
- amplitude of GW
  fraction of length change

$$h = \frac{\delta L}{L}$$

Sources of GWs

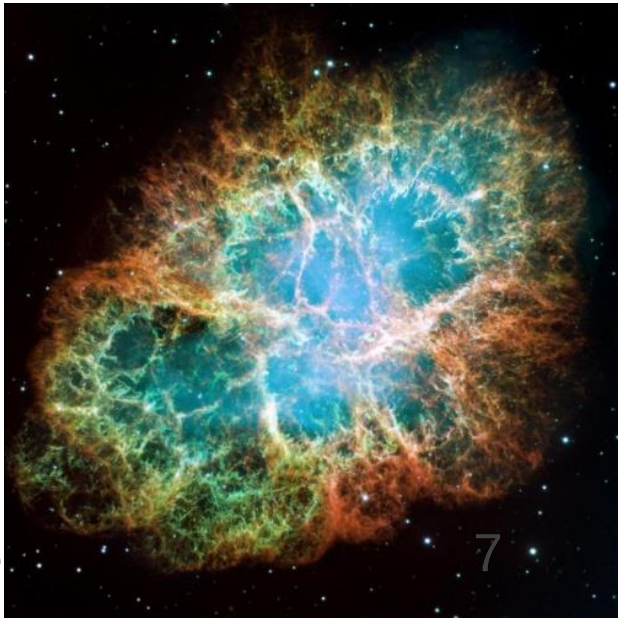


Binary black holes



Binary neutron stars

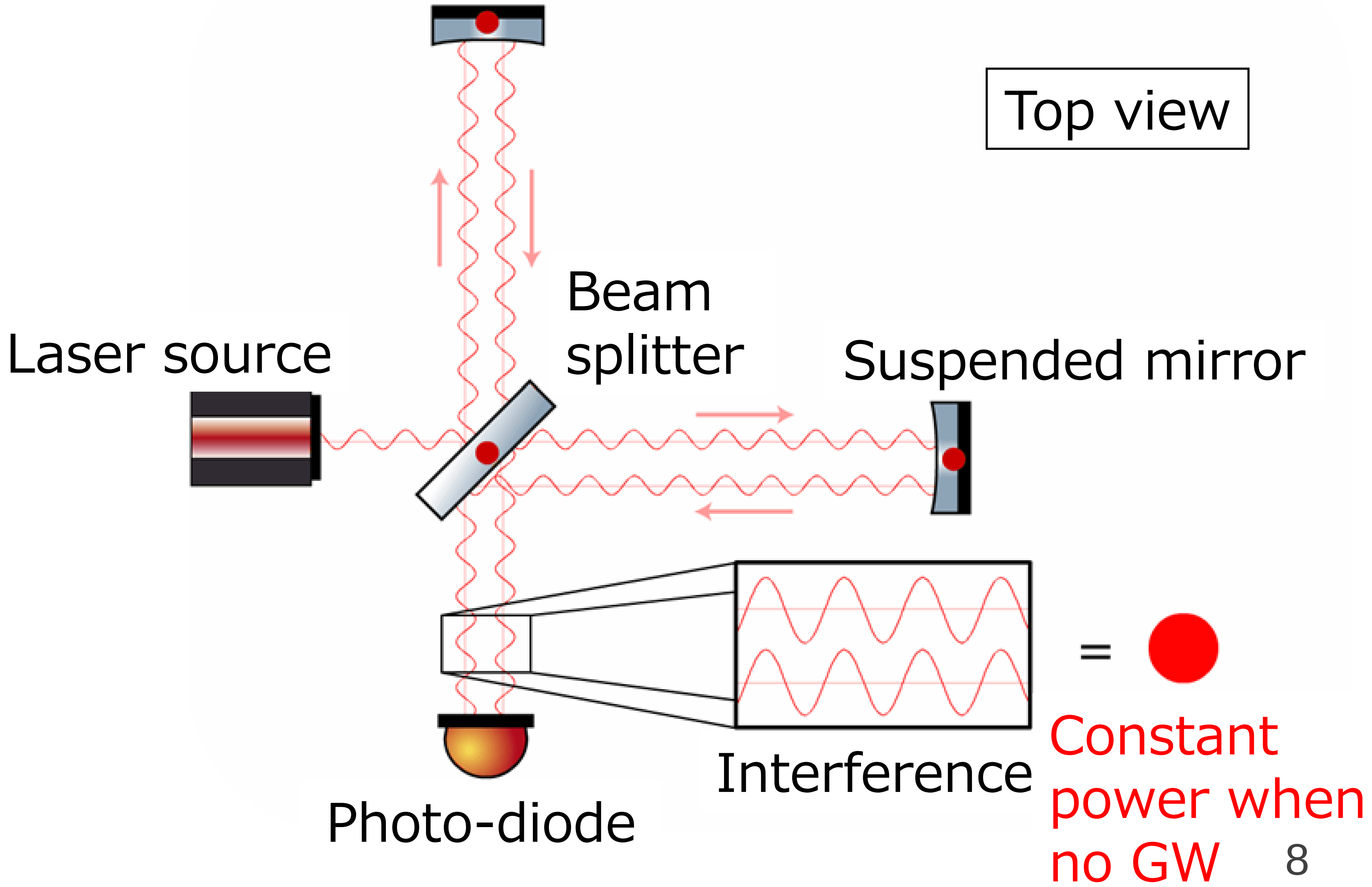
Pulsars



Supernovae

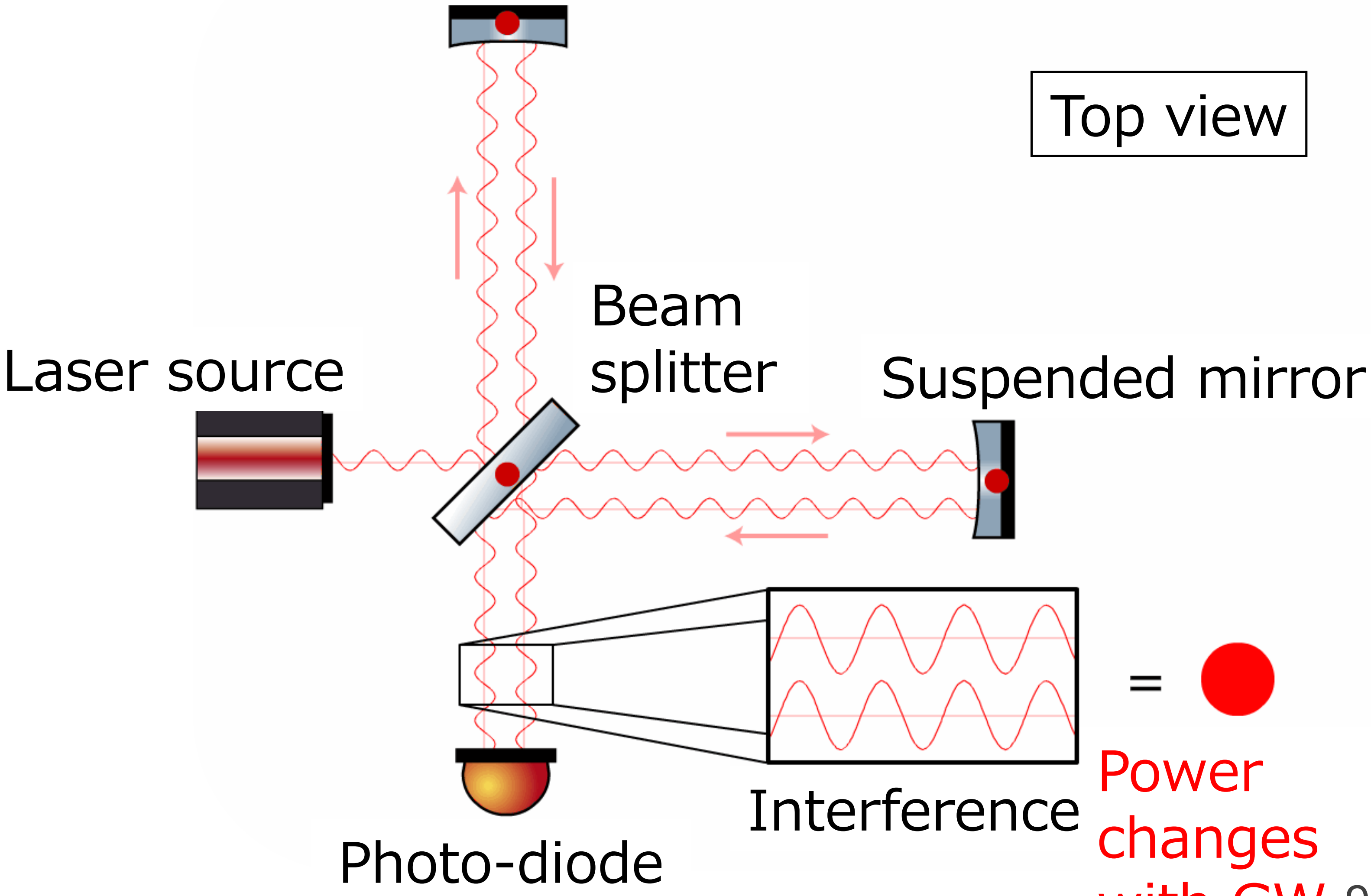
Laser Interferometric GW Detector

- measure differential arm length change



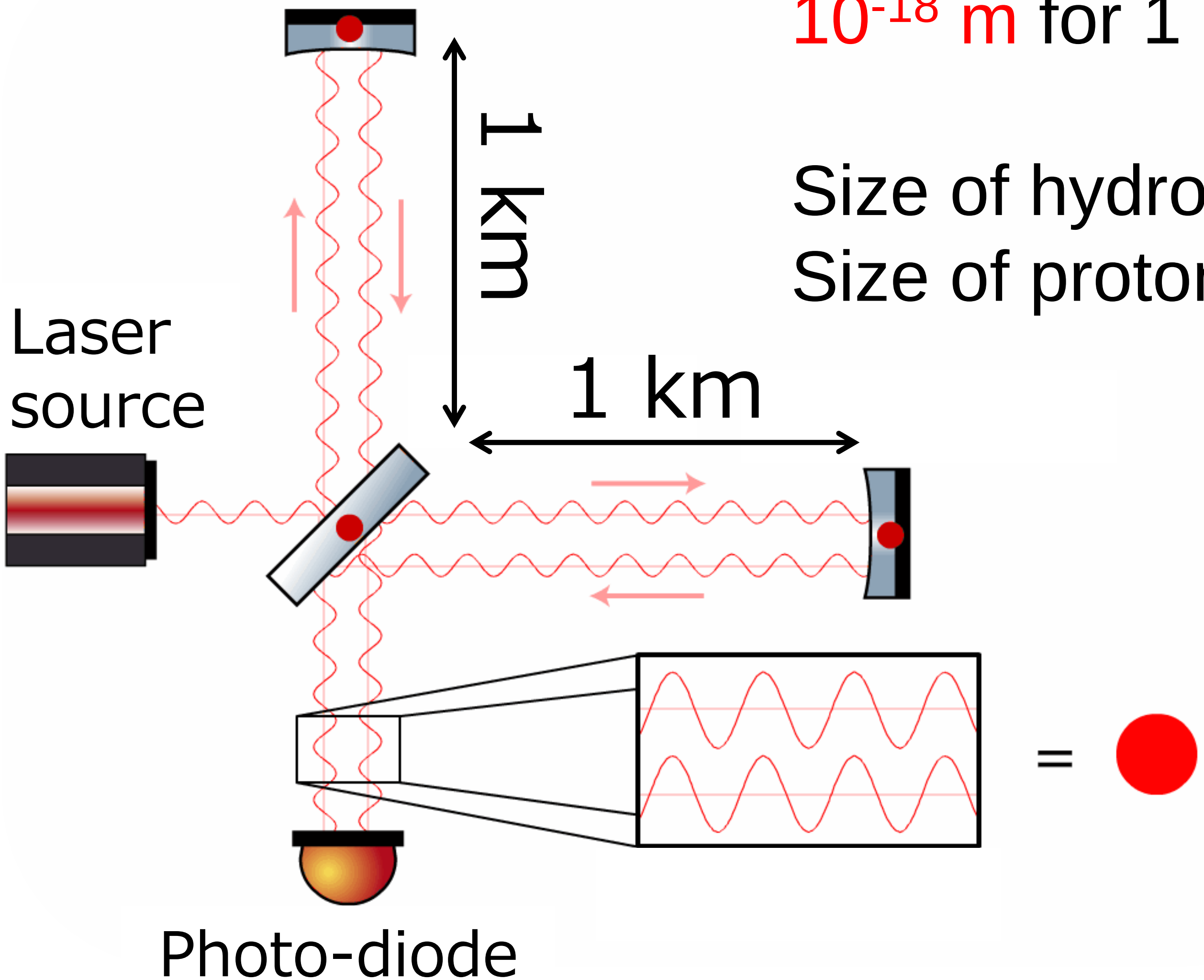
Laser Interferometric GW Detector

- measure differential arm length change



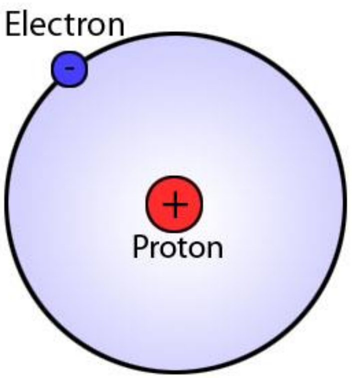
Amplitude of GW is Tiny

- for example, $h \sim 10^{-21}$



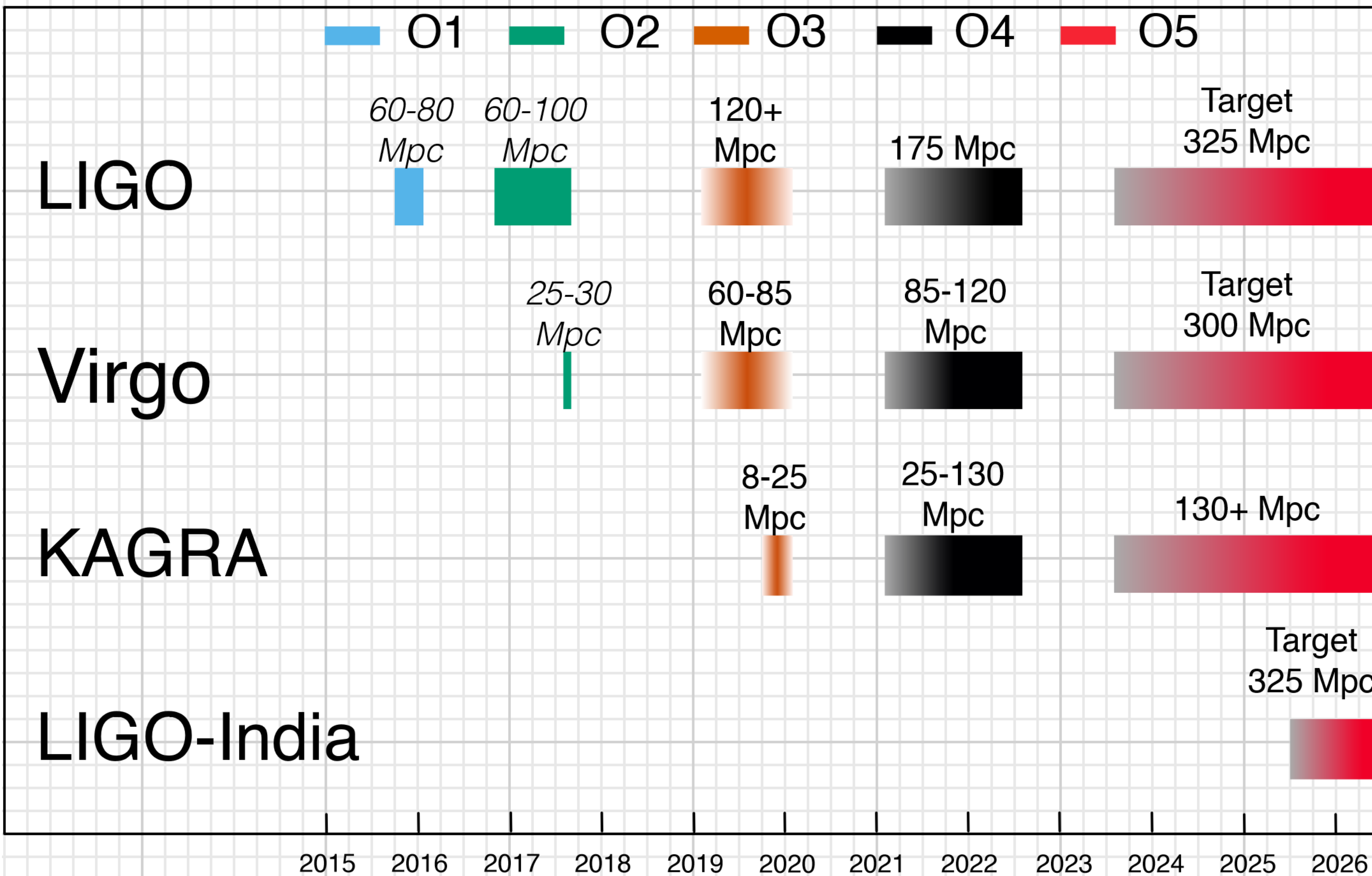
10^{-18} m for 1 km arm

Size of hydrogen atom: 10^{-11} m
Size of proton: 10^{-15} m



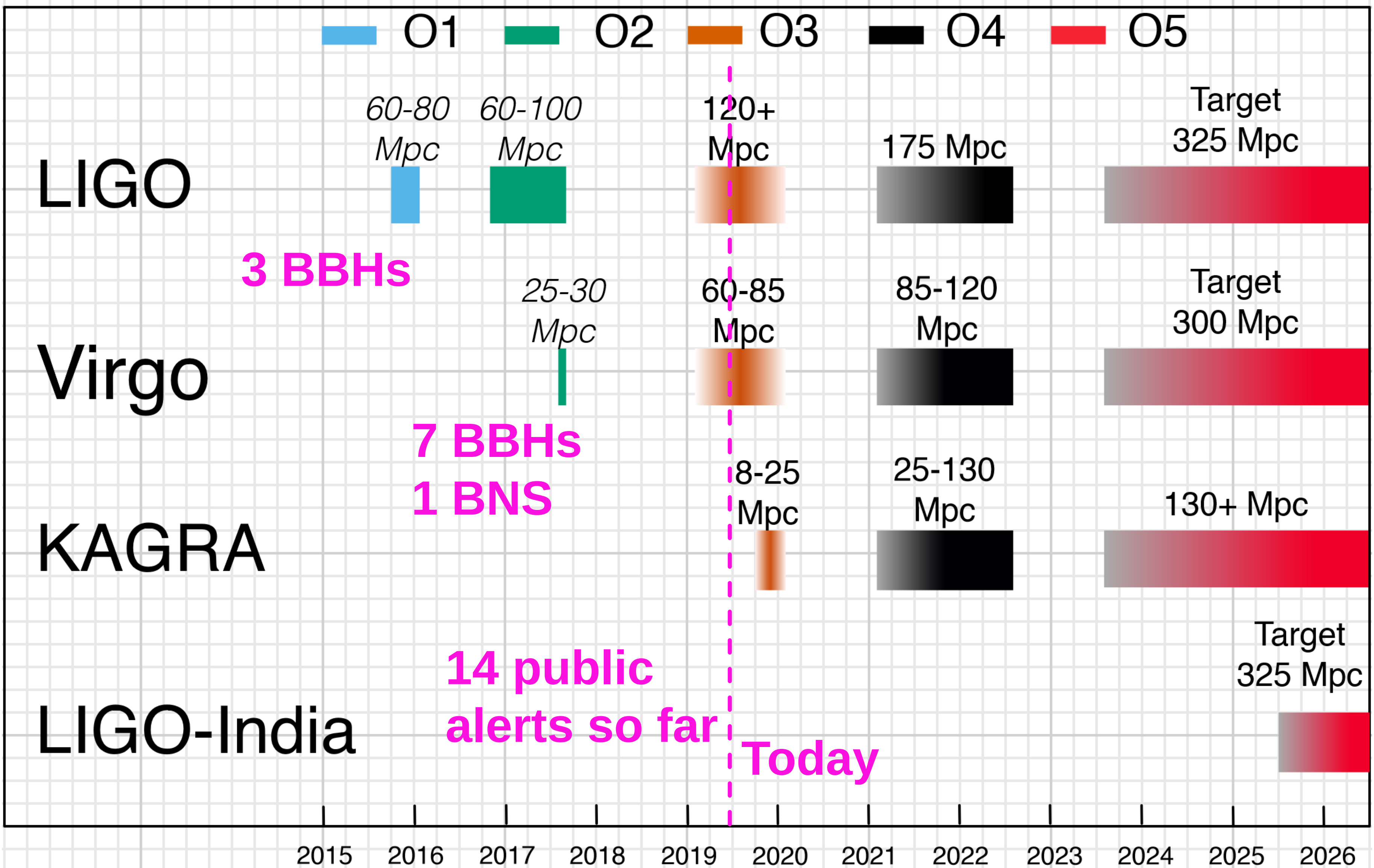
Global Network of GW Telescopes

Observation Scenario



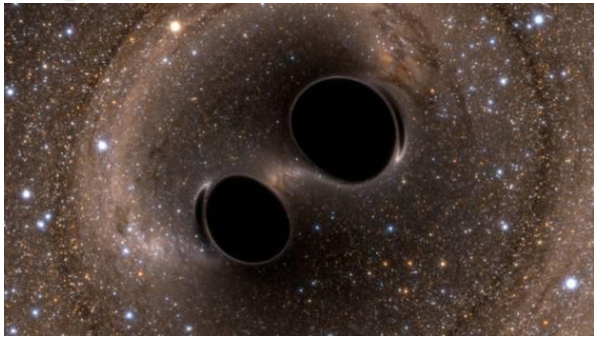
Living Reviews in Relativity 21, 3 (2018); updated version available from https://git.ligo.org/publications/detectors/obs-scenarios-2018/blob/master/Figures/ObsScen_fig2_v12.pdf

Observation Scenario

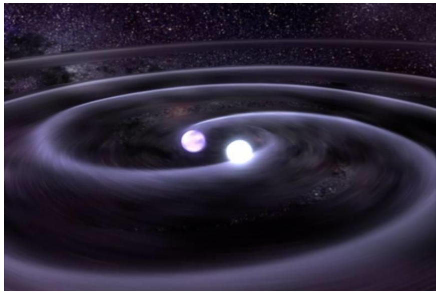


Living Reviews in Relativity 21, 3 (2018); updated version available from https://git.ligo.org/publications/detectors/obs-scenarios-2018/blob/master/Figures/ObsScen_fig2_v12.pdf

Solved and Unsolved Mysteries



- Binary black holes
  - Origin of massive black holes?
  - Intermediate mass black holes?
  - Quasi-normal modes not yet



- Binary neutron stars
  - coincidence with short gamma-ray bursts (but too faint; why?)
  - speed of gravitational waves measured
  - do all heavy elements come from BNS mergers?
  - Remnant?
  - Equation of state?
  - Hubble constant tension

- Other sources not detected yet
  - NS-BH, Supernovae, Pulsars, Primordial gravitational waves……

What's Next?

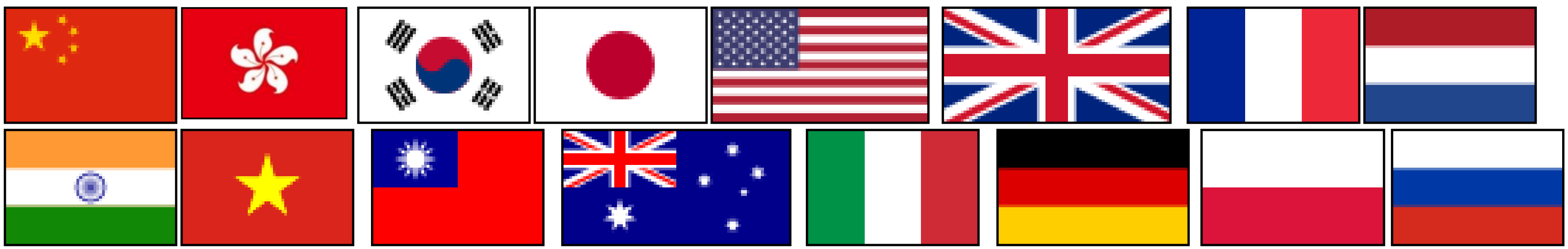
- More sensitive, multiple detectors
  - Better source localization with multiple detectors
    Better multi-messenger observations
  - Polarization resolvable with multiple detectors
    Better inclination angle estimation
      Better Hubble constant measurement
    Non-GR polarization search
  - Twofold sensitivity improvement gives
    x8 event rate
    x1/2 parameter estimation error

- Next to join observation: KAGRA

KAGRA Project

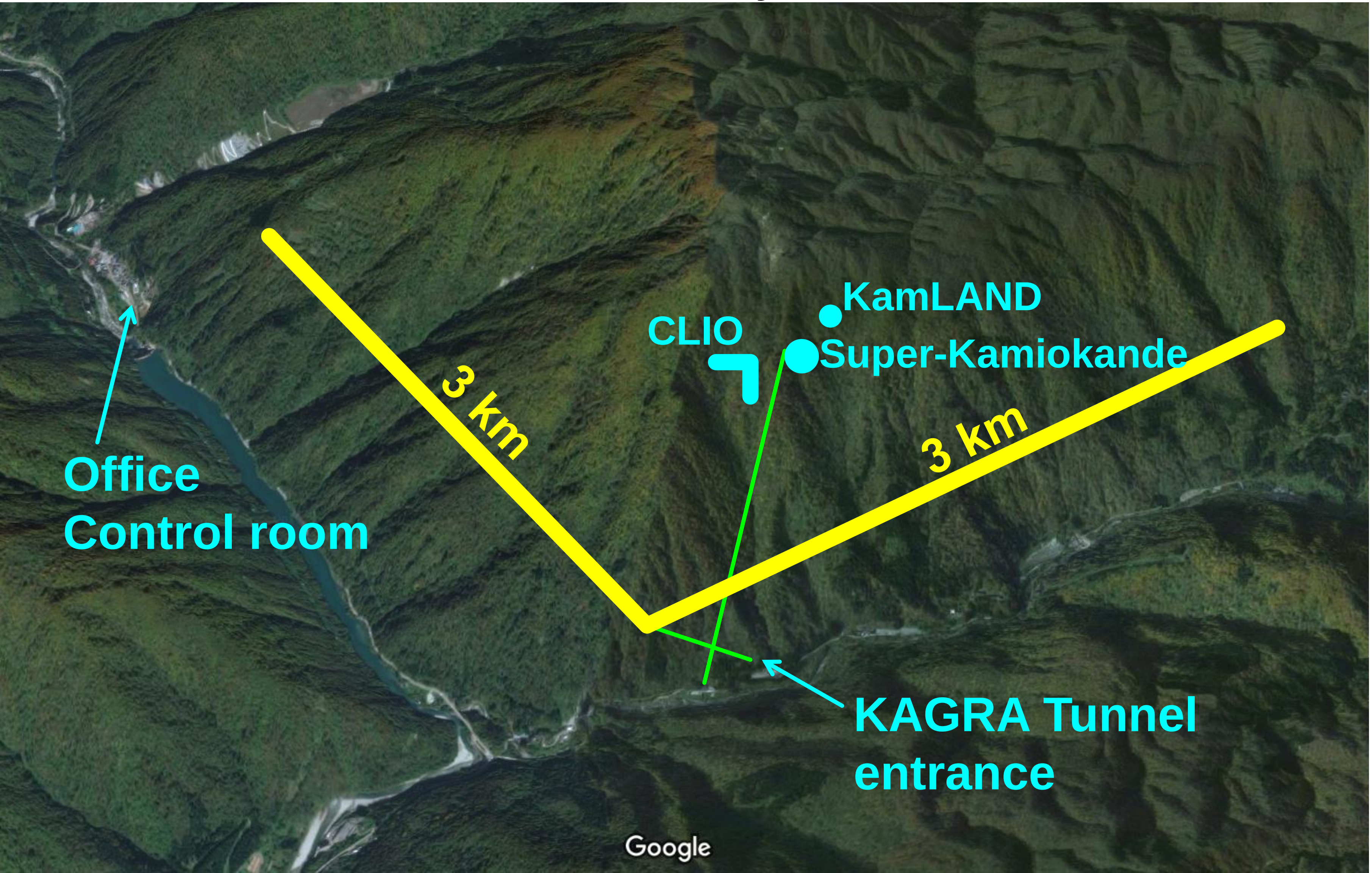
- Underground cryogenic interferometer in Japan
- Funded in 2010
- 97 institutes, 460 collaborators (162 authors)

as of Sept 2018



KAGRA Site

- Located inside Mt. Ikenoyama



KAGRA Site

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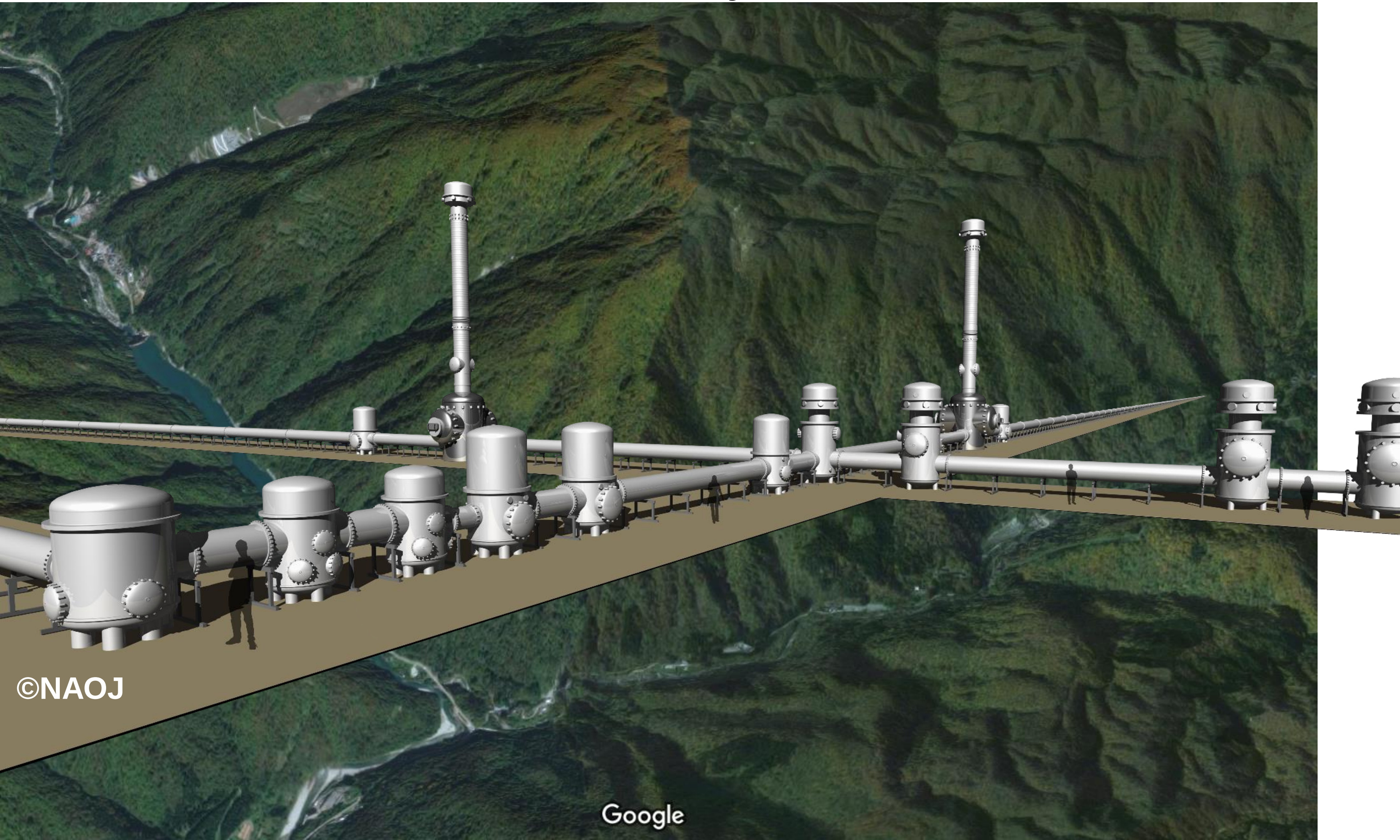
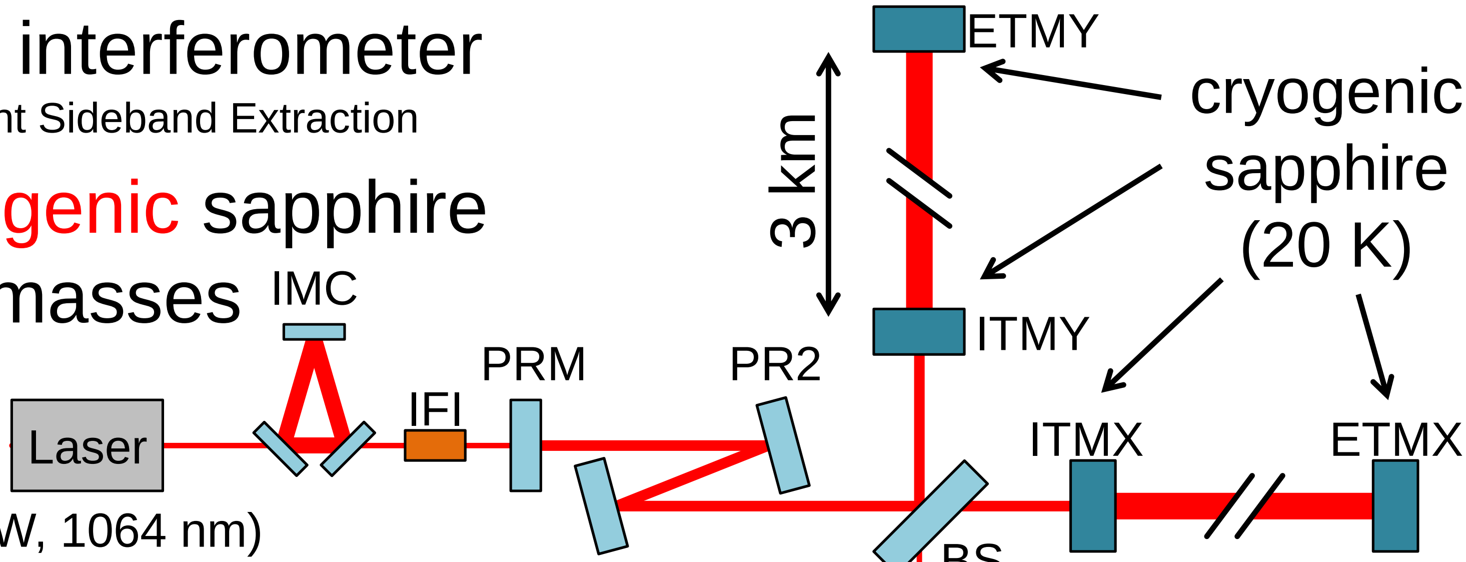
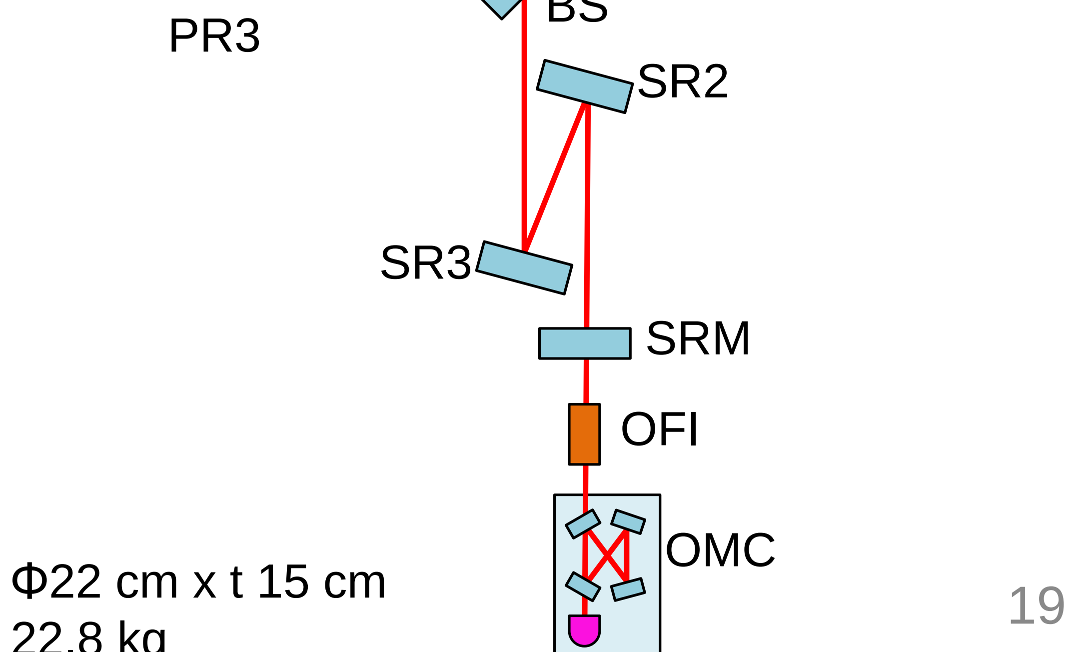
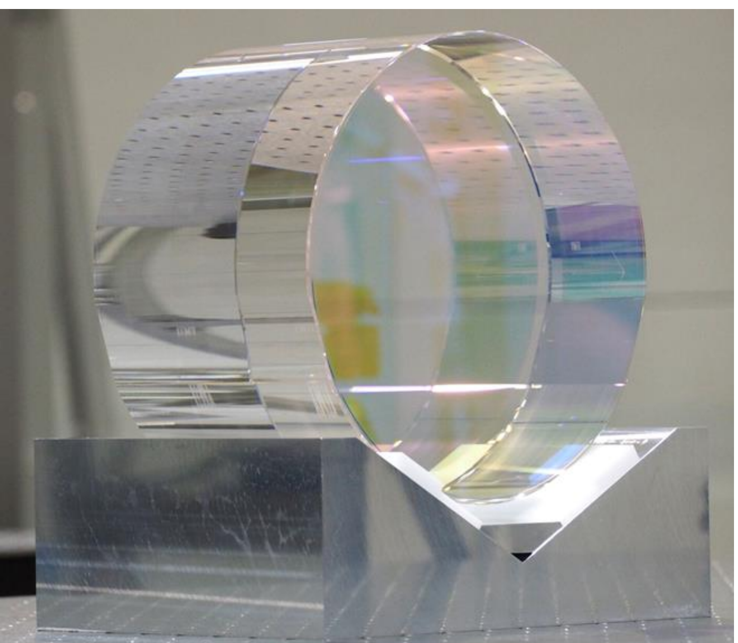


Interferometer Configuration

- RSE interferometer
  Resonant Sideband Extraction
- Cryogenic sapphire test masses



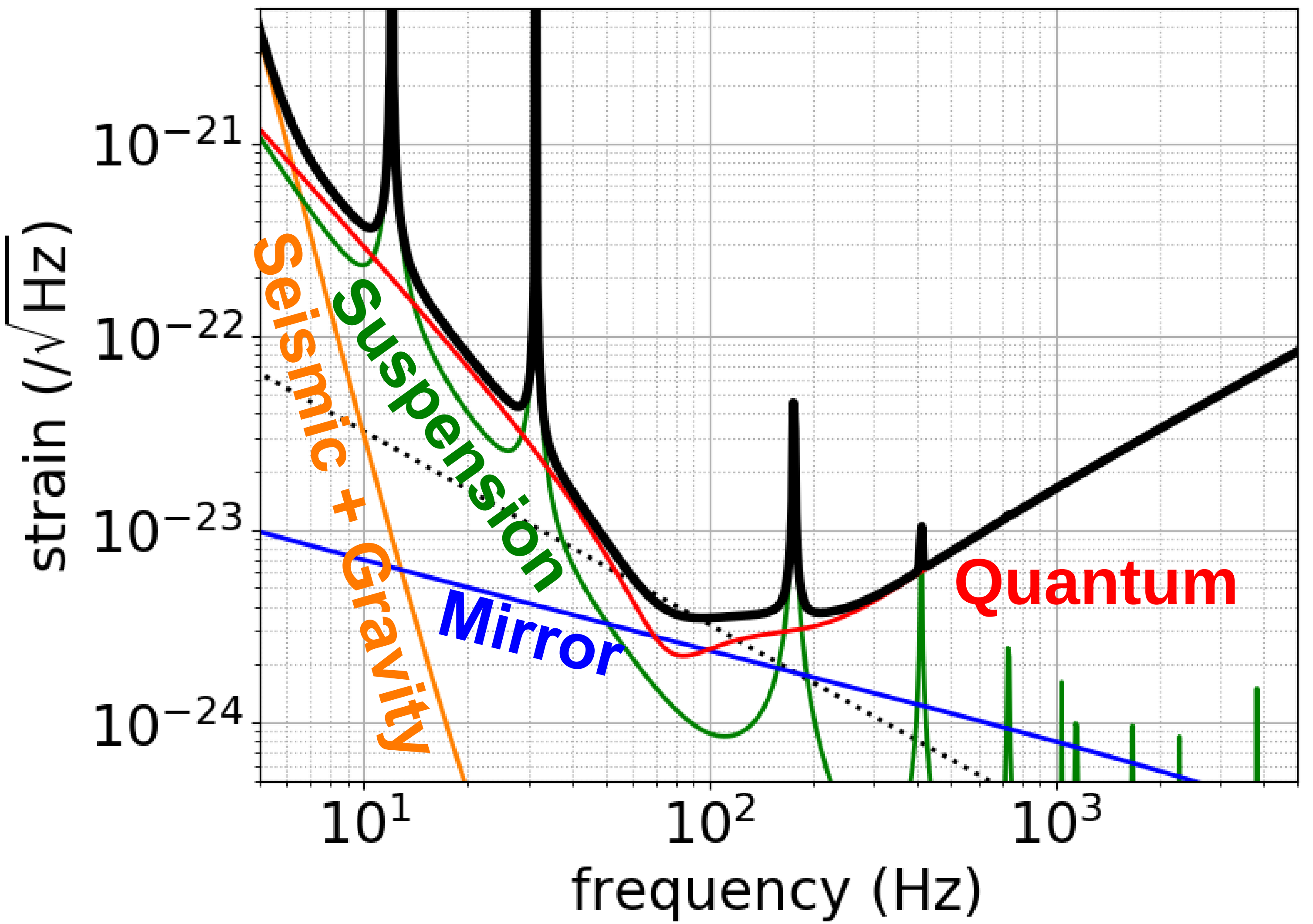




Φ22 cm x t 15 cm
22.8 kg

Design Sensitivity

- Binary neutron star (BNS) range 153 Mpc



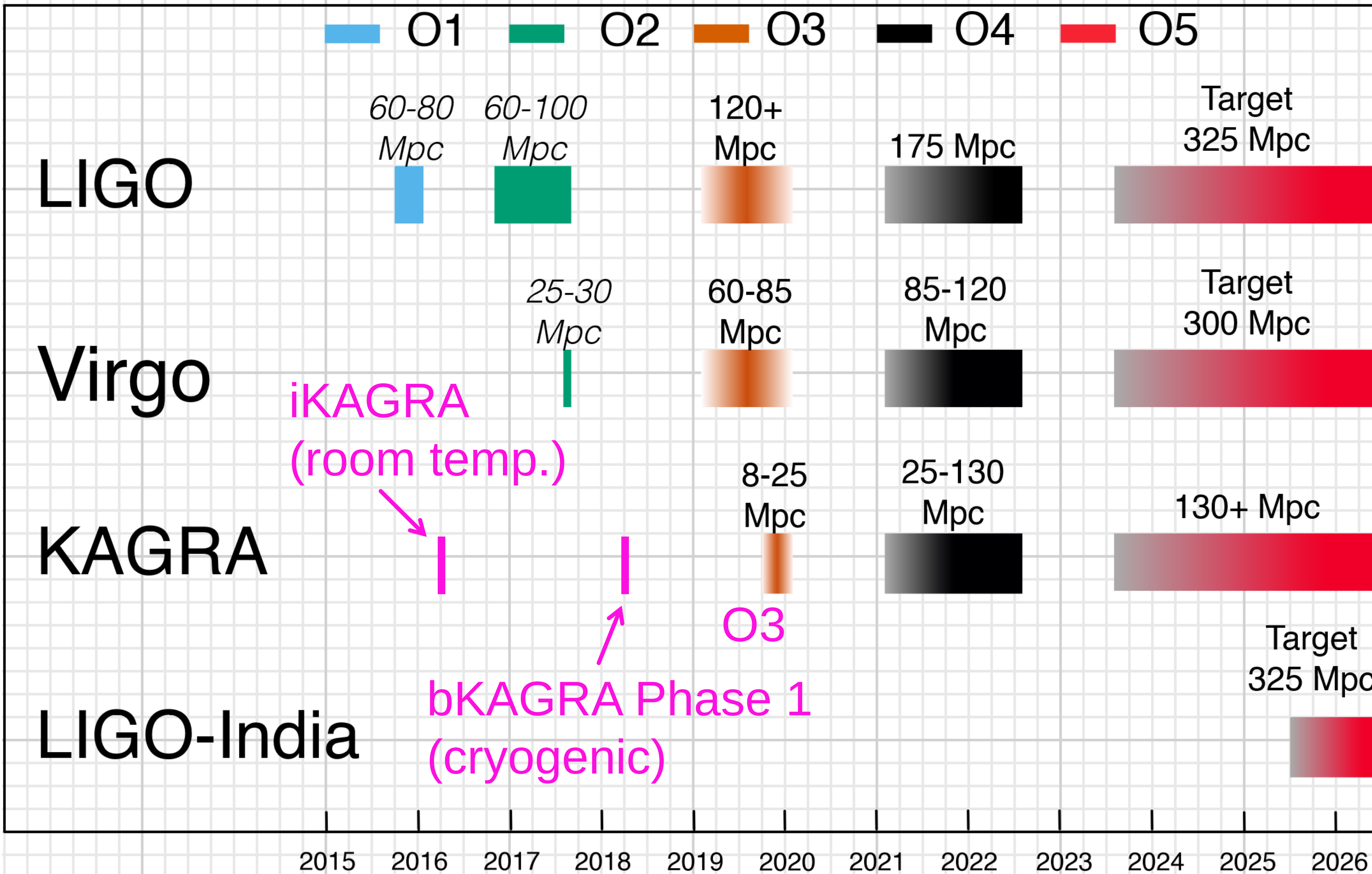
KAGRA Timeline

- 2014 — Tunnel excavation done
- 2015 — Inauguration of initial-phase facility
- 2016 — First test run at room temp. (iKAGRA)

  KAGRA Collaboration, PTEP 2018, 013F01 (2018)
- 2017
- 2018 — First cryogenic test run (Phase 1)

  KAGRA Collaboration, arXiv:1901.03569
- 2019 — Expect to join observing run O3
- 2020

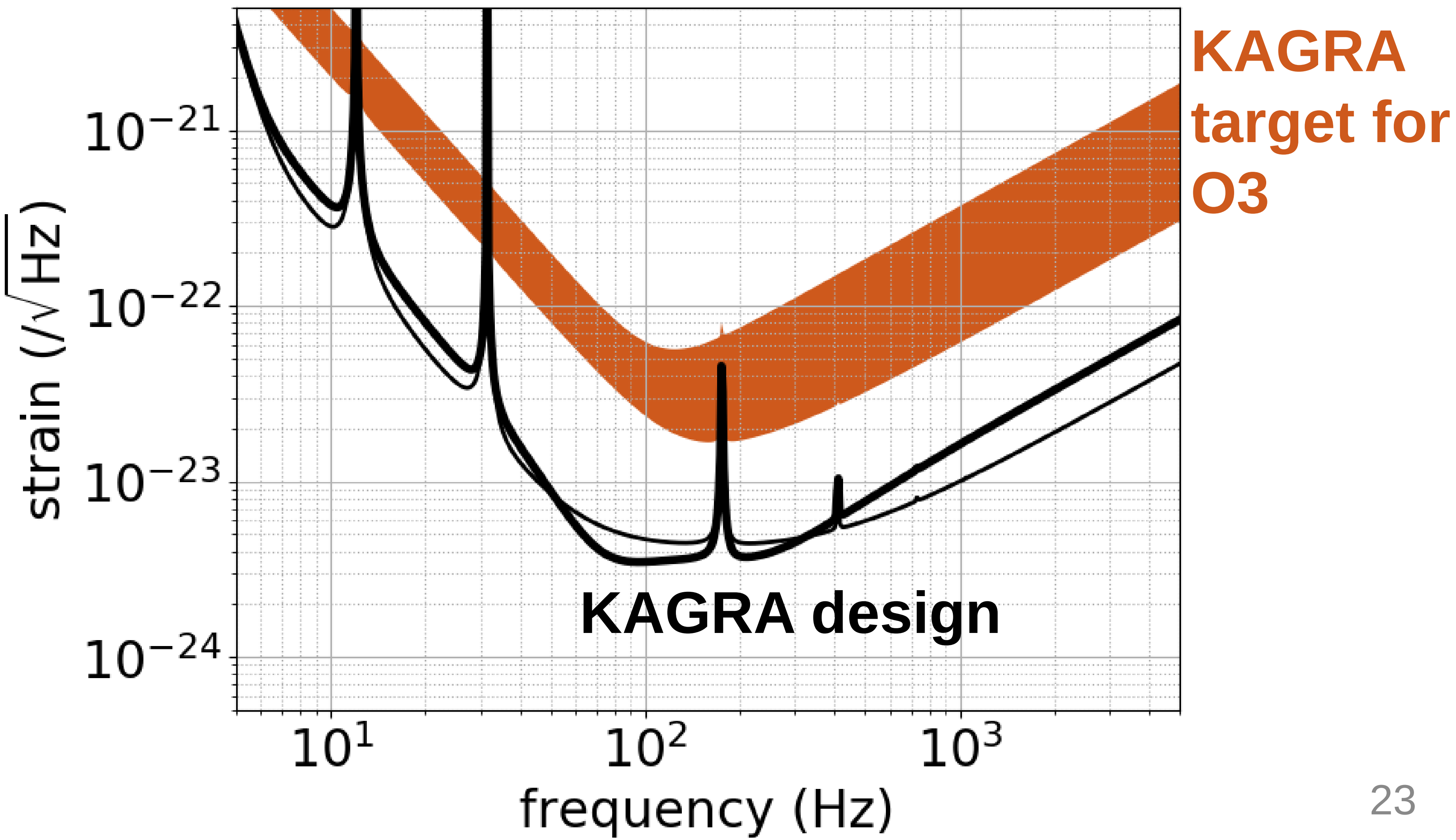
Observation Scenario



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]()

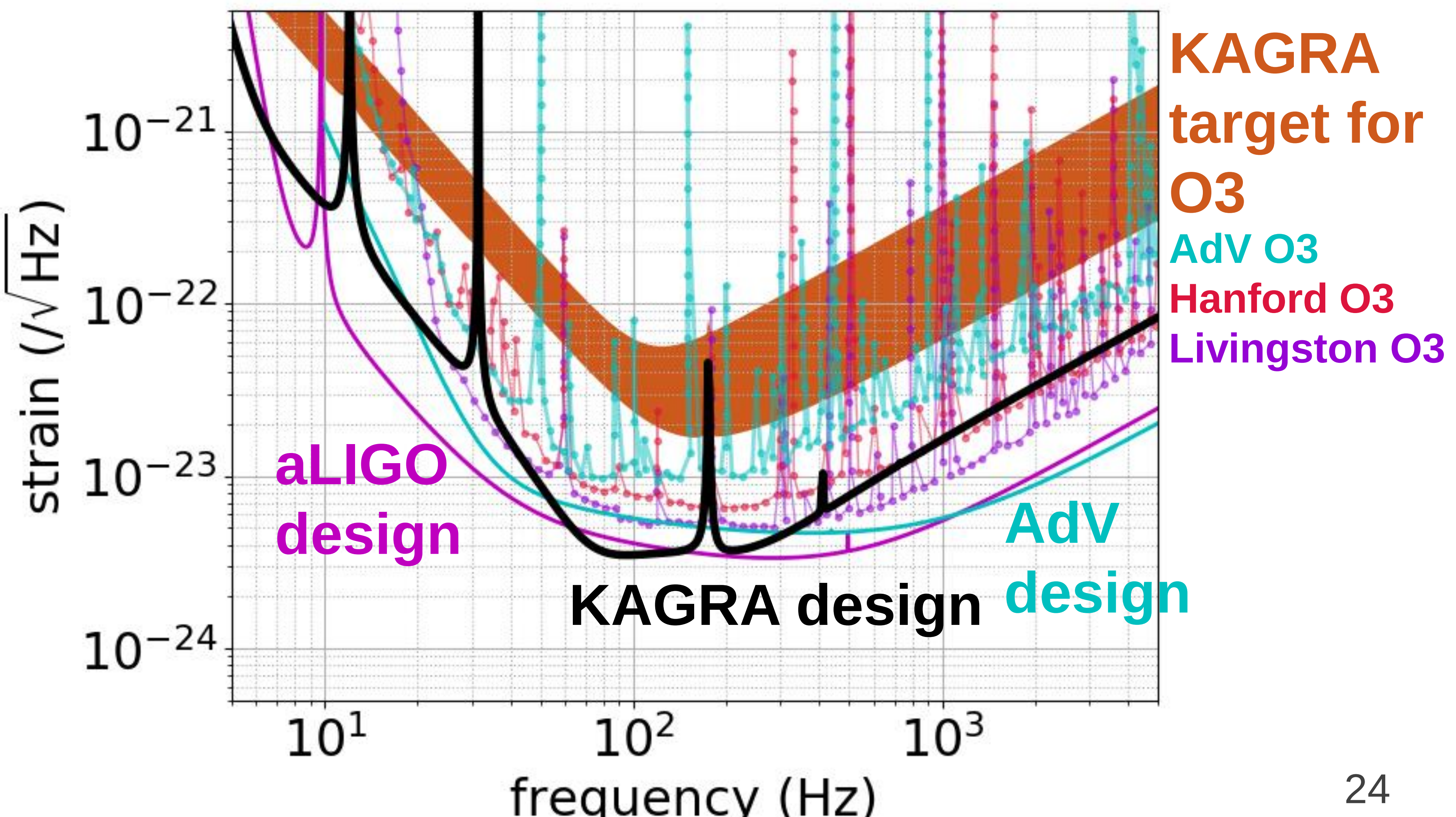
Target Sensitivity for O3

- Aims for 8-25 Mpc in binary neutron star range



Comparison with LIGO/Virgo

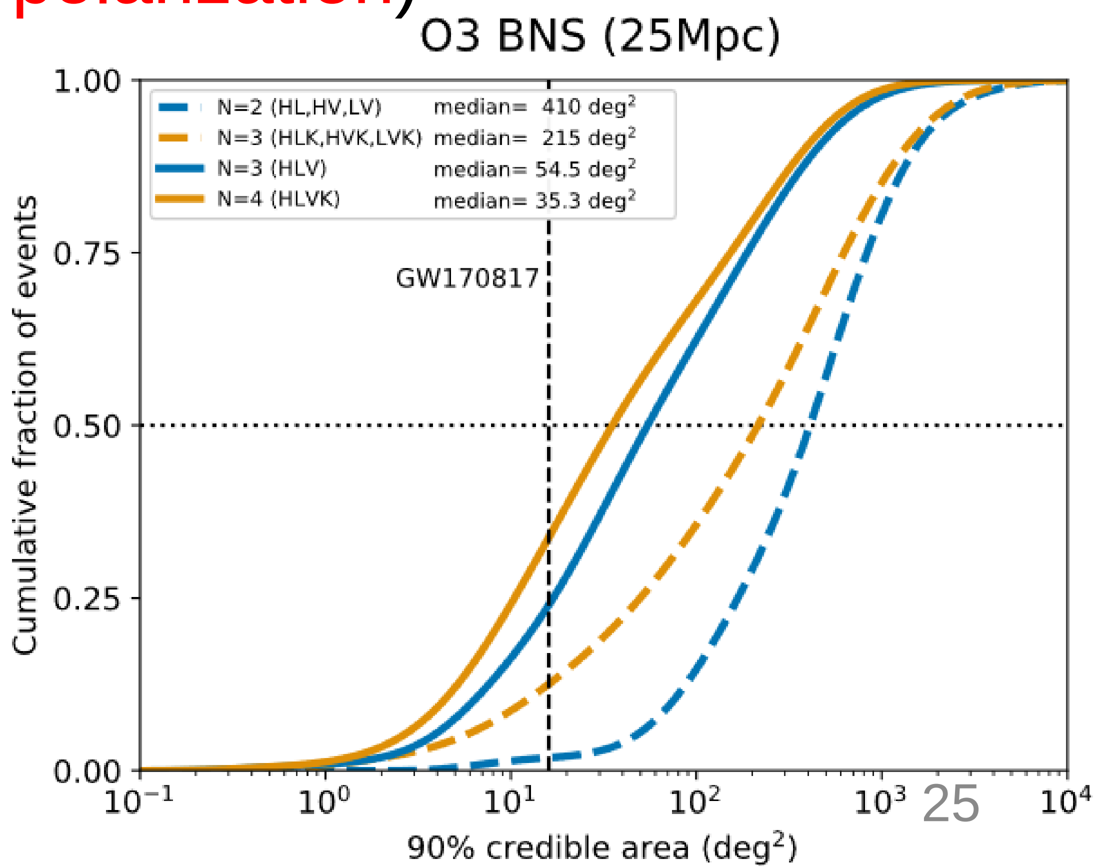
- Aims for 8-25 Mpc in binary neutron star range



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)

BNS sky localization improves by ~15-30 % if KAGRA is 25 Mpc

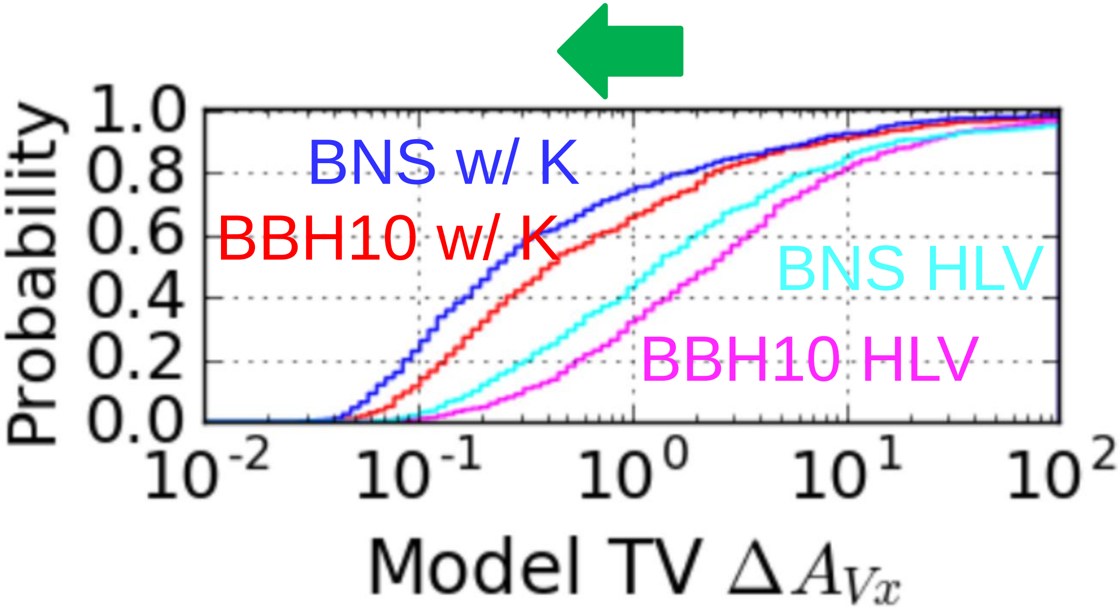


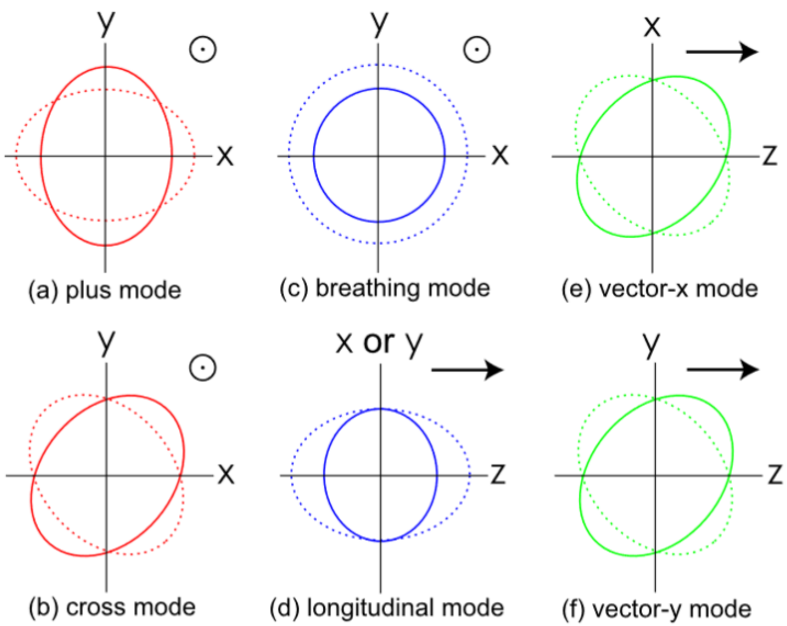
JGW-T1910330
Calculation
by S. Haino
(L: 120 Mpc, V: 60 Mpc, K: 15 Mpc)

Test of GR with CBC Polarization

- Fourth detector necessary to distinguish four polarizations
  H. Takeda+, PRD 98, 022008 (2018)
- Number of detectors matters!

error reduces to < 1 with KAGRA

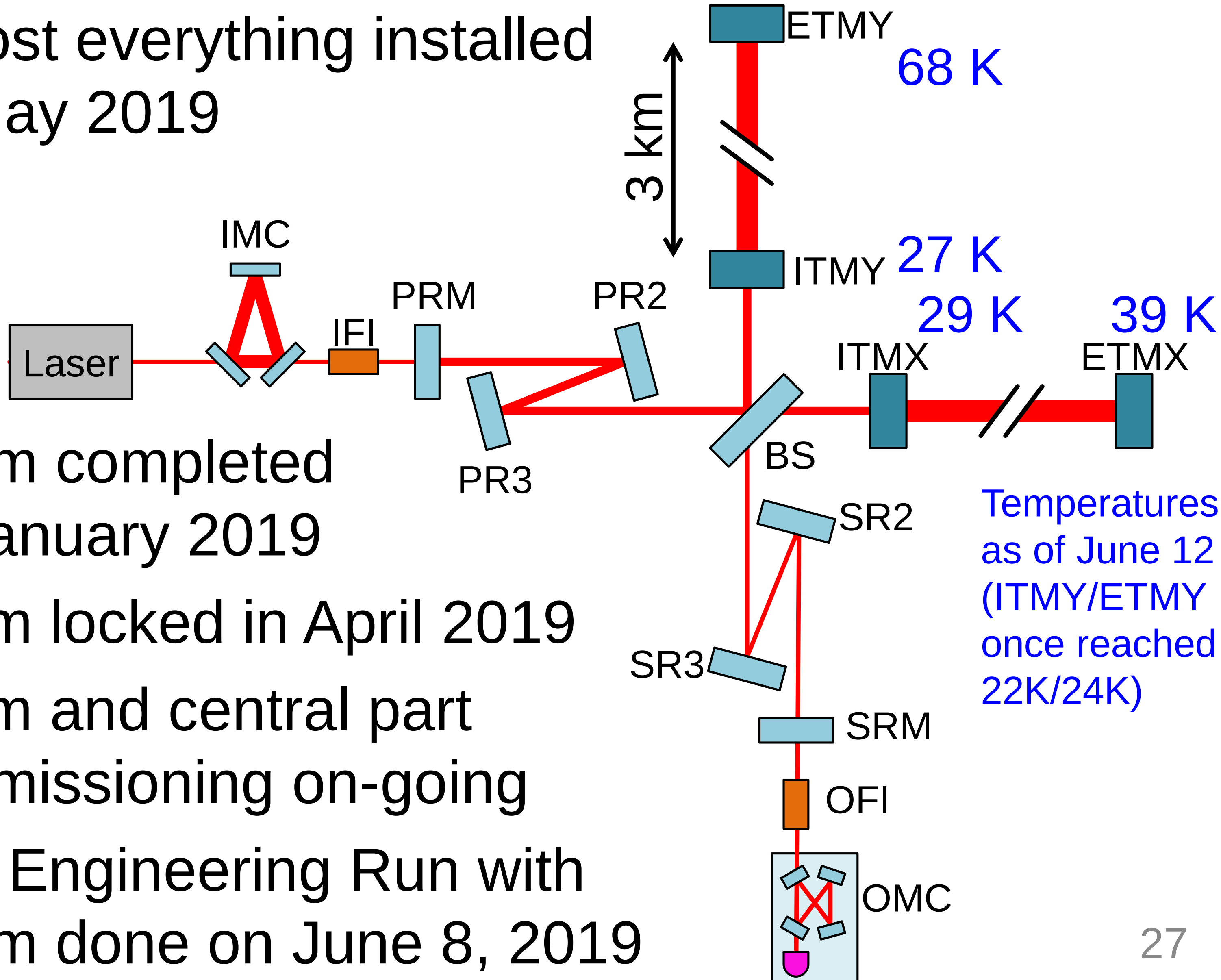




Error in vector-x mode amplitude

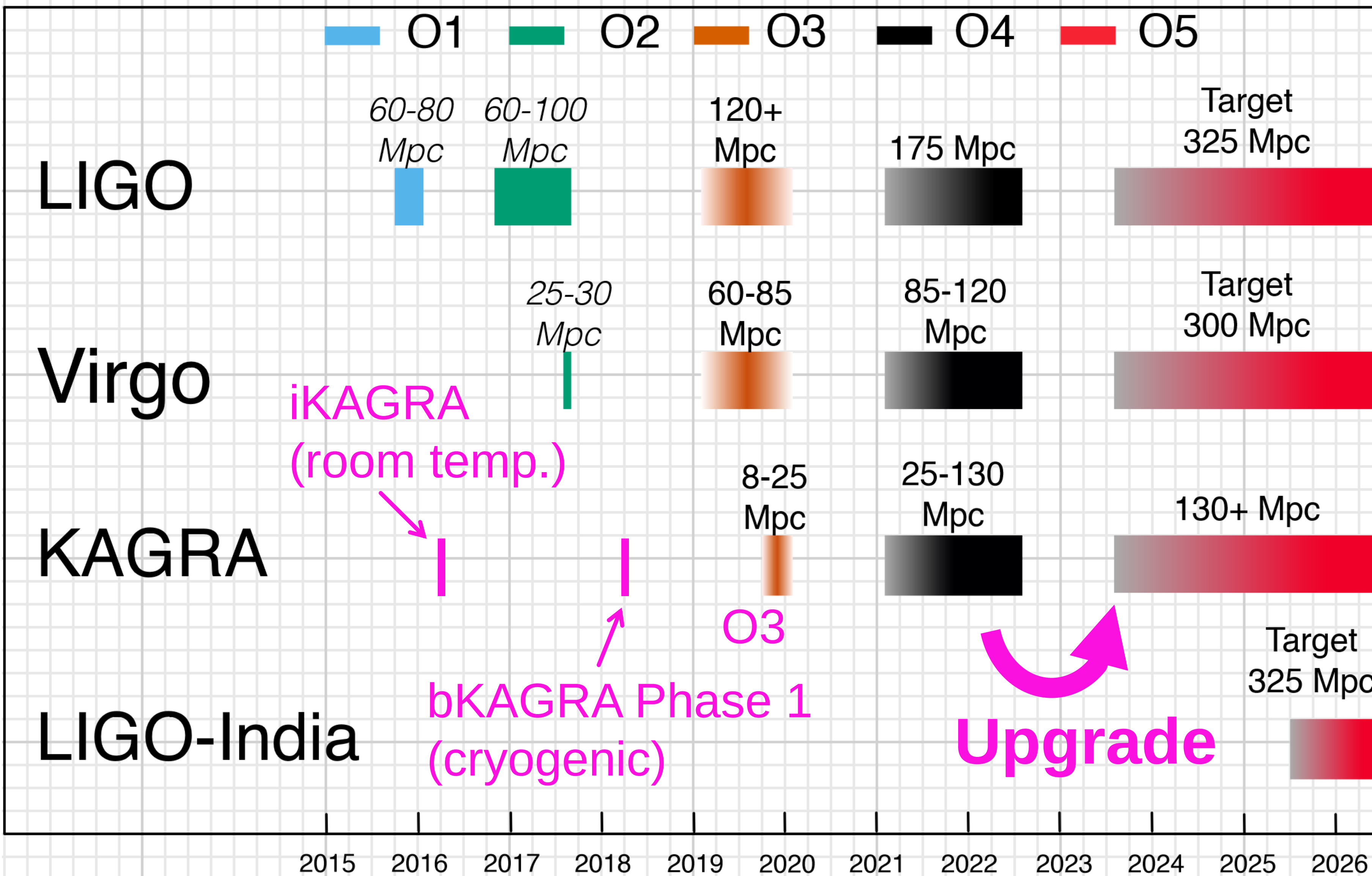
Recent News from KAGRA

- Almost everything installed by May 2019



- X-arm completed by January 2019
- Y-arm locked in April 2019
- Y-arm and central part commissioning on-going
- First Engineering Run with X-arm done on June 8, 2019

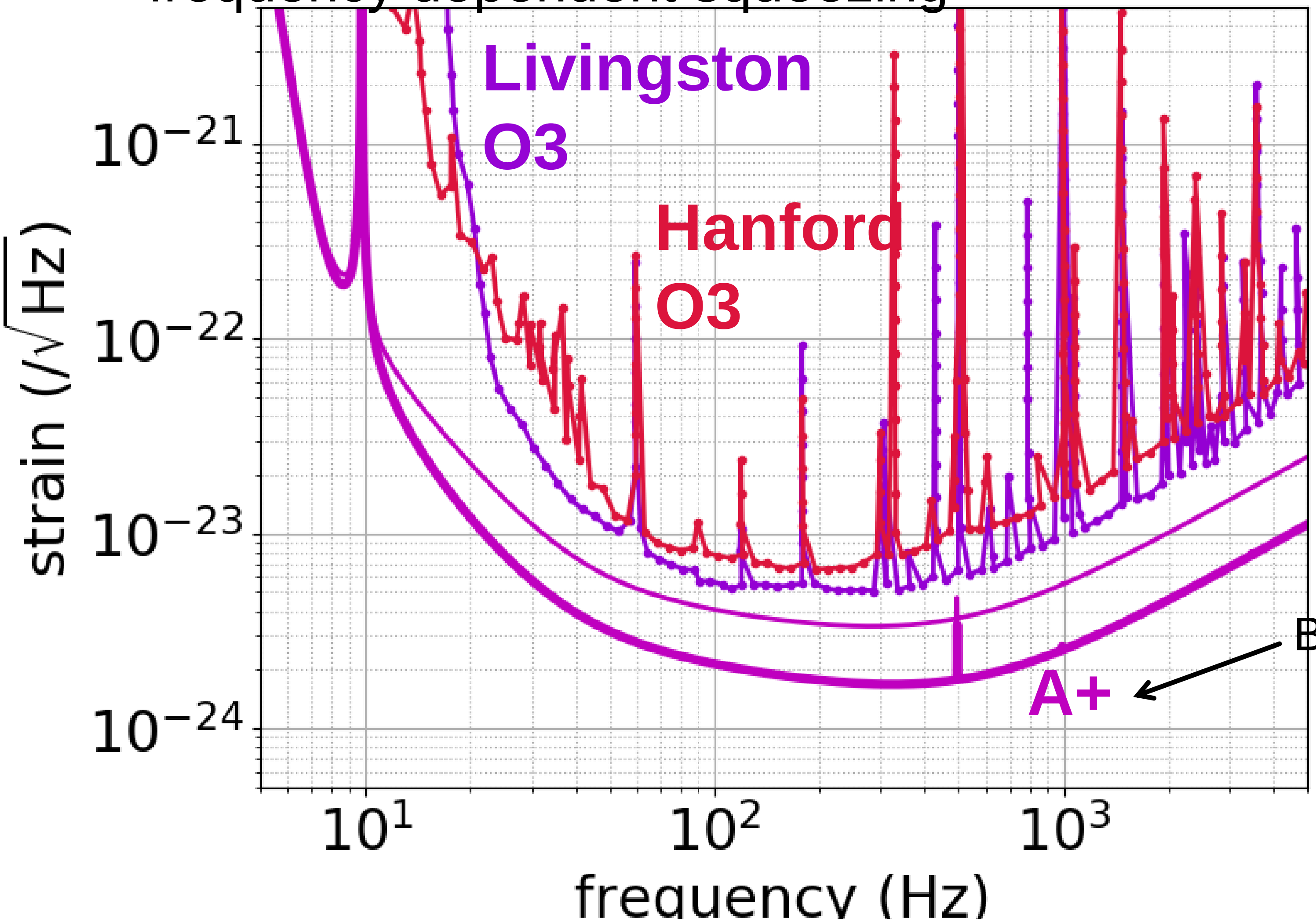
Observation Scenario



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

Advanced LIGO Upgrade: A+

- Reaches 325 Mpc with coating improvement and frequency dependent squeezing

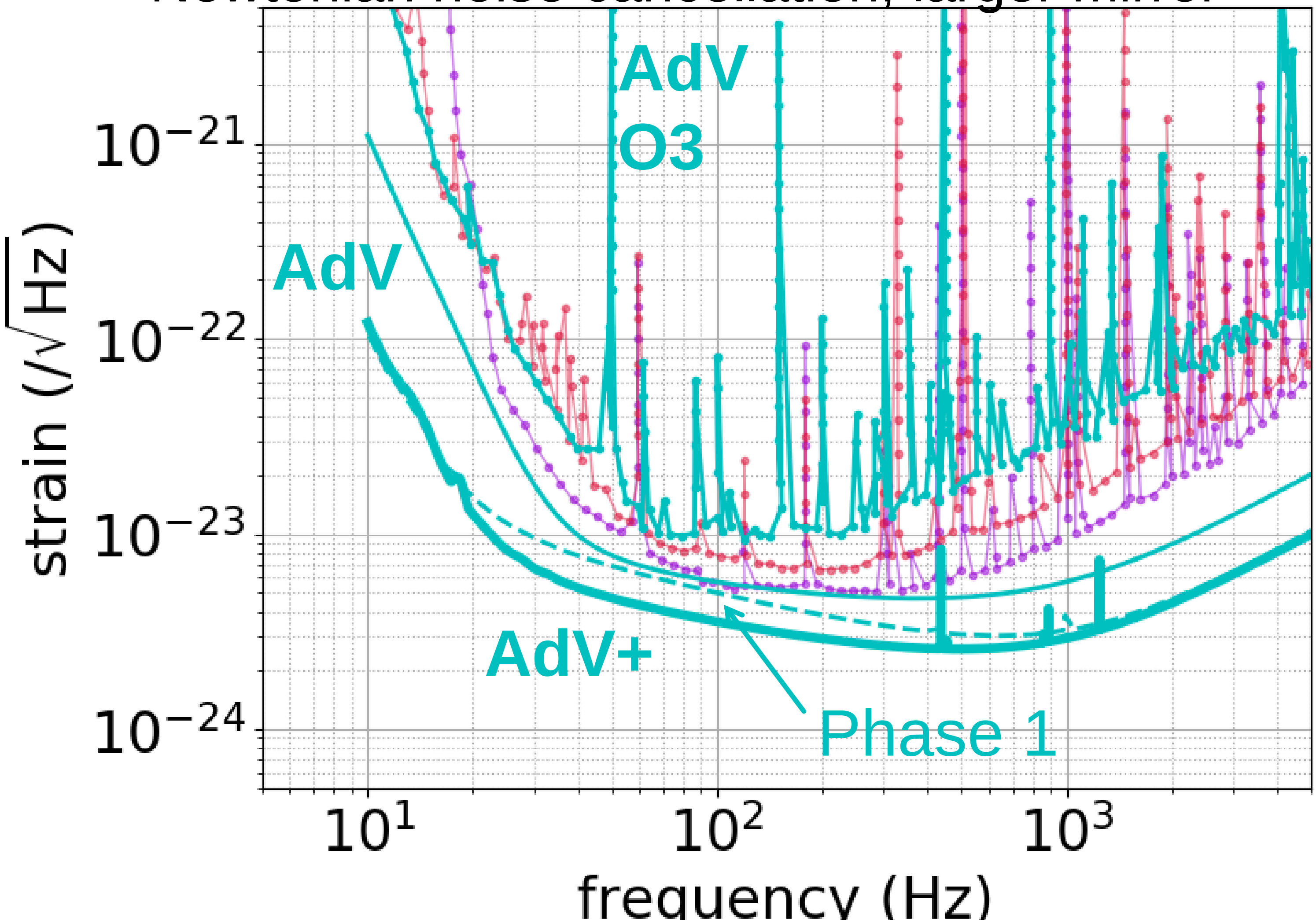


4 km arm
40 kg mirror
Fused silica

Budget approved
NSF $20.4M
UKRI £10.7M
+ Australia

Advanced Virgo Upgrade: AdV+

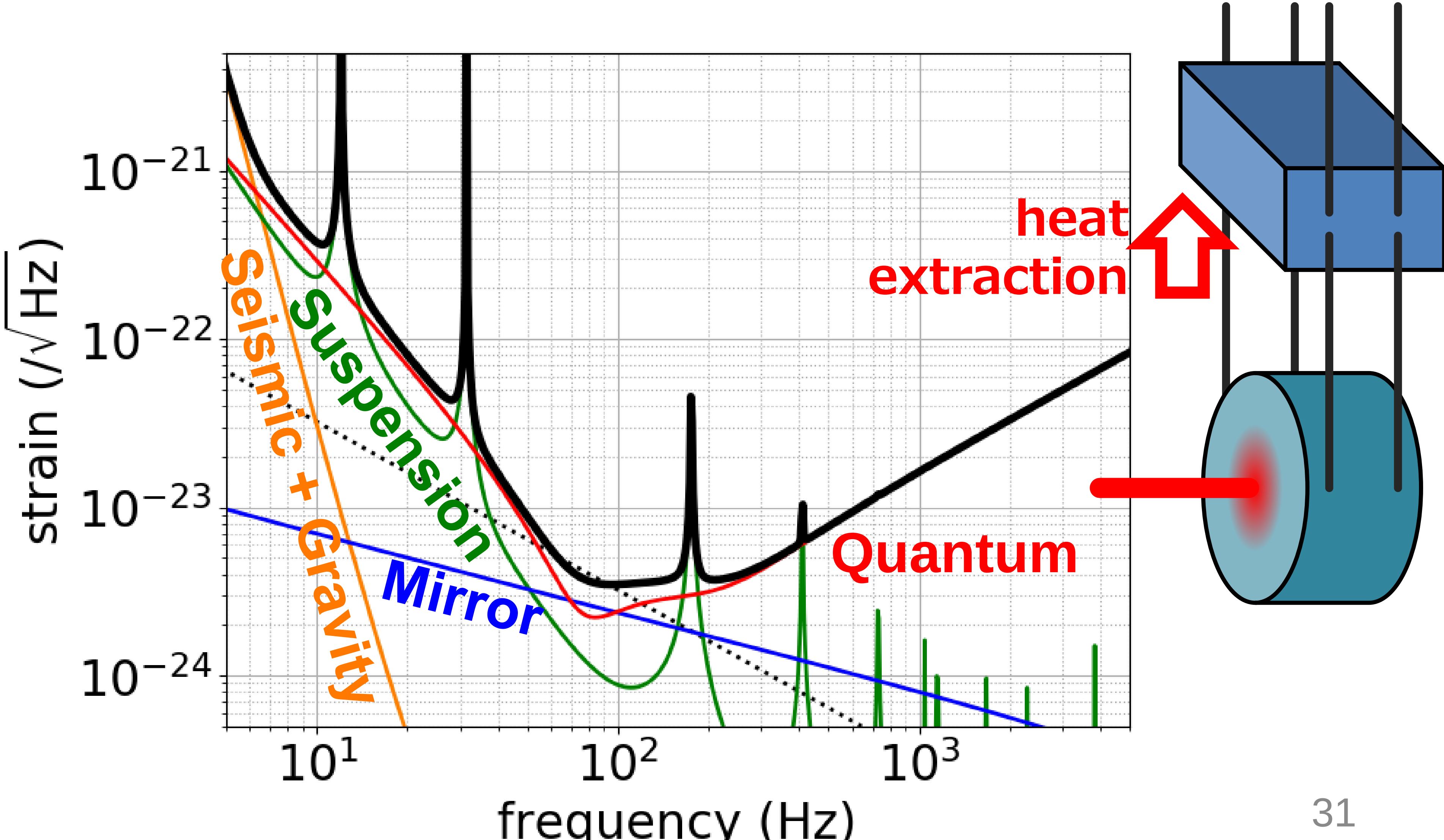
- Reaches 300 Mpc with frequency dependent squeezing, Newtonian noise cancellation, larger mirror



3 km arm
42 kg mirror
Fused silica

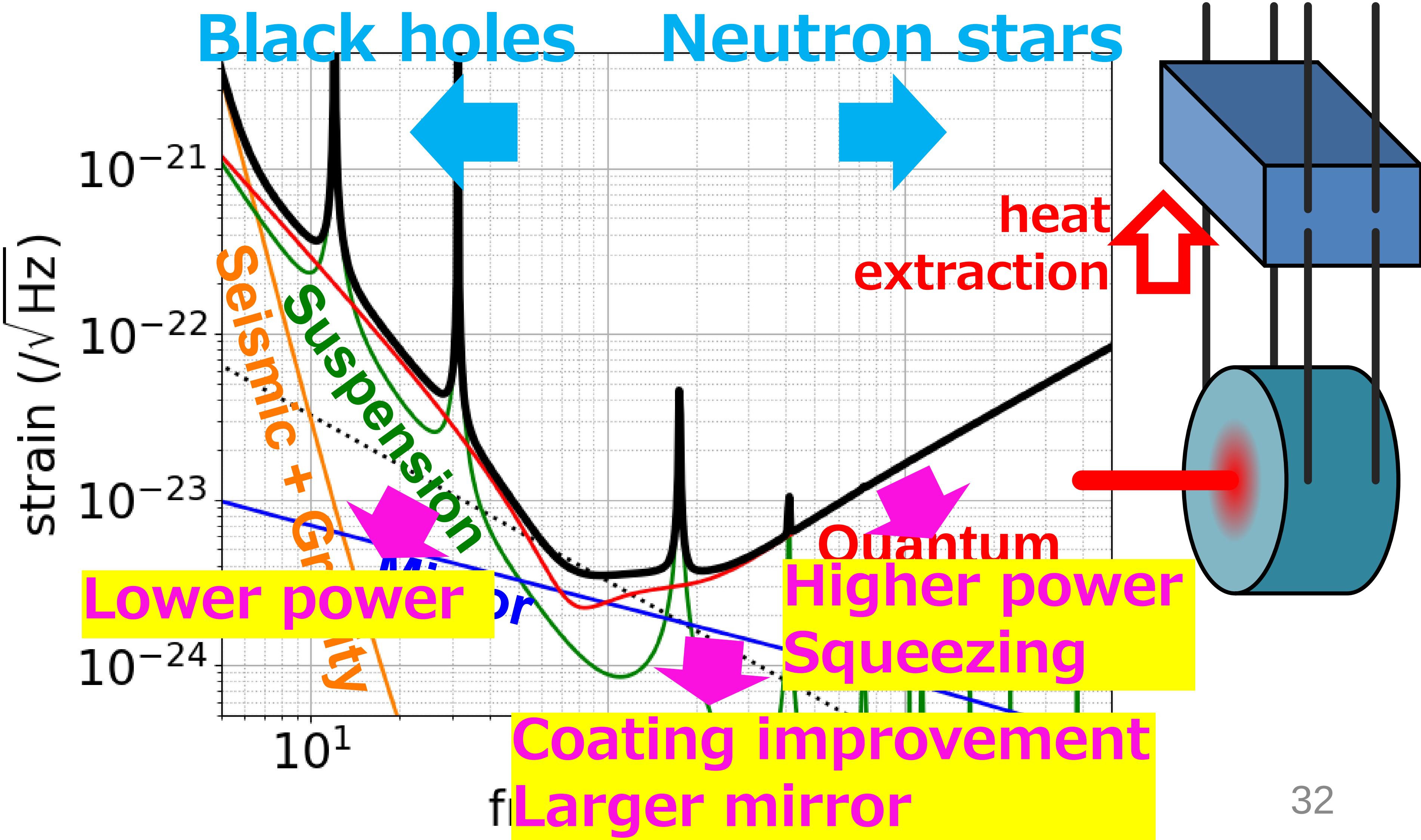
How about KAGRA?

- Upgrade study *formally* started in December 2018



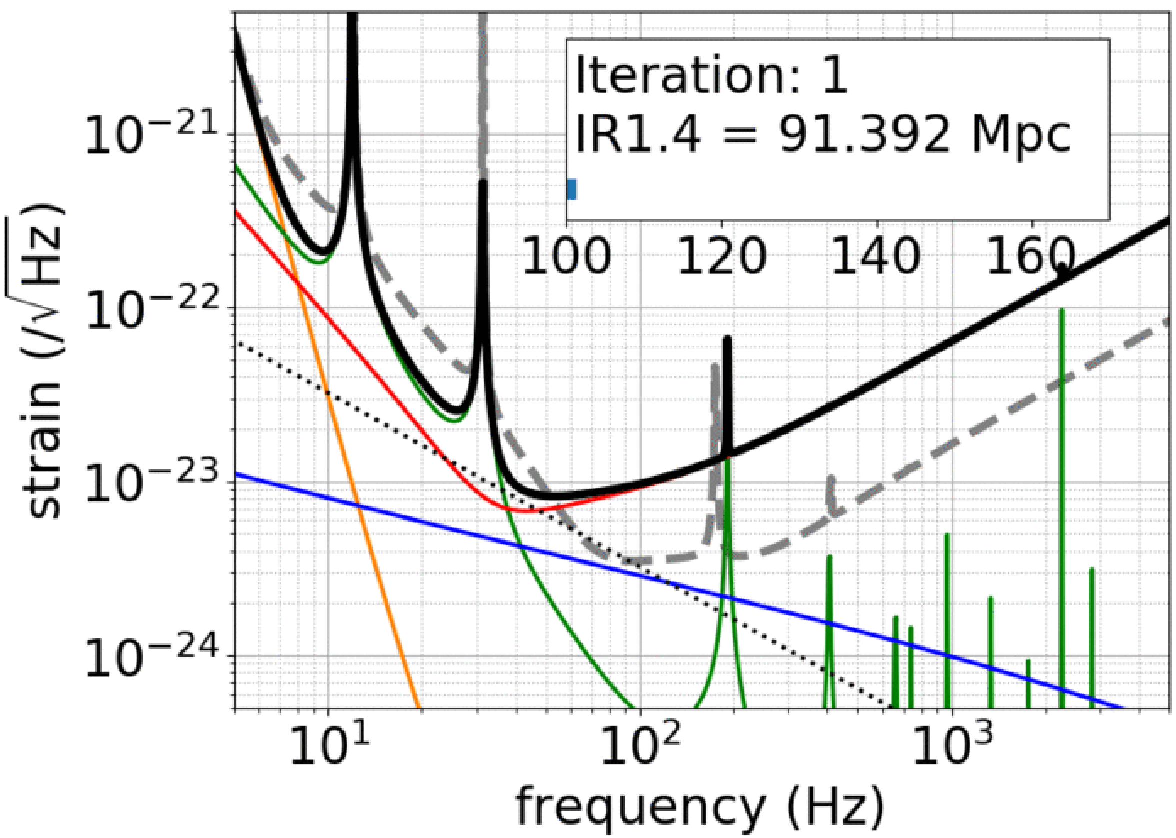
How about KAGRA?

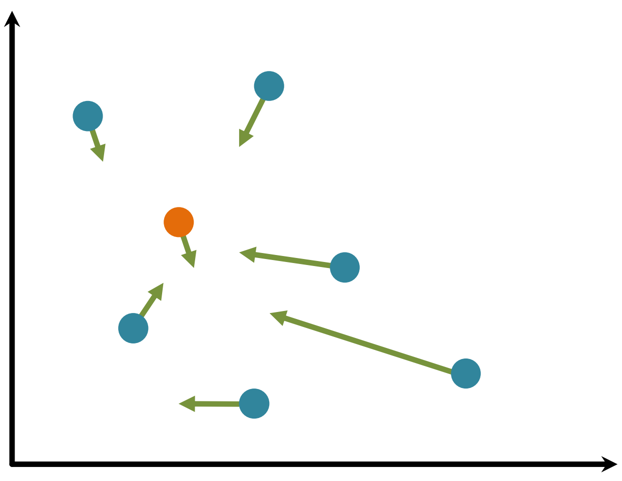
- Different investigation necessary due to cryogenic



Sensitivity Optimization

- Simultaneous tuning of multiple interferometer parameters necessary
- Developed a code to optimize the sensitivity with Particle Swarm Optimization

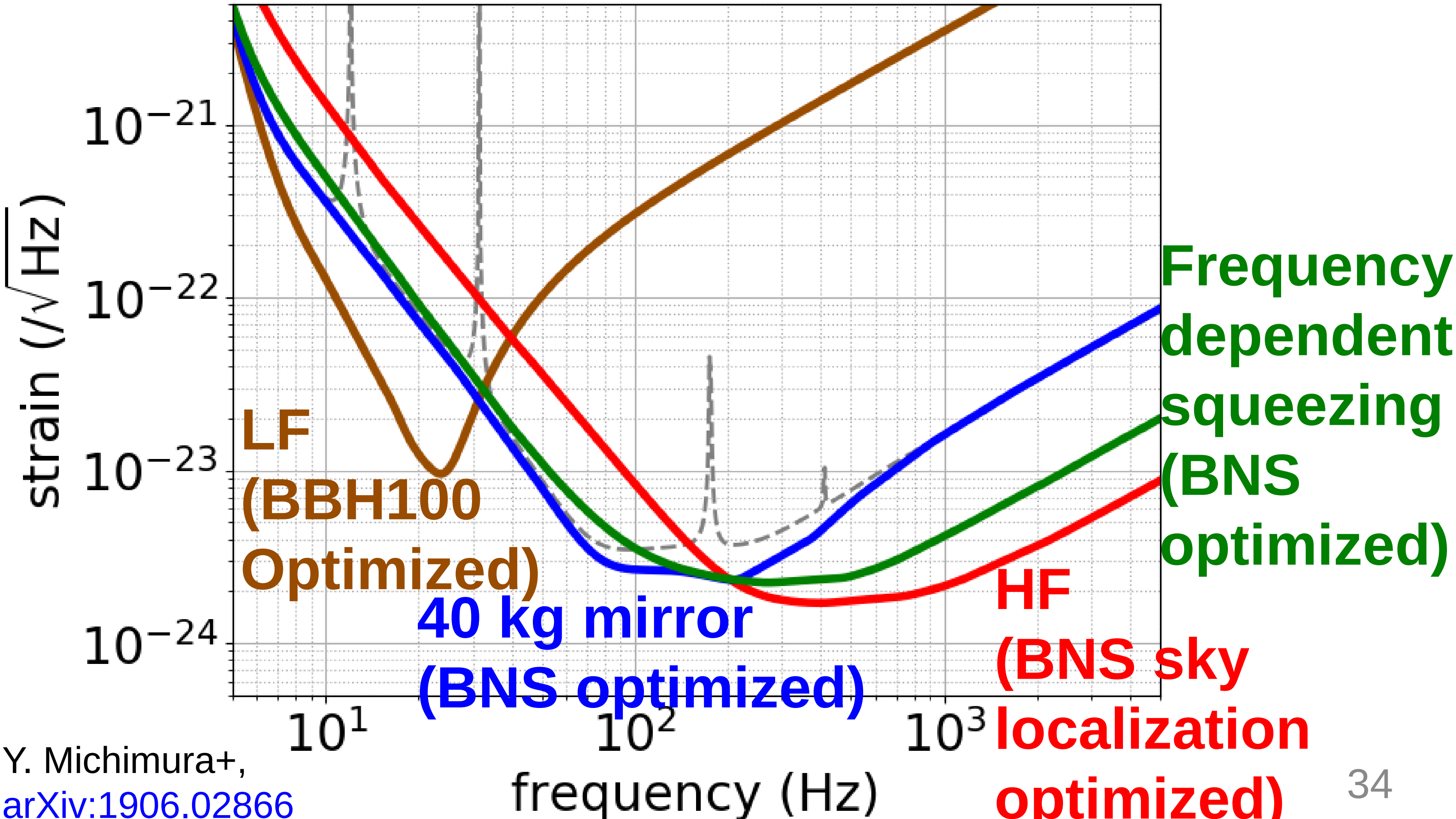




Y. Michimura+, PRD 97, 122003 (2018)

Possible Near Term Upgrade Plans

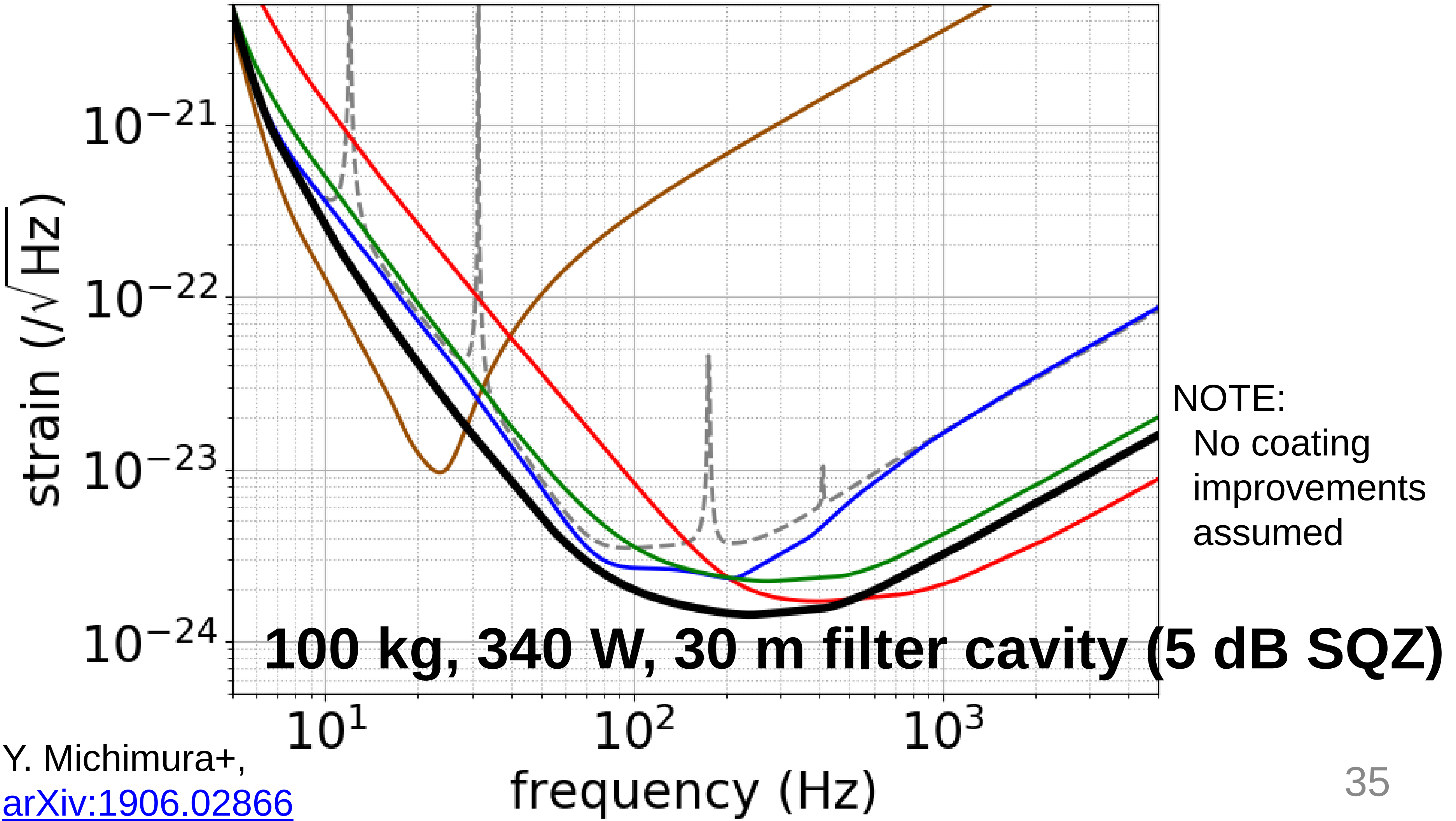
- Based on technical feasibility, facility and budget constraints (~5億円)



Y. Michimura+, arXiv:1906.02866

Possible Longer Term Upgrade

- Reaches BNS range of 300 Mpc by combining technologies (~20億円?)

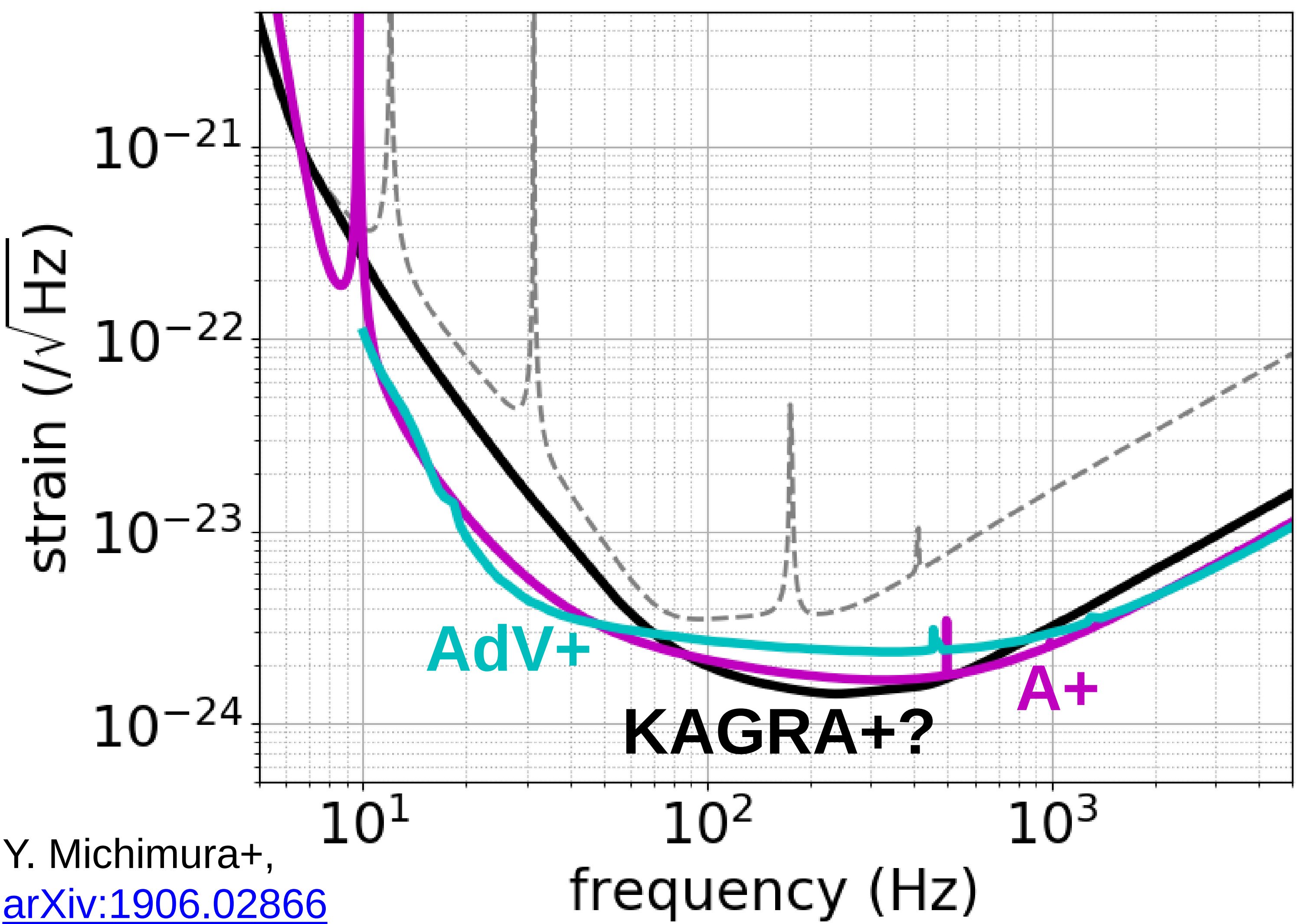


NOTE:
No coating improvements assumed

Y. Michimura+, arXiv:1906.02866

Possible Longer Term Upgrade

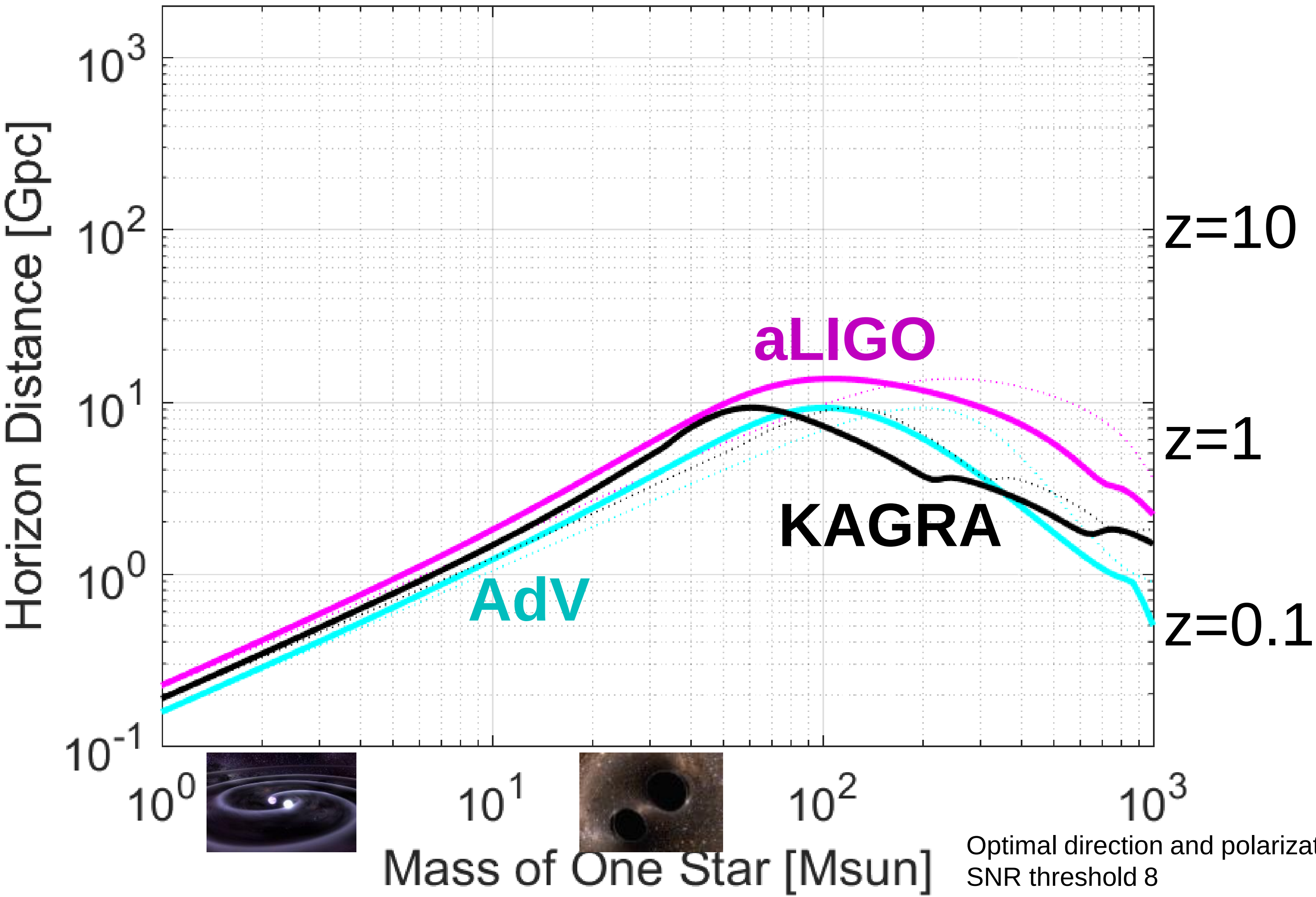
- Comparable to A+ (325 Mpc) and AdV+ (300 Mpc)



Y. Michimura+, [arXiv:1906.02866](https://arxiv.org/abs/1906.02866)

Horizon Distance Comparison

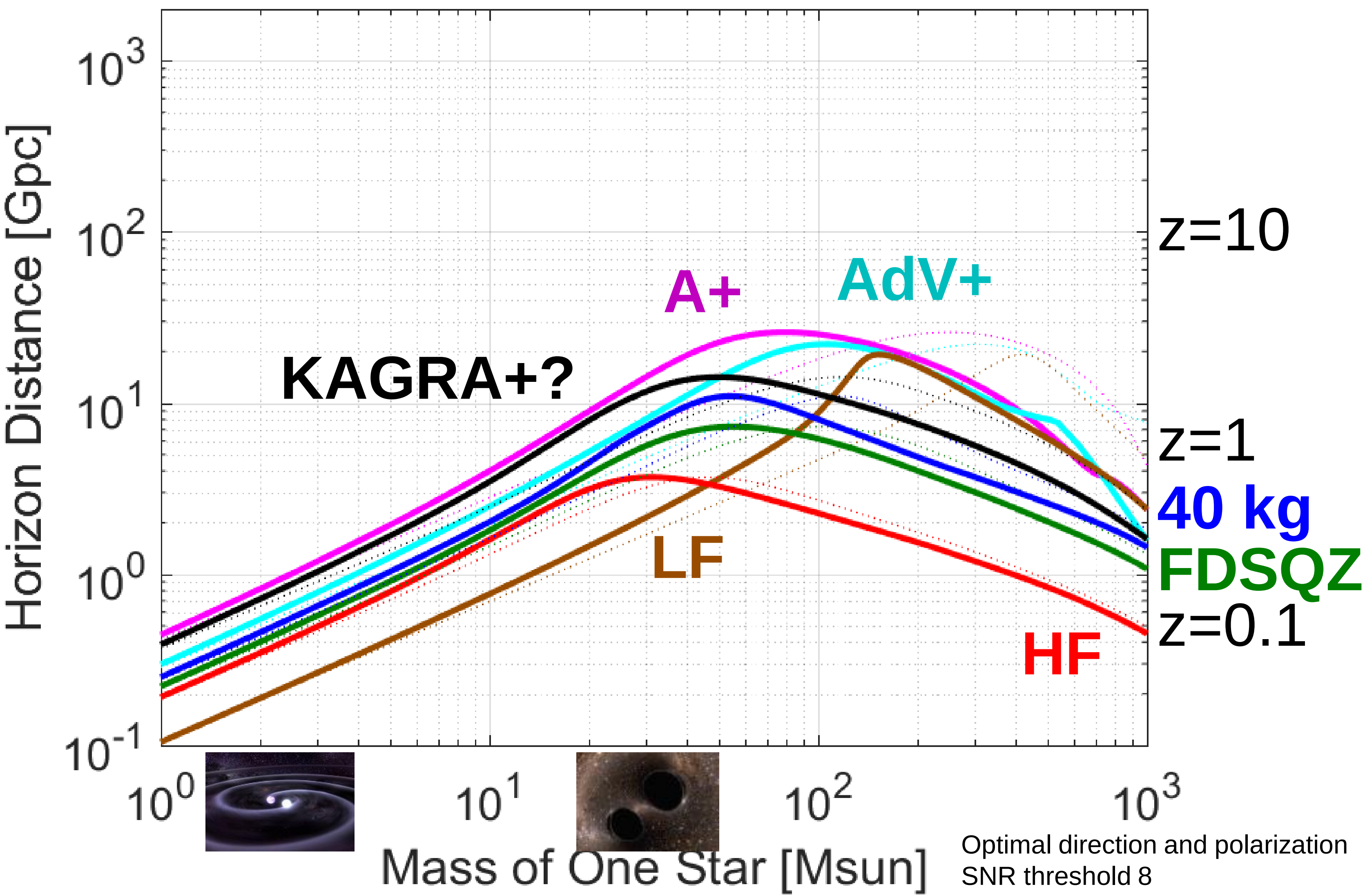
- O(10^2) events/year with designed sensitivity (~2021)



Optimal direction and polarization
SNR threshold 8

Horizon Distance Comparison

- O(10^3) events/year with upgrades (~2024)



Optimal direction and polarization
SNR threshold 8

Effective Progression of Upgrades?

- **Low frequency** is uncertain since many low frequency excess noises exist
- **40 kg mirror** would be feasible but even larger mirror is required for longer term
- **Higher power laser** and **frequency dependent squeezing** are attractive in terms of feasibility
- **HF** plan has better sensitivity than A+ and AdV+ at high frequencies

- **Higher power laser** → **Squeezing** → **Frequency dependent squeezing** → **Larger mirror** might be an effective progression

Future Planning Committee

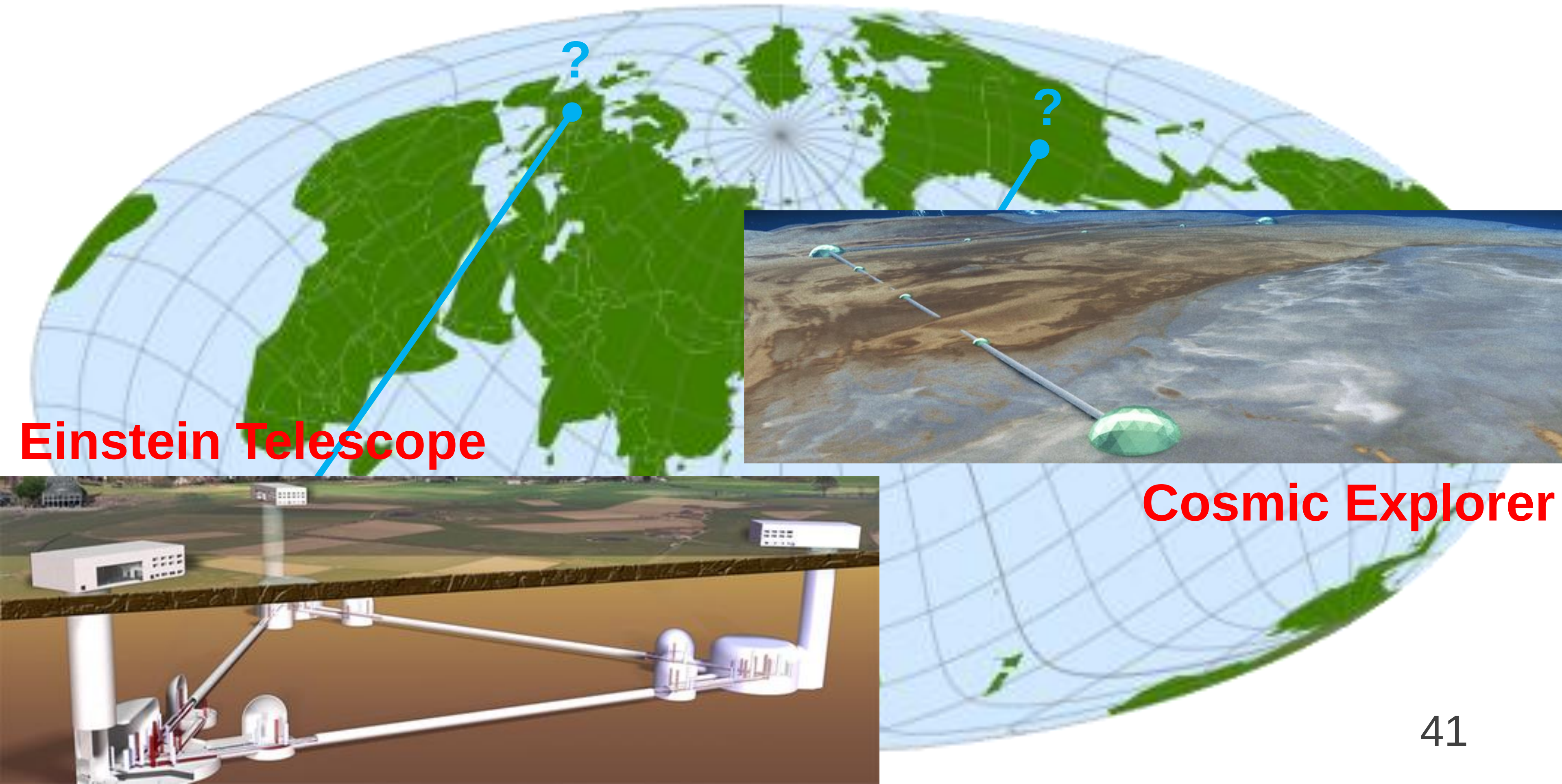
- Formulated inside KAGRA Collaboration in December 2018
  - Sadakazu Haino (chair)
  - Chunglee Kim
  - Kentaro Komori
  - Matteo Leonardi
  - Yuta Michimura
  - Atsushi Nisizawa
  - Kentaro Somiya

category	topic	KLF	K40	KSQ	KHF	KCo
stellar-mass BBH	formation scenarios (SNR of BBH)	0	0	0	0	☆
	formation scenarios (spin of BBH)	0	0	0	0	0
	host galaxy identification of BBH	★★	☆☆	☆	0	☆☆☆
intermediate-mass BBH	formation scenarios (SNR of IMRB)	☆☆☆	0	★★★	★★★	0
BNS and BHNS	binary evolution (SNR of BH-NS)	☆☆	☆☆	☆☆	☆☆	☆☆
	EM follow-up obs for BH-NS	0	☆☆	☆☆	☆☆	☆☆☆
	binary evolution (SNR of BNS)	☆☆	☆☆	☆☆	☆☆	☆☆
	EM follow-up obs for BNS	0	☆	☆☆	☆☆☆	☆☆☆
accreting binaries	low-mass X-ray binaies	★★★	☆☆	☆	★★	☆☆☆
isolated pulsar	pulsar ellipticity	---	0	☆☆☆	☆☆☆	☆☆☆
	magnetor flare & pulsar glitches	---	☆	☆☆☆	☆☆☆	☆☆☆
	stellar oscillation	---	☆	☆☆☆	☆☆☆	☆☆☆
supernova	explosion mechanism	---	cannot choose			☆☆☆
the early Universe	GW from inflation	☆☆☆	☆	0	★★★	☆☆☆
	GW from phase transition	cannot choose				
test of gravity	Test of consistency with GR	×	○	○	×	○
	GW generation in modified gravity	×	○	○	×	○
	GW propagation test	☆	☆☆	☆☆	☆☆	☆☆
	GW polarization test	☆	☆☆	☆☆	☆☆	☆☆
	BH spectroscopy w/ 20 Msun – 40 Msun BBH	---	☆	☆☆	☆☆☆	☆☆☆
	BH spectroscopy w/ 233 Msun – 466 Msun BBH	☆☆☆	0	0	---	☆☆☆
late-time cosmology	measurement of the Hubble constant w/ BBH	★★	☆☆	☆	☆	☆☆☆
	measurement of the Hubble constant w/ BNS	0	☆☆	☆☆☆	☆☆☆	☆☆☆
	GW lensing	★★	☆☆	☆	☆	☆☆☆
multimessengers	short gamma-ray bursts	×	○	○	×	○
	long gamma-ray bursts (inspiral GW from a disk)	★★★	☆☆	☆☆	☆	☆☆☆
	long gamma-ray bursts (burst memory GW)	★★★	☆	☆☆☆	☆☆☆	☆☆☆
	fast radio bursts	0	☆	☆☆	☆☆☆	☆☆☆
others	cosmic string	☆☆☆	☆	0	★★★	☆☆
	BH echoes	cannot choose				

- White paper on KAGRA upgrade work in progress (to be finalized by August 2019)
  - Available technology survey
  - Science case study

Next Generation Detectors

- Laser interferometric detector with 10-40 km arms
- Places not decided yet



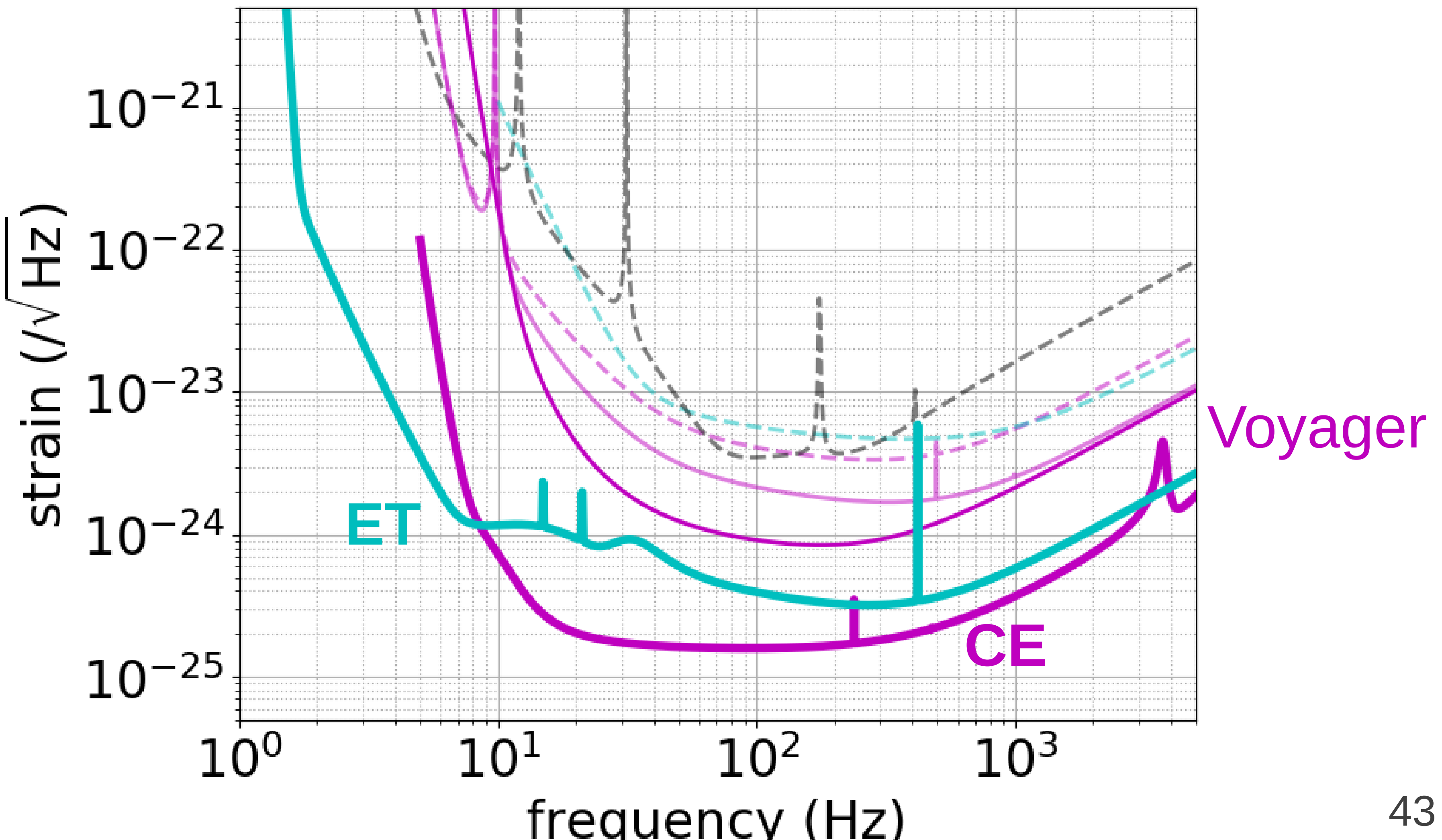
Next Generation Detectors

- Einstein Telescope
  - 10 km、200 kg silicon mirror, underground
    10 K and room temperature interferometers
  - Two candidate locations (decide by 2022)
    Sardinia, Italy
    Bergium-Germany-Netherlands border
  - Final design by 2023
  - Anticipate to start installation from 2032
- Cosmic Explorer
  40 km, 320 kg silicon mirror, 120 K

- KAGRA is pioneering cryogenic and underground

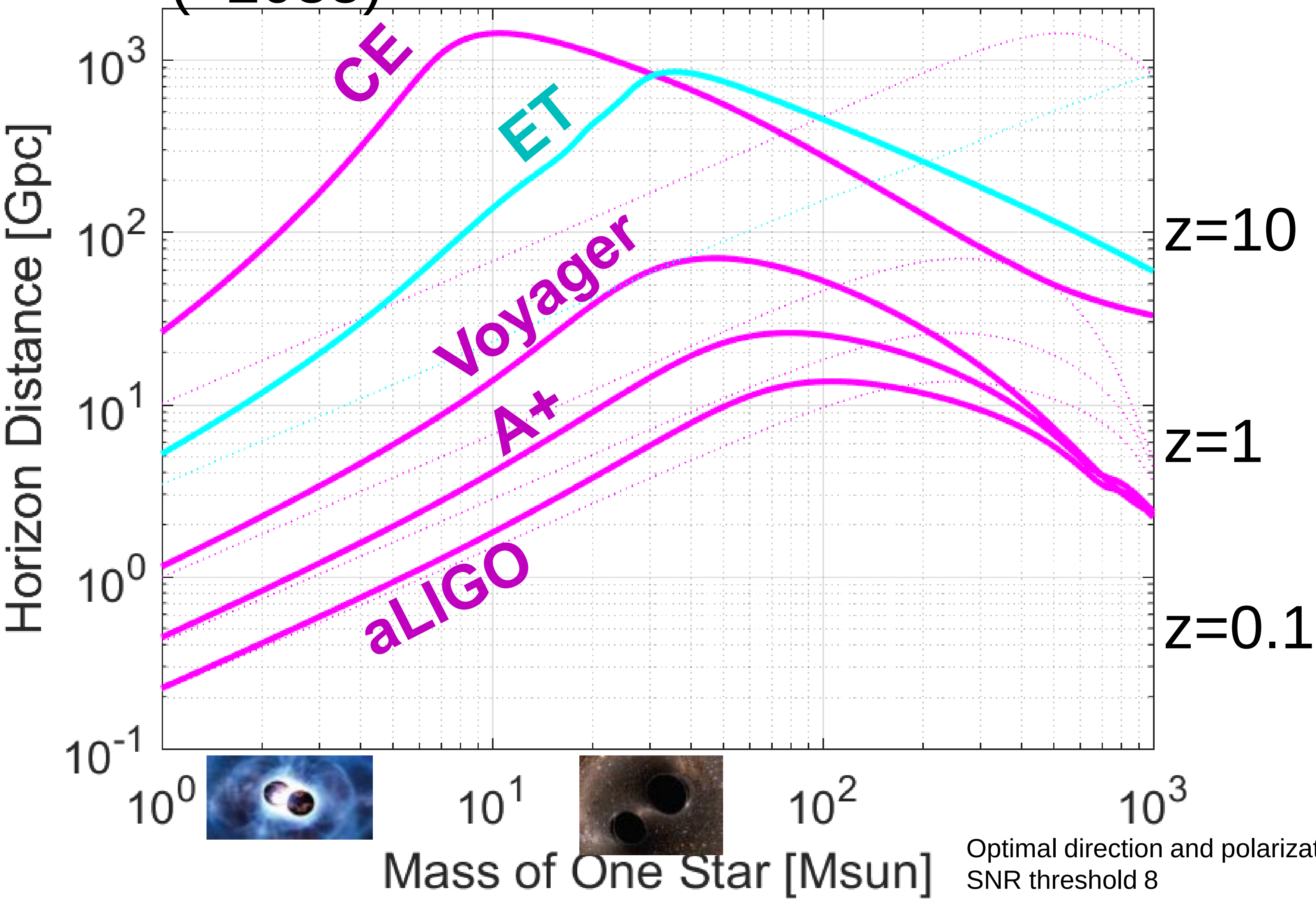
Sensitivity of Next Generations

- An order of magnitude improvement



Horizon Distance

- O(10^5) events/year with next generation detectors (~2035)



Optimal direction and polarization
SNR threshold 8

Summary

- KAGRA is an underground cryogenic GW detector pioneering next generation detectors
- First observing run with LIGO and Virgo expected late 2019
- KAGRA joining the observation improves sky coverage, network duty factor, source parameter estimation
- KAGRA upgrade study on-going, aiming for the upgrade by ~2024
- Twofold sensitivity improvement is feasible for KAGRA

Additional 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)

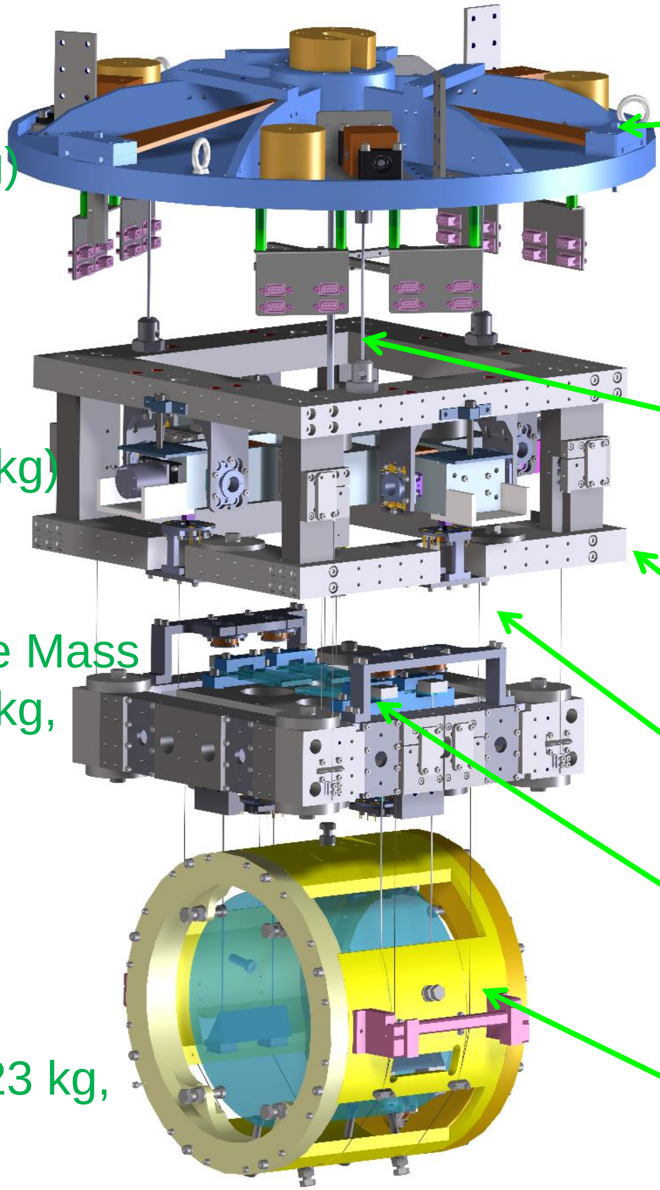
KAGRA Detailed Parameters

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)

3 CuBe blade springs

Marionette
(SUS, 22.5 kg)

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

Heat link attached to MN

Intermediate Mass
(SUS, 20.1 kg,
16 K)

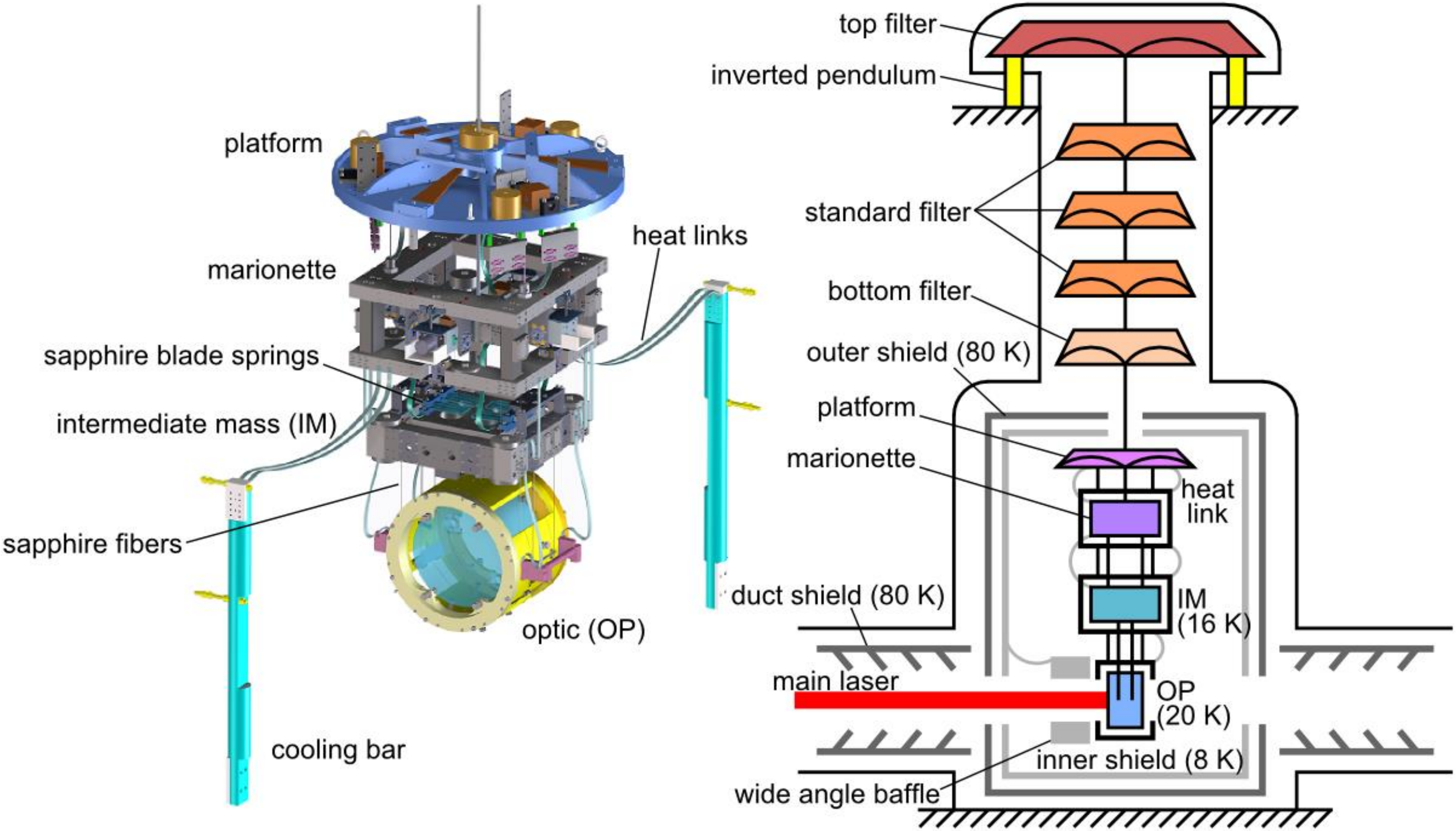
IM suspended by 4 CuBe fibers
(24 cm long, 0.6 mm dia)
IRM suspended by 4 CuBe fibers

4 sapphire blades

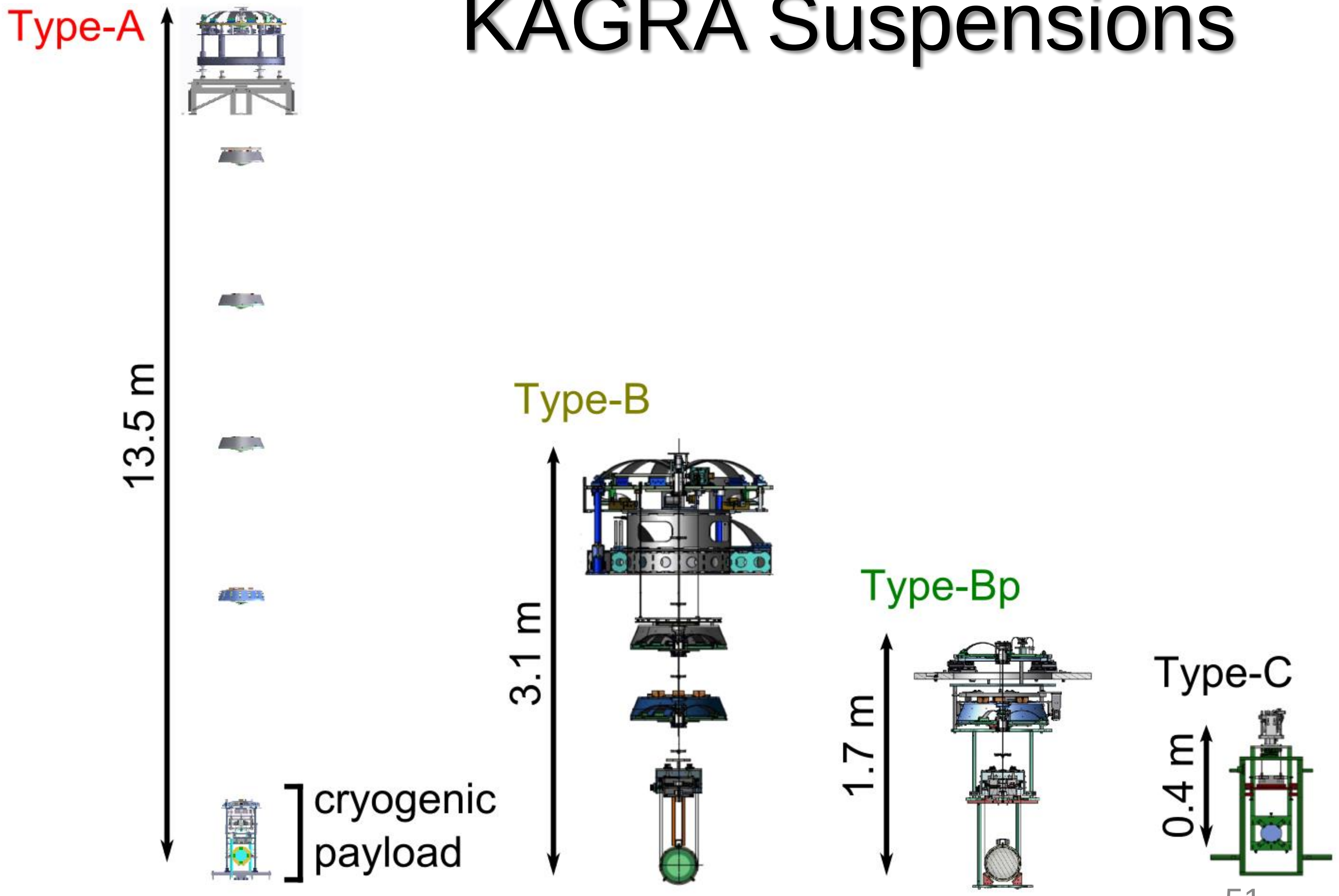
Test Mass
(Sapphire, 23 kg,
22 K)

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

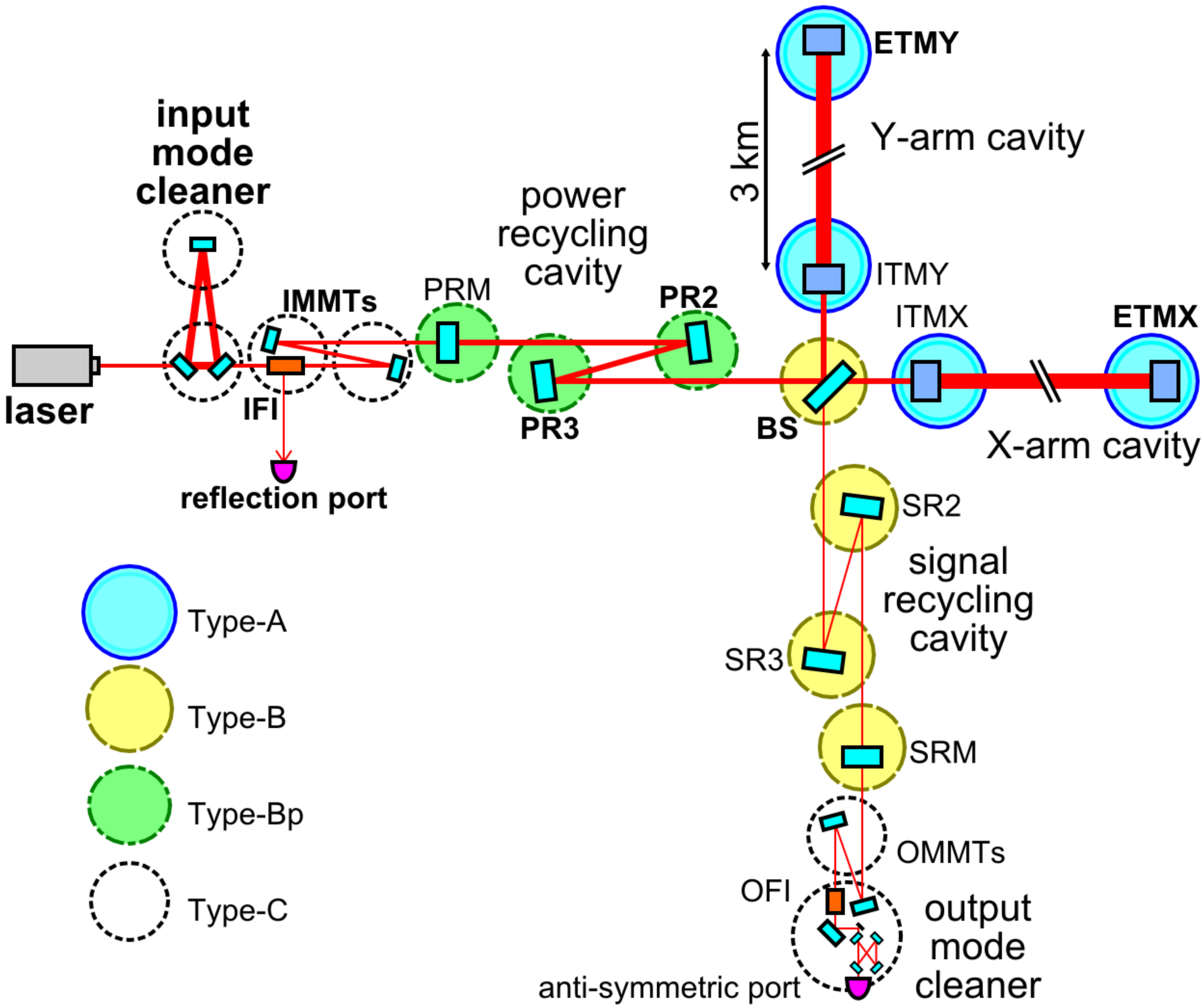
KAGRA Cryostat Schematic



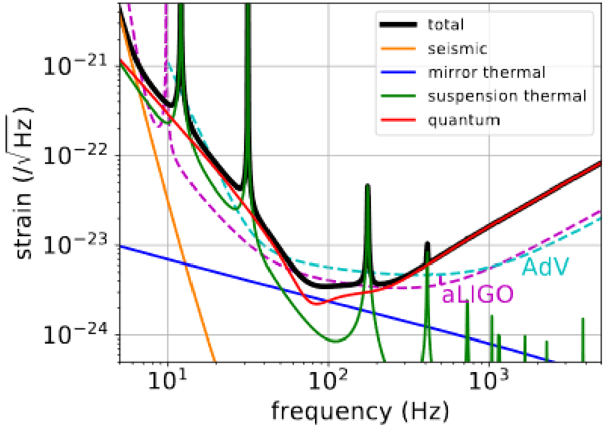
KAGRA Suspensions



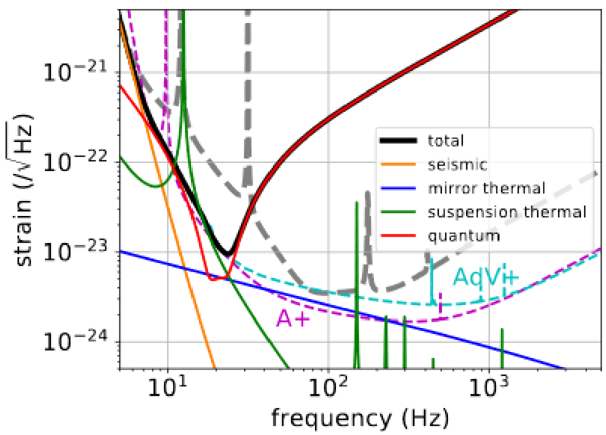
KAGRA Interferometer



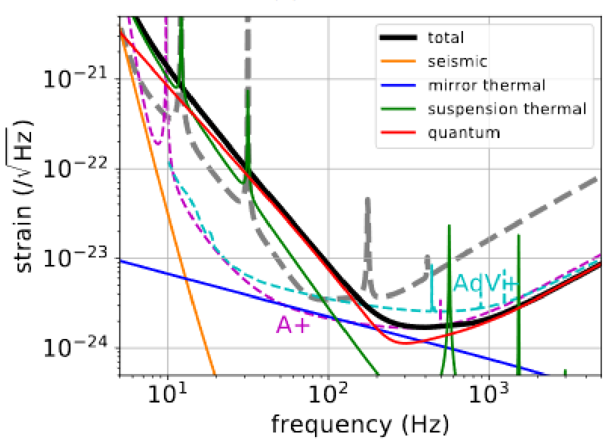
Possible KAGRA Upgrade Plans



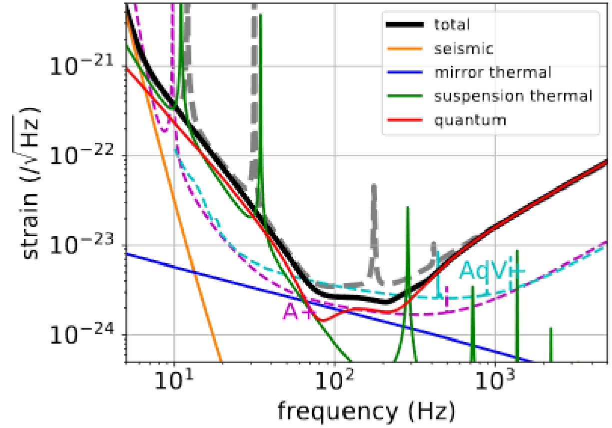
(a) bKAGRA



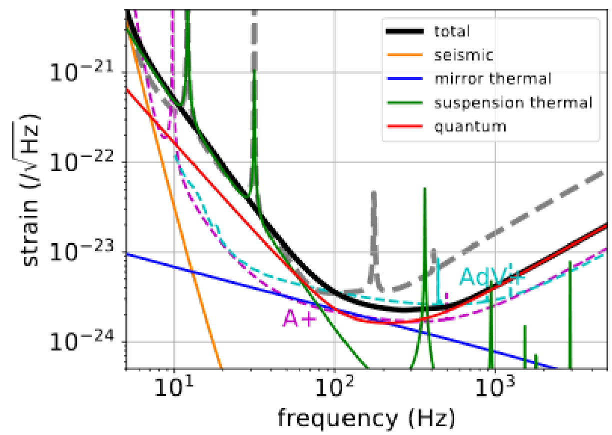
(b) LF



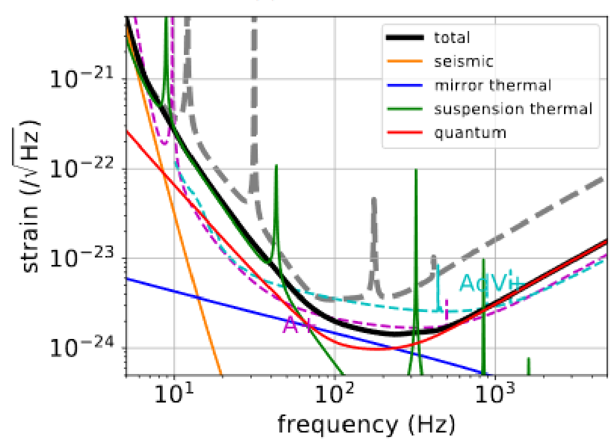
(c) HF



(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)	$\phi_{\rm det}$	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
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