Laser Interferometry for Gravitational Wave Observations

4. Status of KAGRA

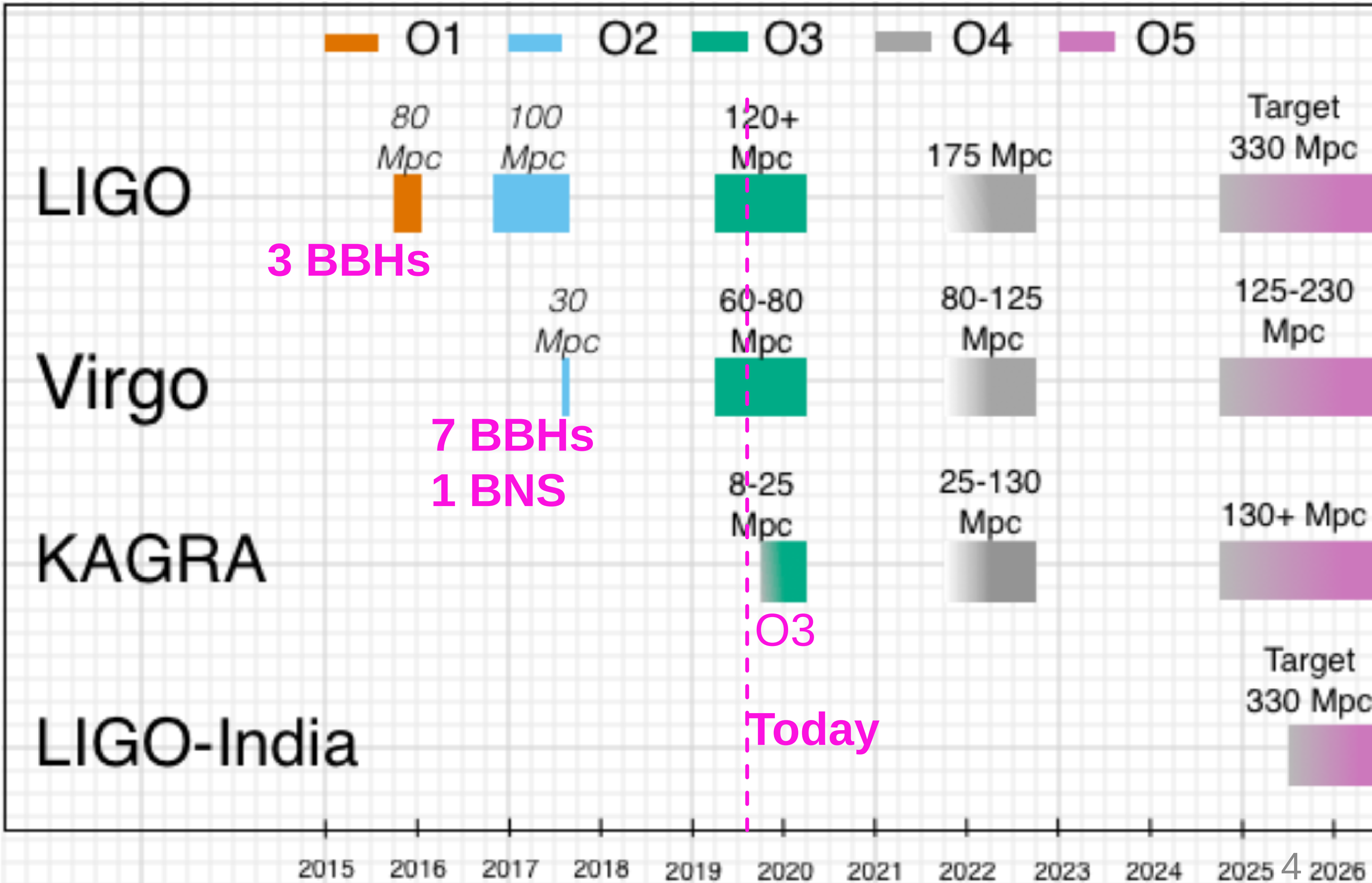
Yuta Michimura
Department of Physics, University of Tokyo

Contents

1. Laser Interferometers (July 25 PM)
   Michelson interferometer
   Fabry-Pérot interferometer
2. Quantum Noise (July 25 PM)
   Shot noise and radiation pressure noise
   Standard quantum limit
3. Sensitivity Design (July 26 AM)
   Force noise and displacement noise
   Inspiral range and time to merger
   Space interferometer design
4. Status of KAGRA (July 26 AM)
   Status of KAGRA detector in Japan
   Future prospects

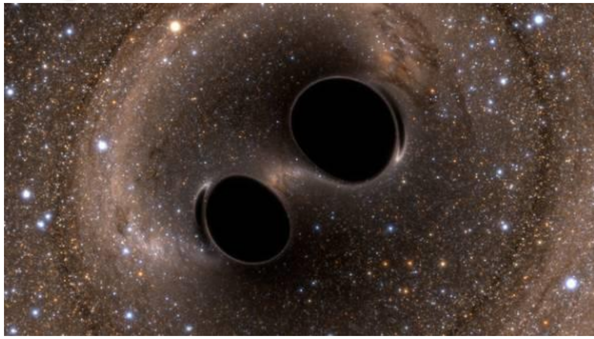
Global Network of GW Telescopes

Observation Scenario

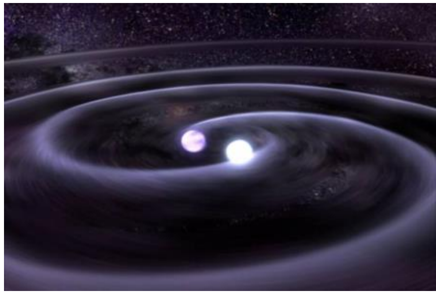


Updated version of [Living Reviews in Relativity 21, 3 (2018)](); available from [LIGO-P1200087]()

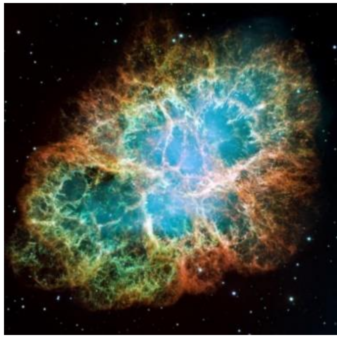
Solved and Unsolved Mysteries



- 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?

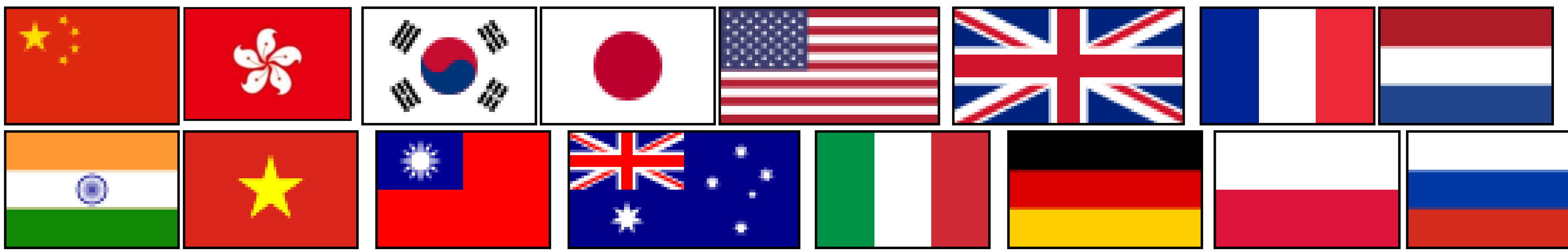
- More sensitive, multiple detectors
  - Better source localization with multiple detectors
    Better multi-messenger observations
  - Polarization resolvable with multiple detectors
    Better inclination angle estimation
      Better Hubble constant measurement
    Non-GR polarization search
  - Twofold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

- Next to join observation: KAGRA

KAGRA Project

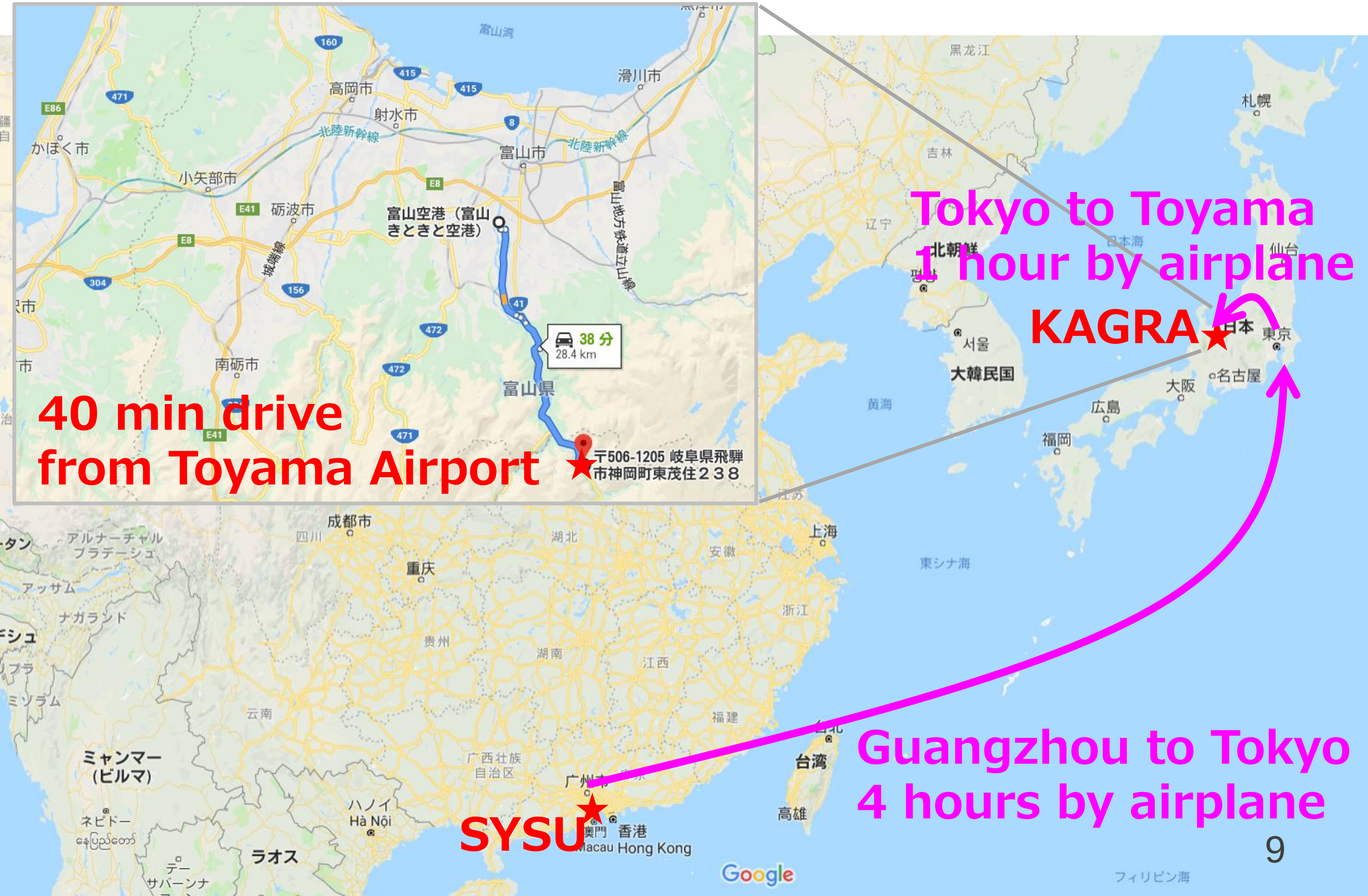
- Underground cryogenic interferometer in Japan
- Funded in 2010
- 97 institutes, 460 collaborators (162 authors)

as of Sept 2018



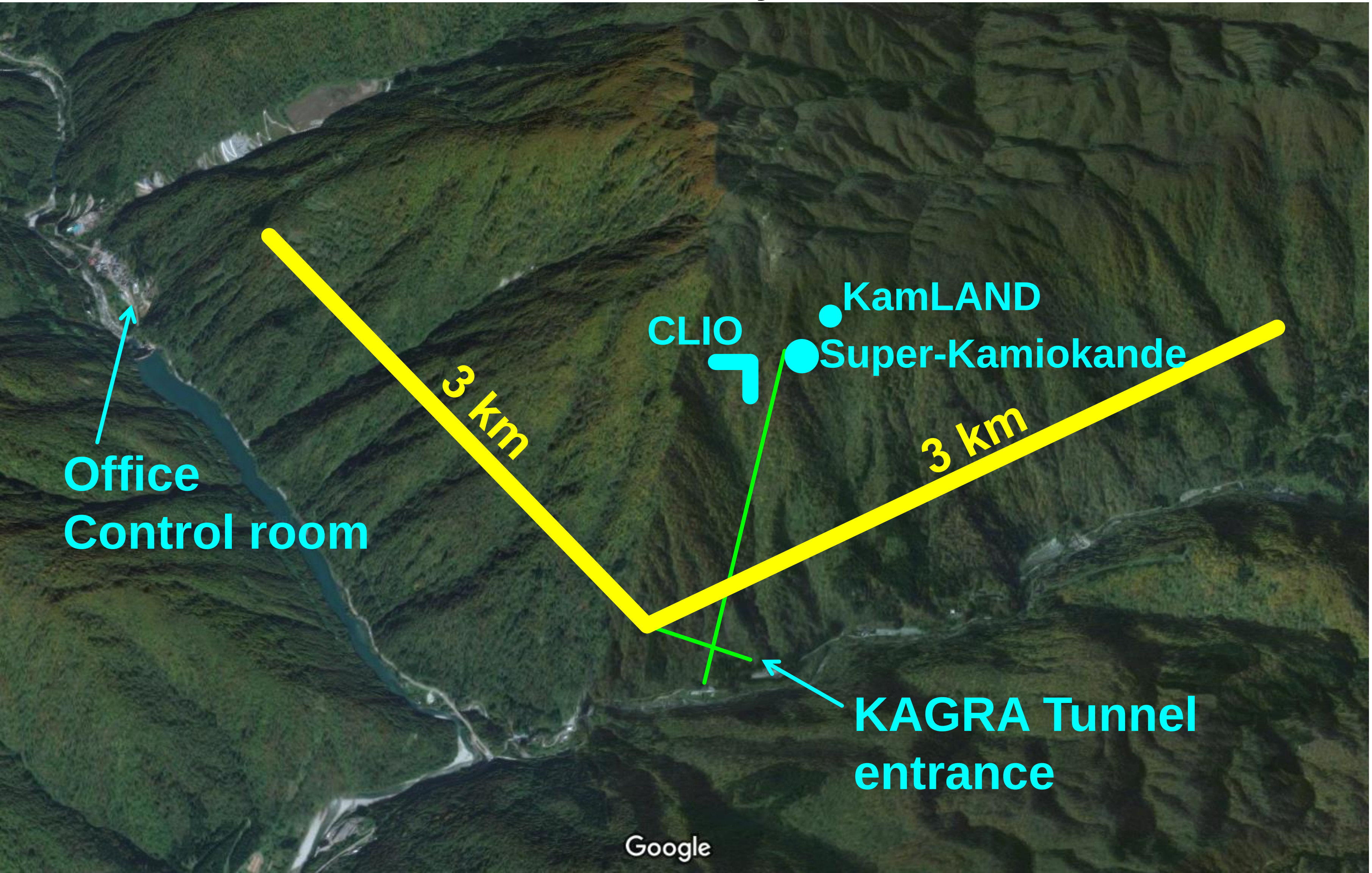
Location of KAGRA

Location of KAGRA



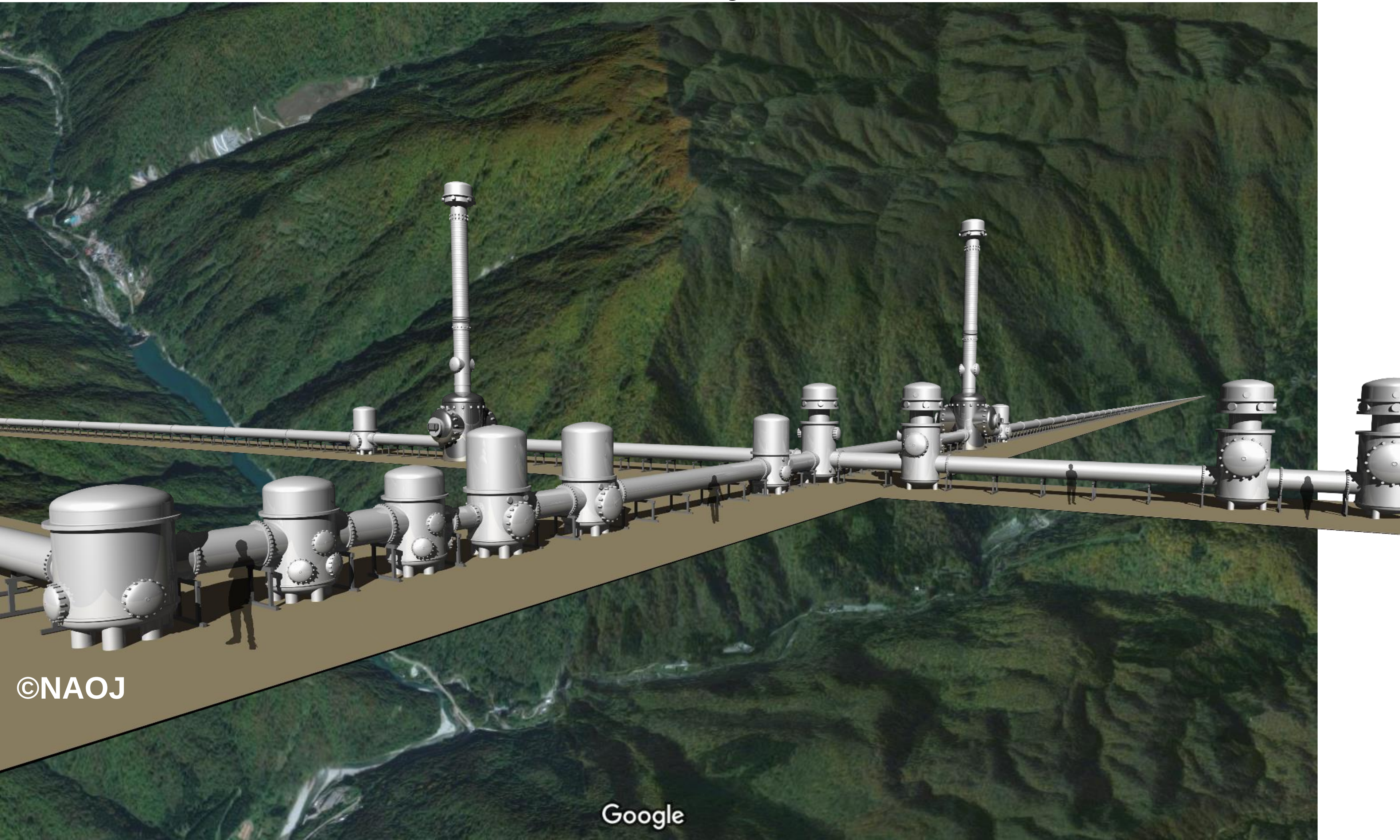
KAGRA Site

- Located inside Mt. Ikenoyama



KAGRA Site

- Located inside Mt. Ikenoyama



Kamioka

Mozumi area around GW Office

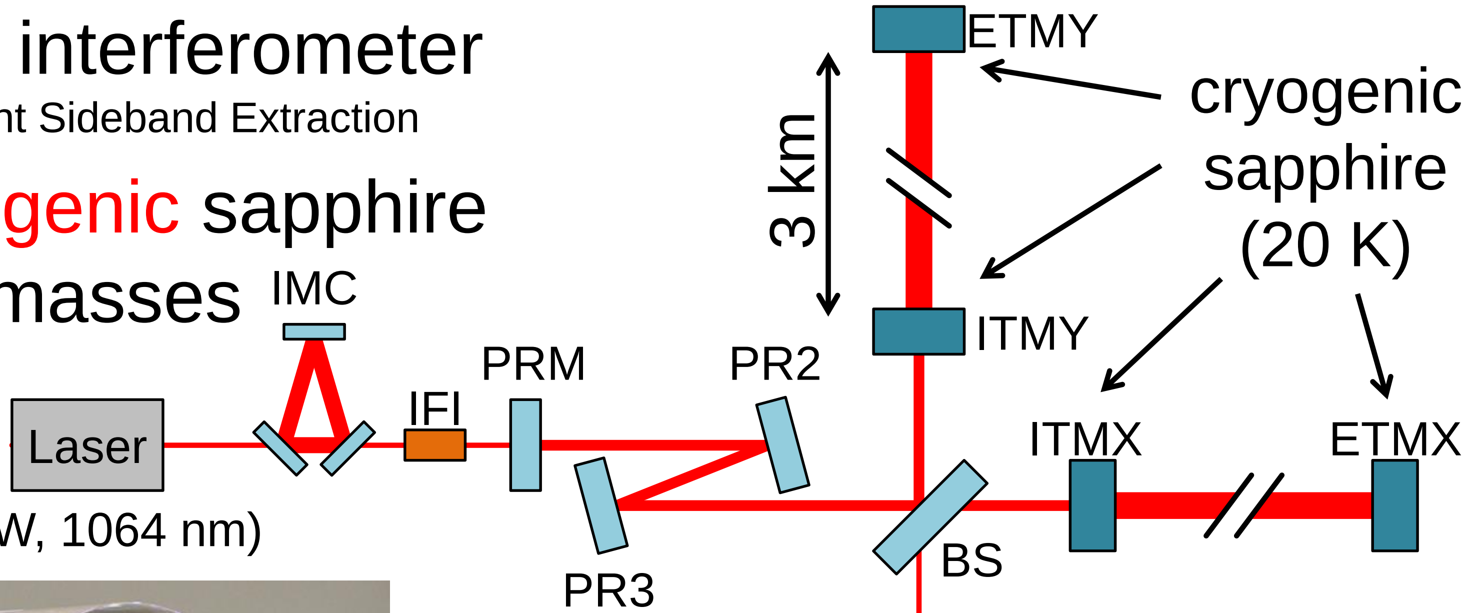
KAGRA Tunnel

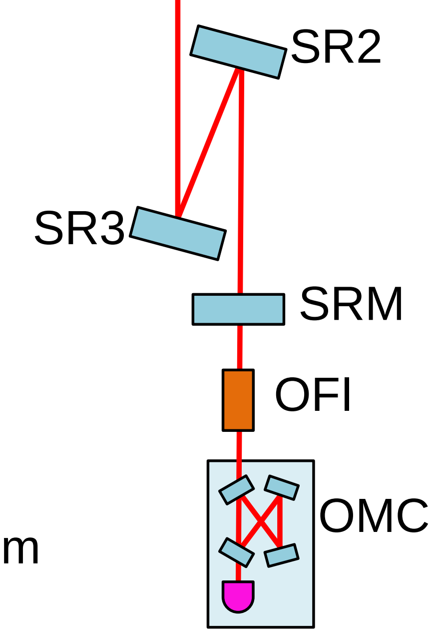
- two 3-km long vacuum pipes for laser beams to go back and forth

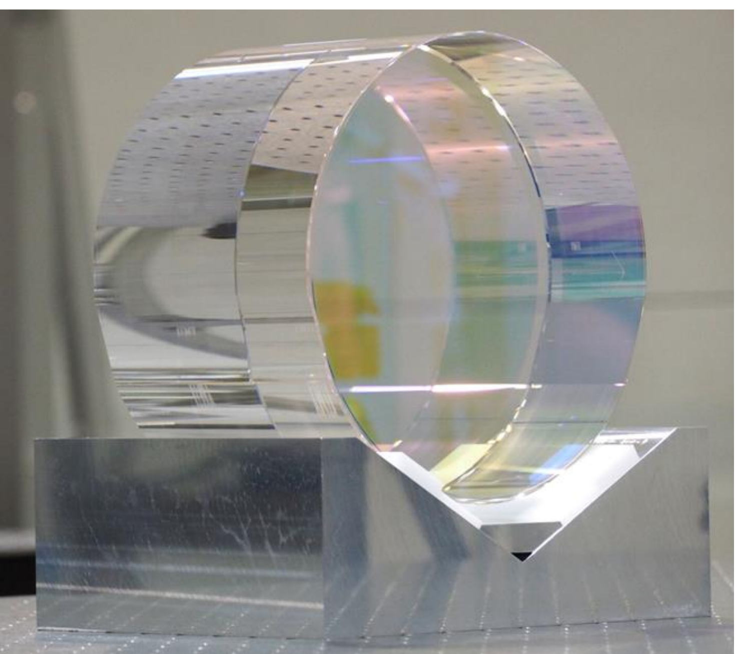
Entrance
(2016.2.8)

Interferometer Configuration

- RSE interferometer
  Resonant Sideband Extraction
- Cryogenic sapphire test masses



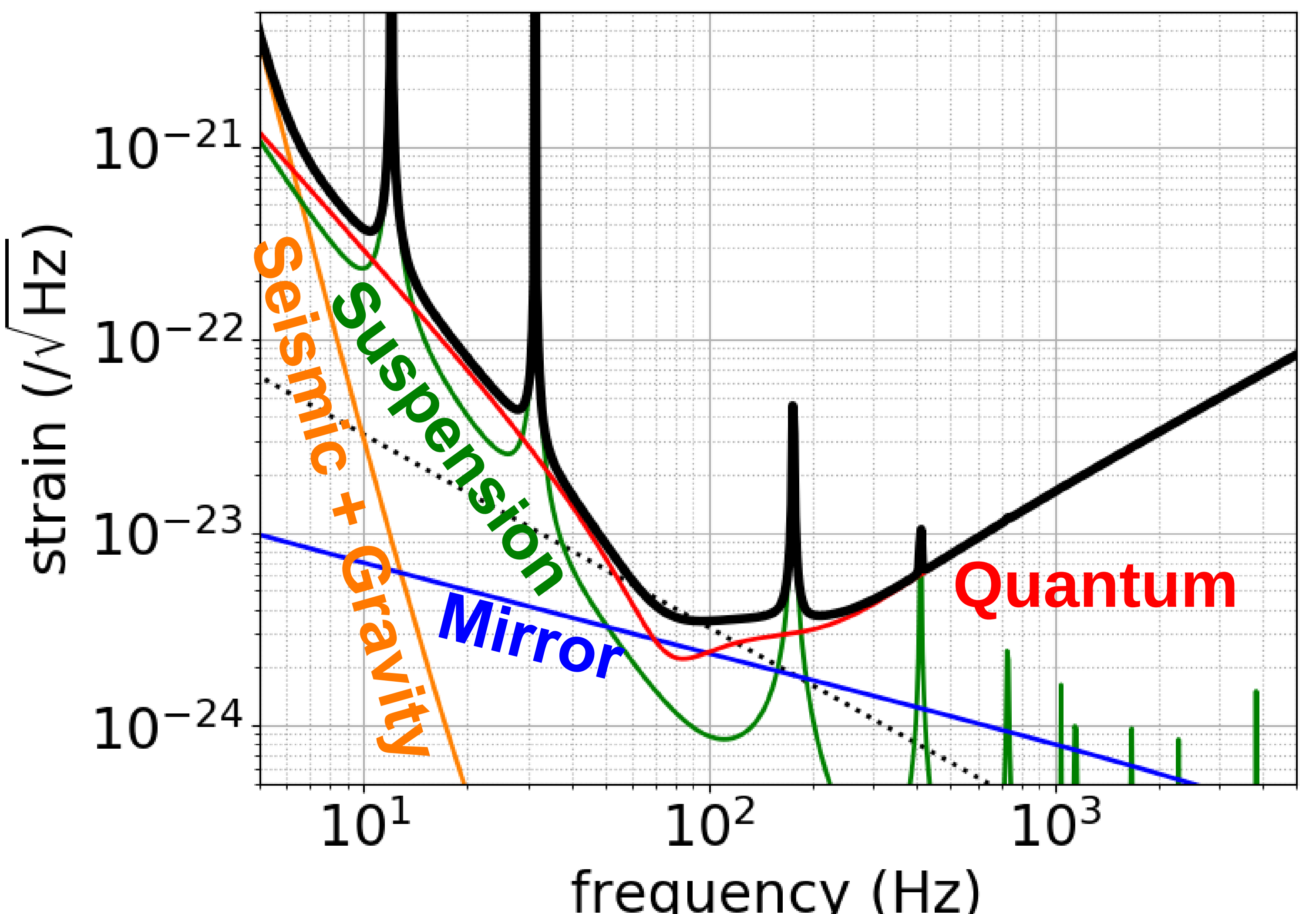




Φ22 cm x t 15 cm
22.8 kg

Design Sensitivity

- Binary neutron star (BNS) range 153 Mpc



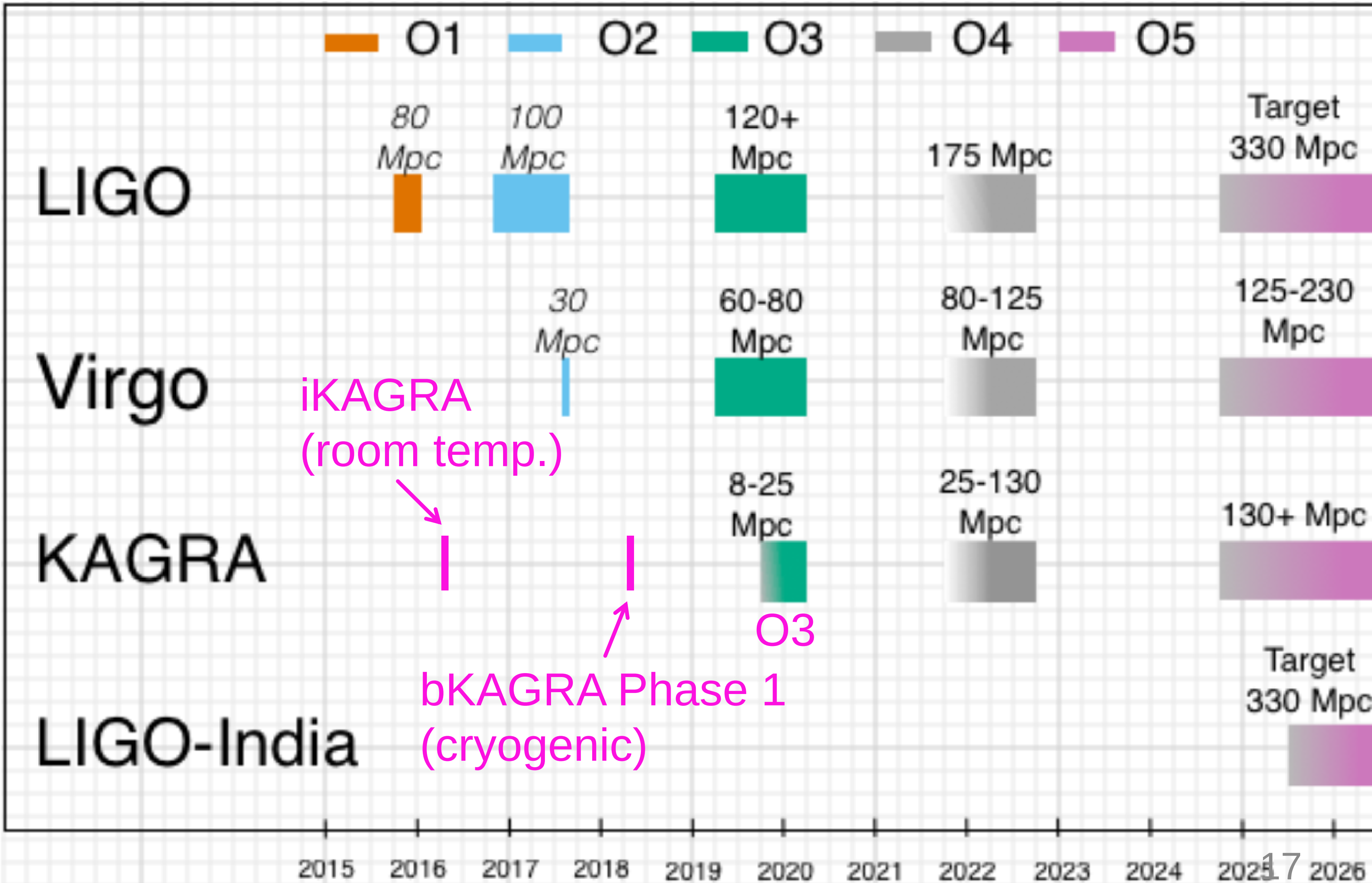
KAGRA Timeline

- 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, CQG 36, 165008 (2019)
- 2019 — Expect to join observing run O3
- 2020

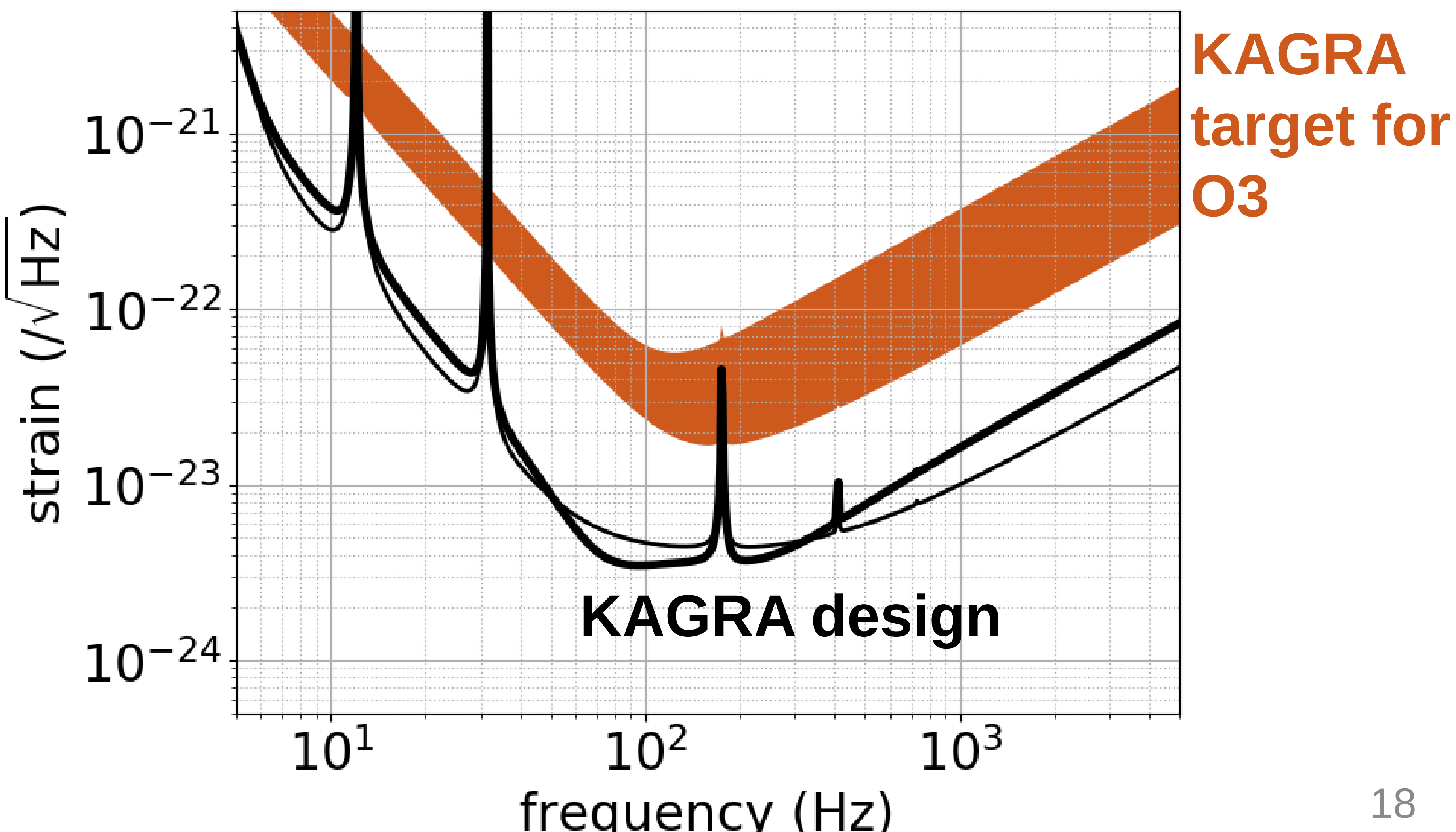
Observation Scenario



Updated version of Living Reviews in Relativity 21, 3 (2018); available from LIGO-P1200087

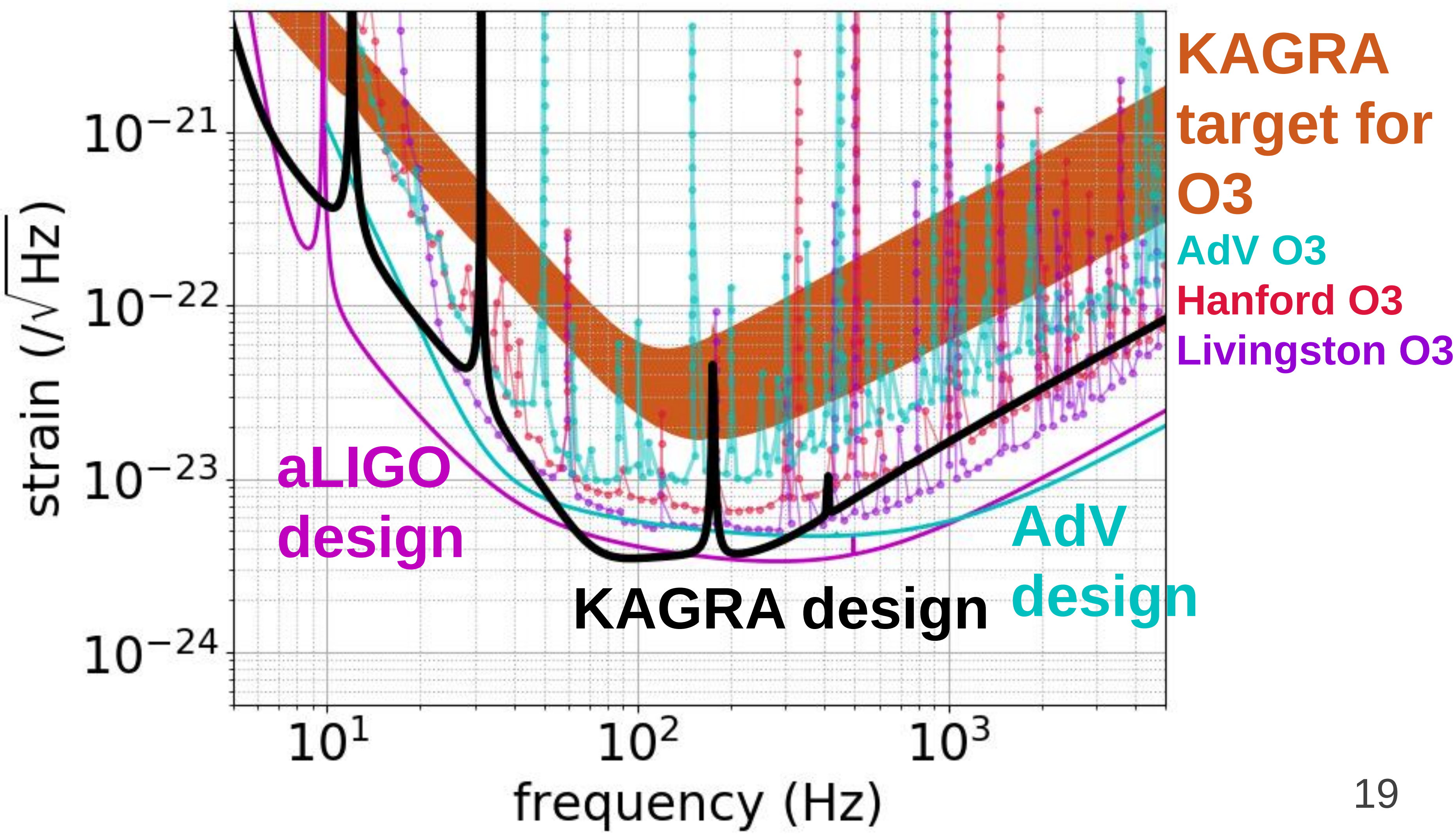
Target Sensitivity for O3

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



Comparison with LIGO/Virgo

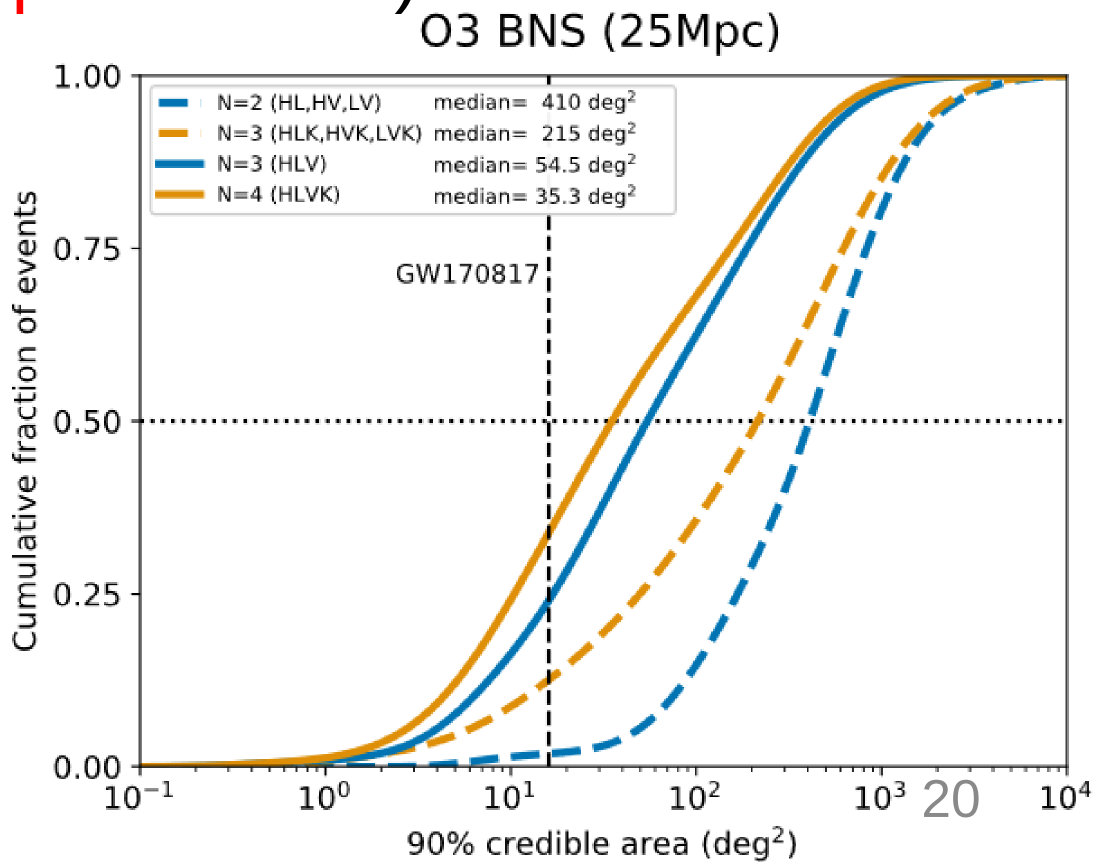
- Aims for 8-25 Mpc in binary neutron star range



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

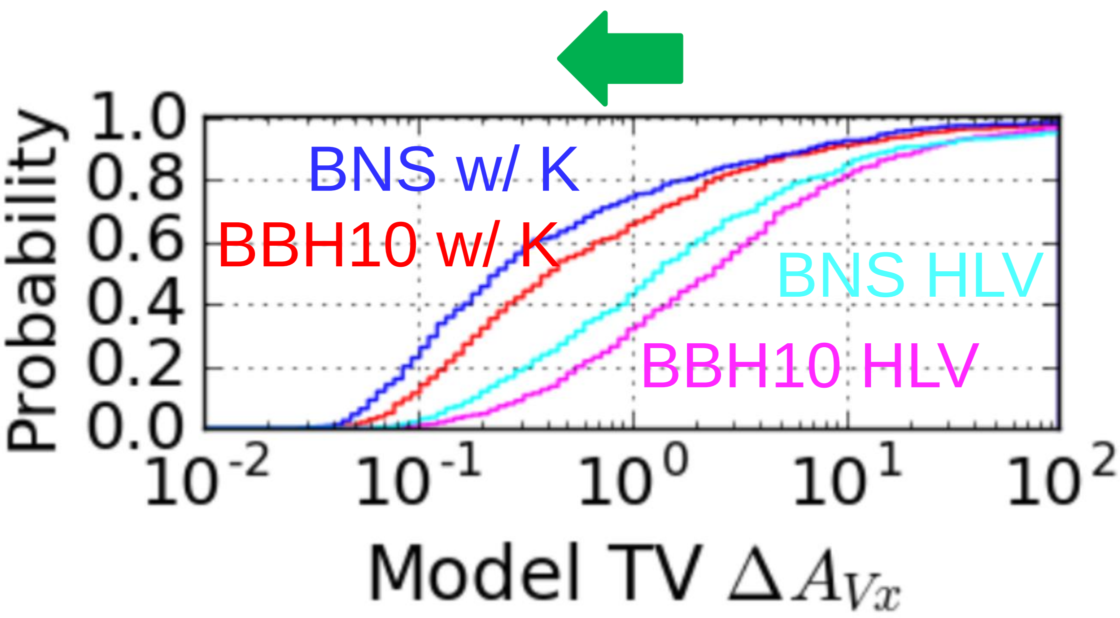


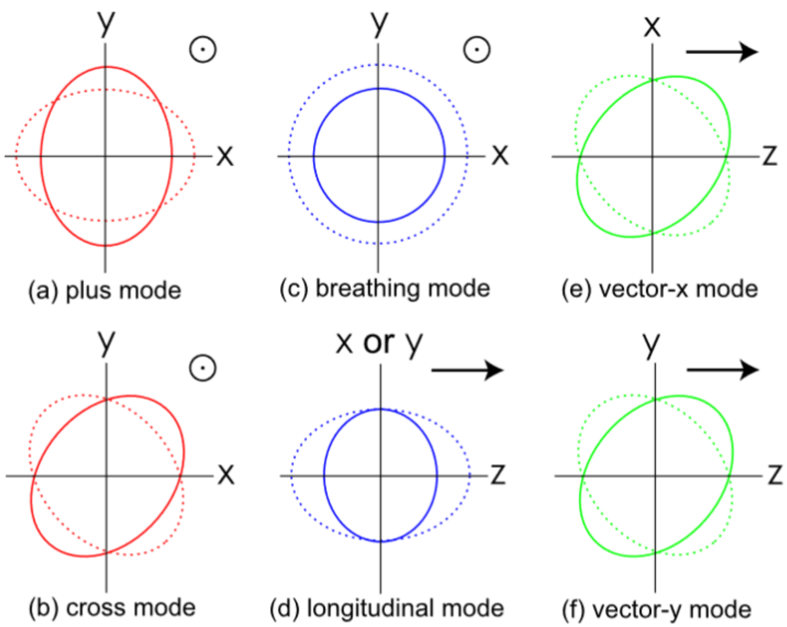
JGW-T1910330
Calculation
by S. Haino
(L: 120 Mpc, V: 60 Mpc, K: 15 Mpc)

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

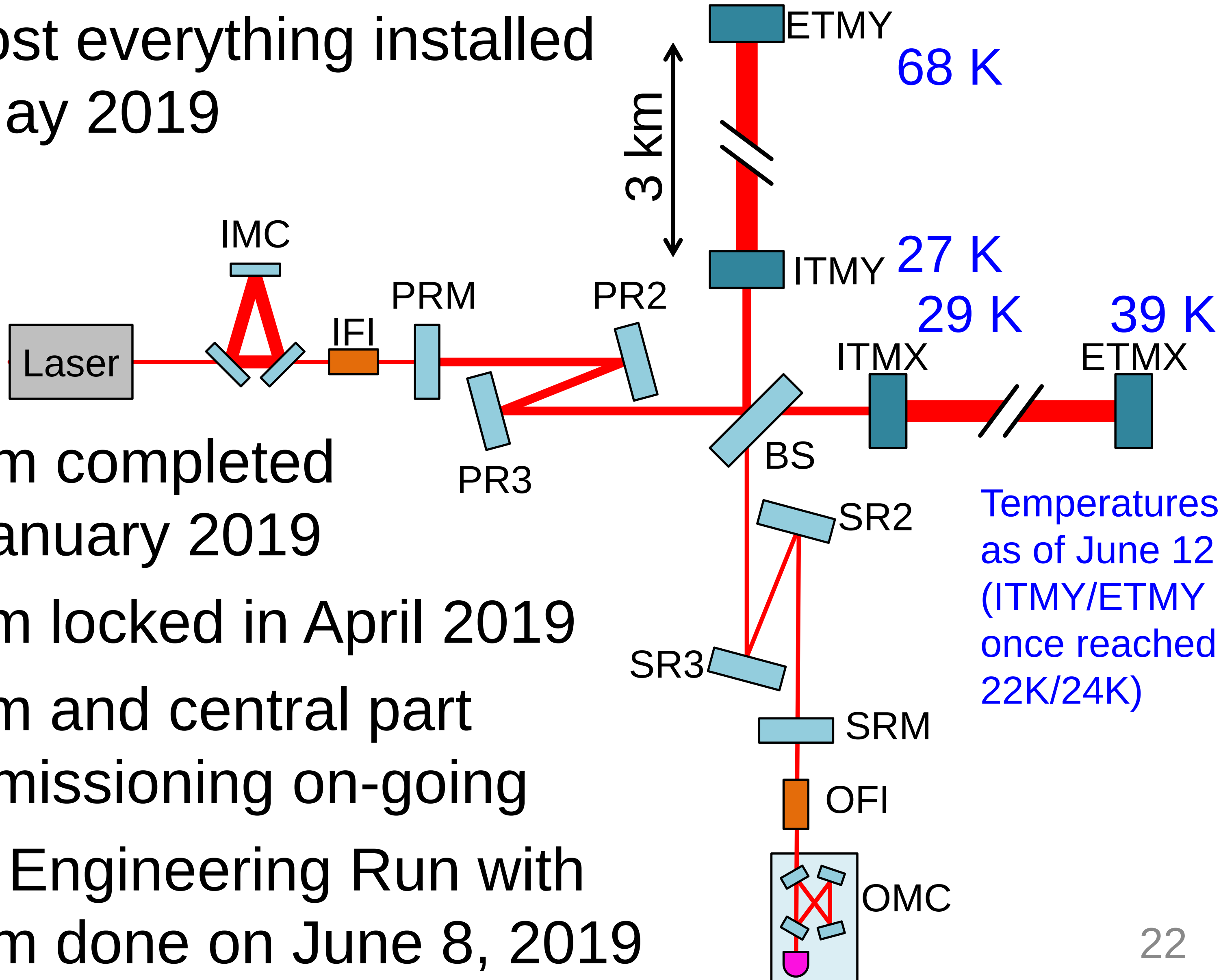




Error in vector-x mode amplitude

Recent News from KAGRA

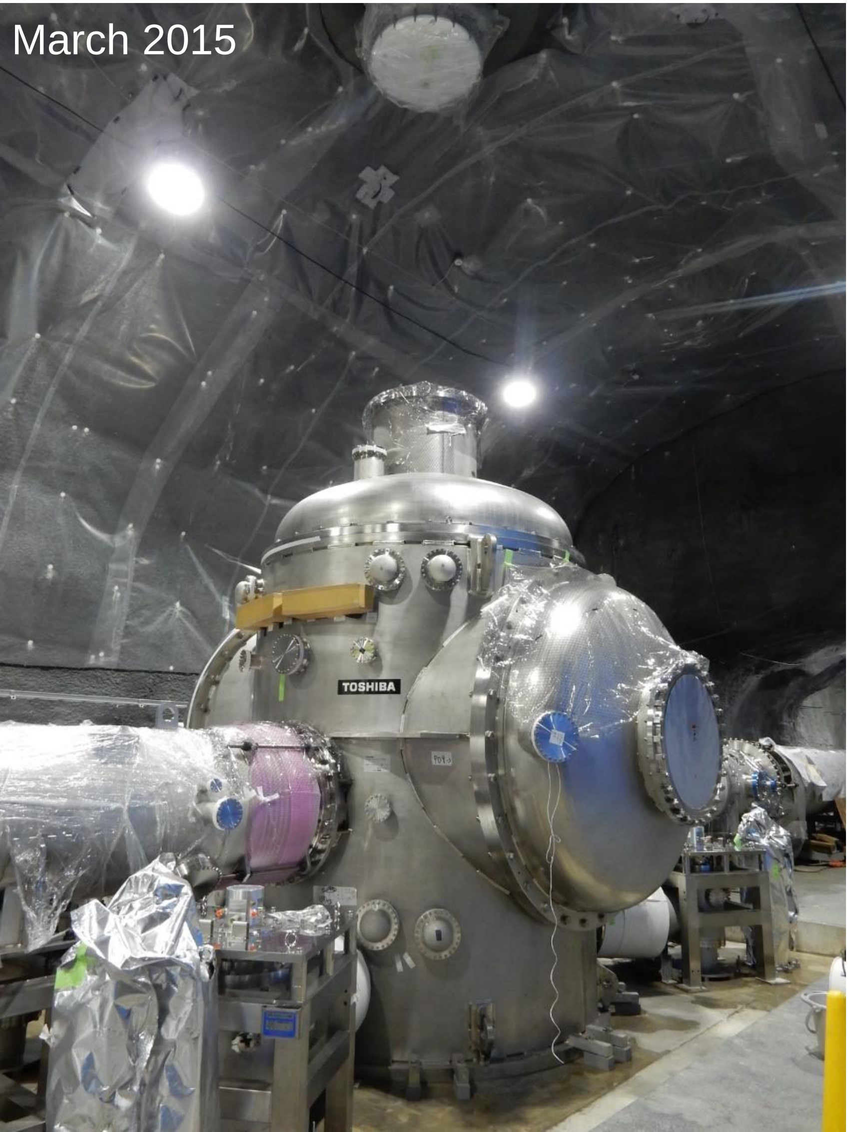
- Almost everything installed by May 2019

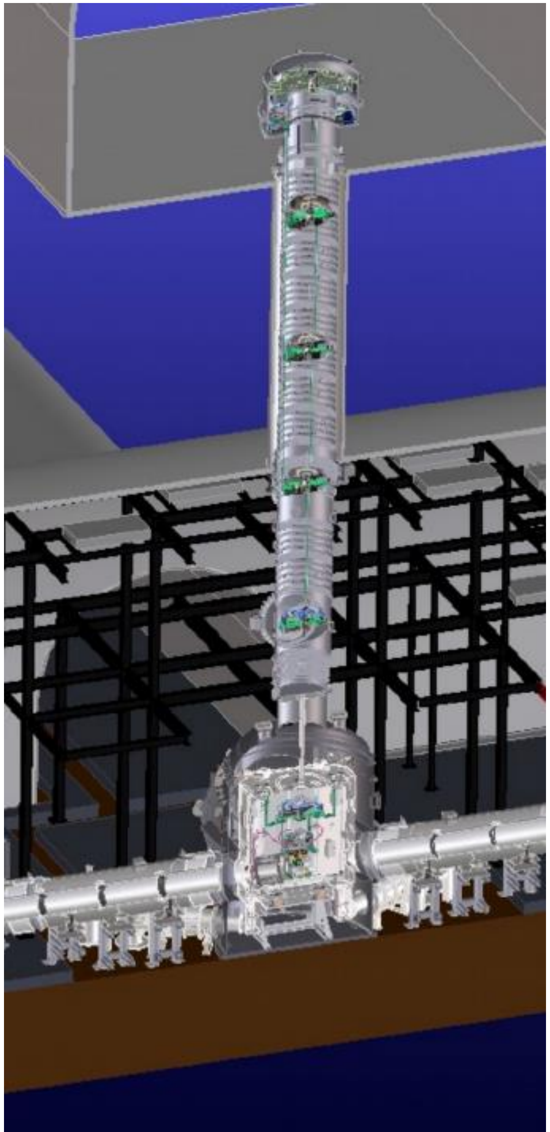


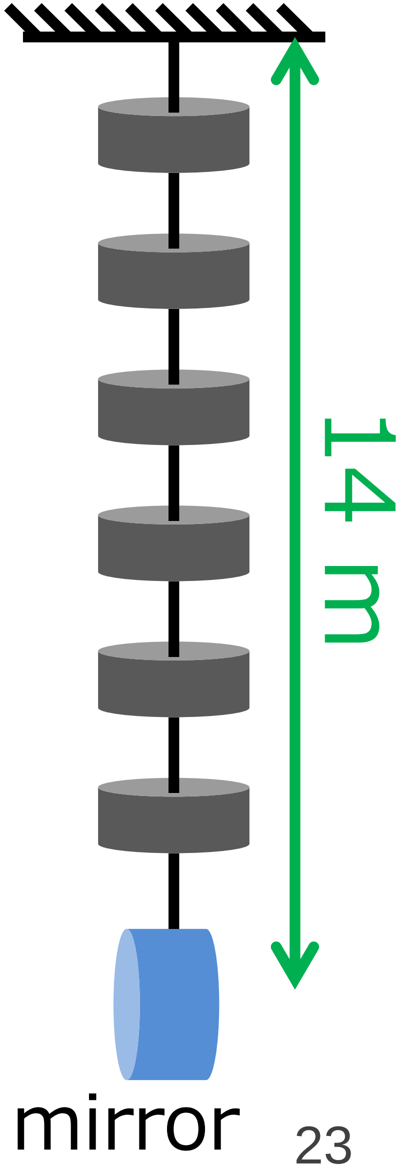
- X-arm completed by January 2019
- Y-arm locked in April 2019
- Y-arm and central part commissioning on-going
- First Engineering Run with X-arm done on June 8, 2019

Test Mass Suspension

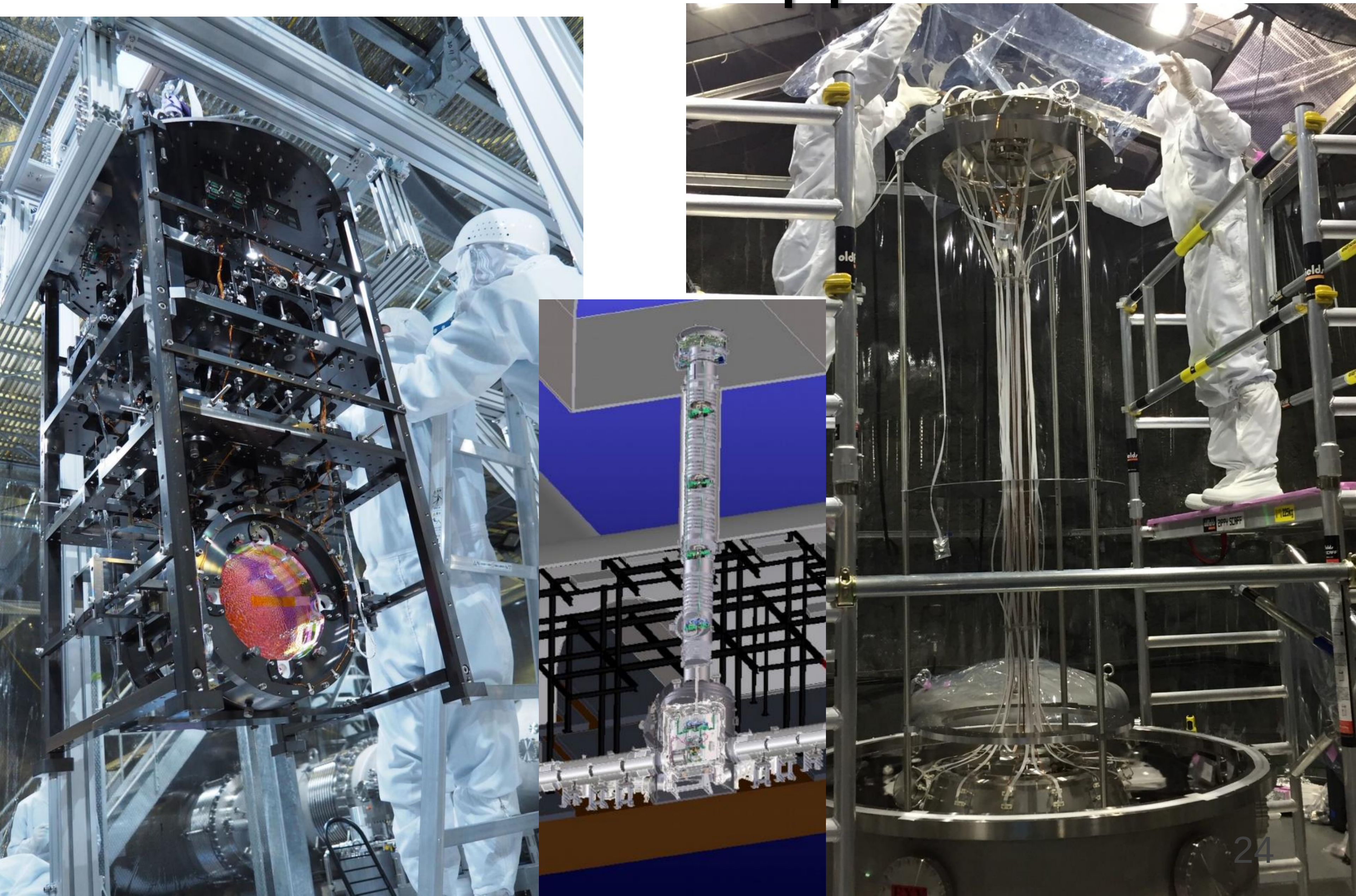
- 7-stage pendulum over two stories



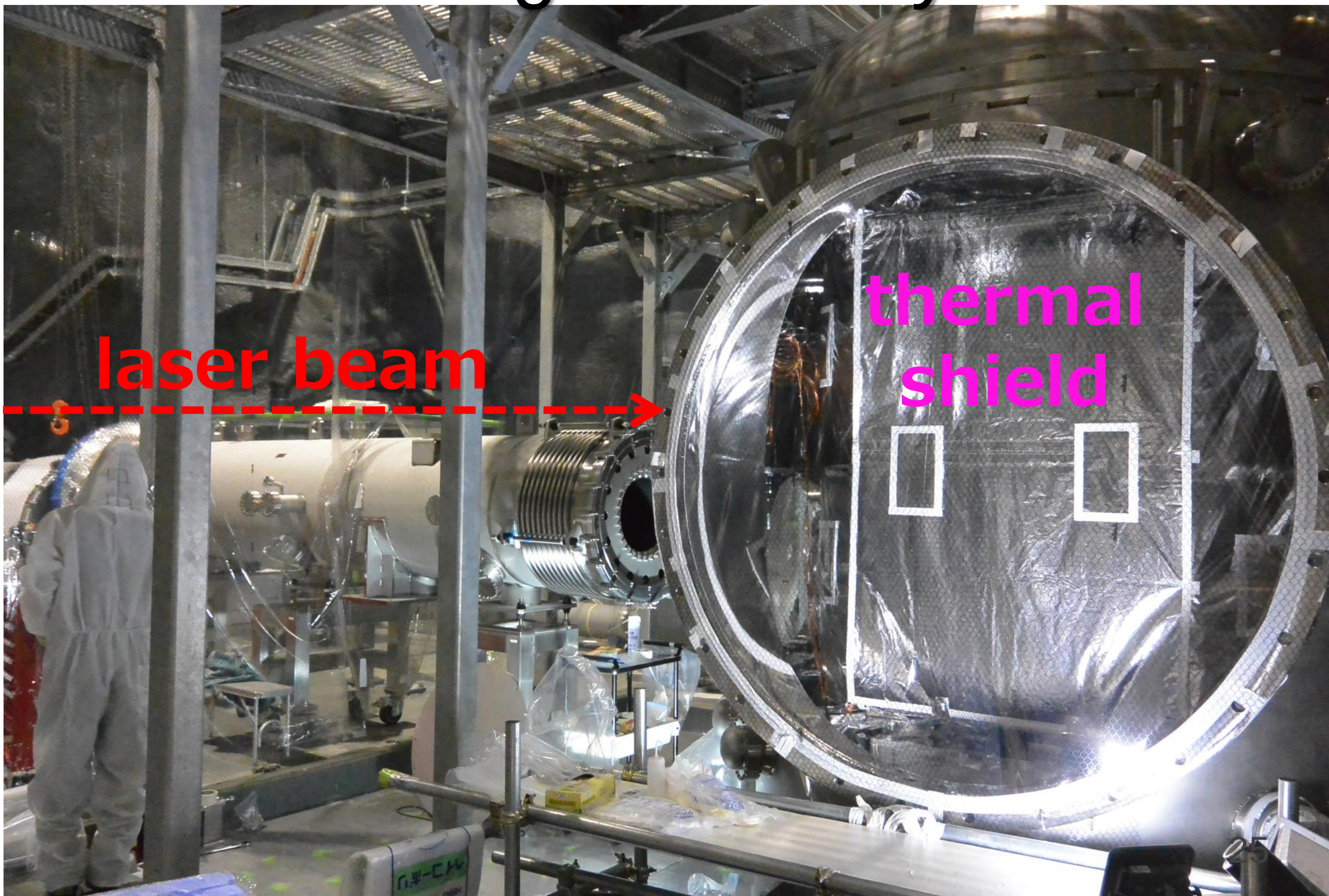




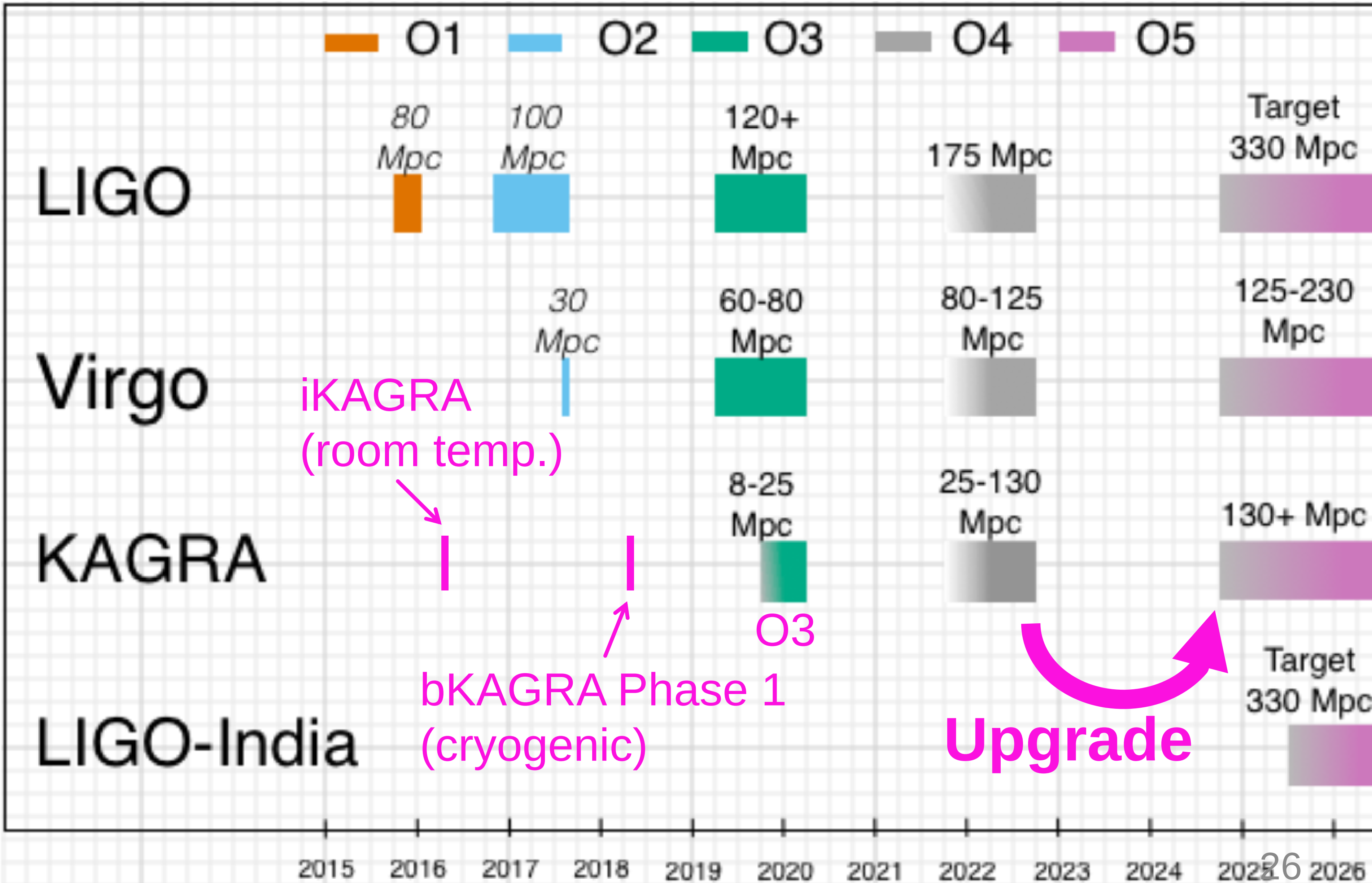
Test Mass Susppension



Shielding Inside Cryostat



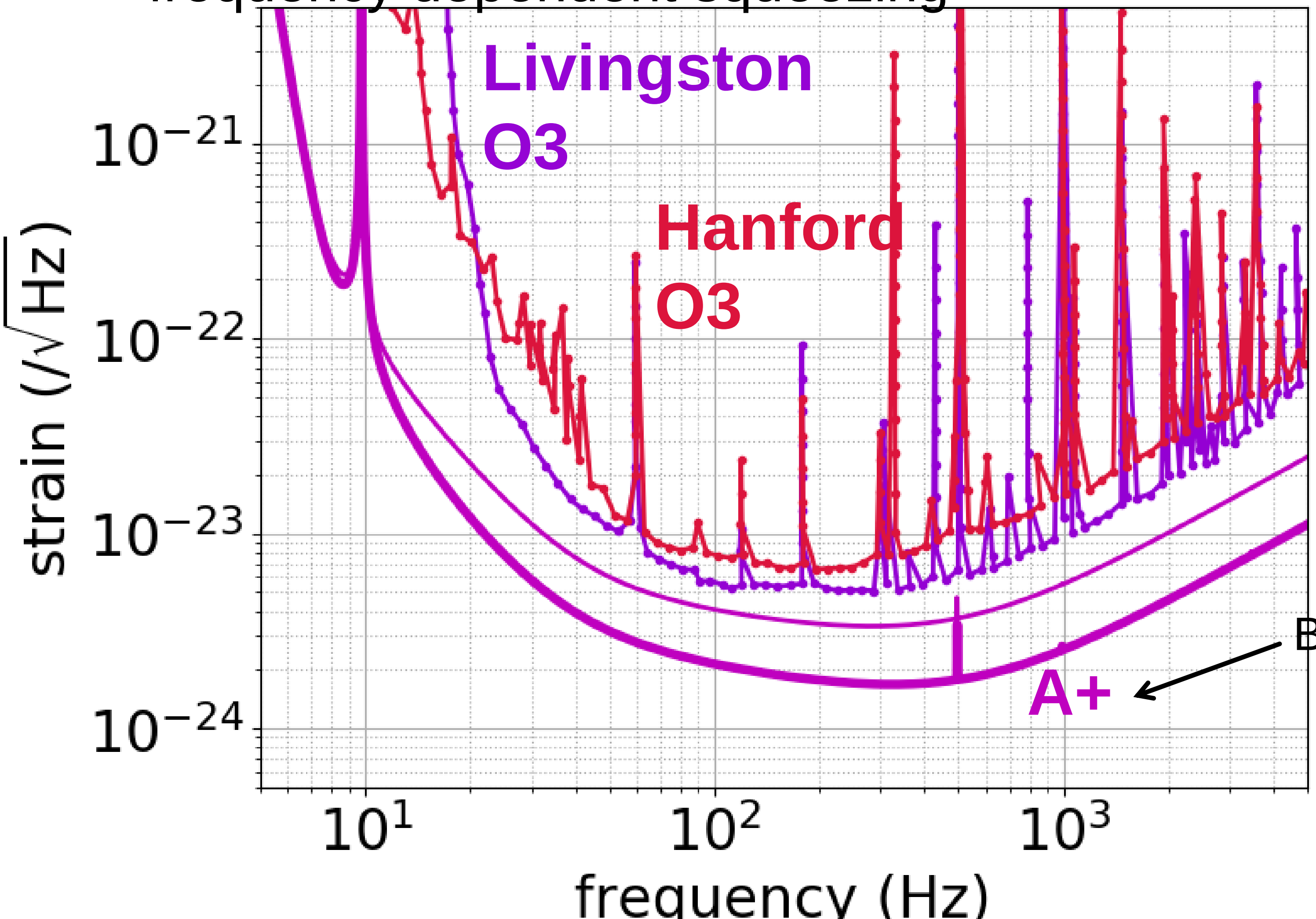
Observation Scenario



Updated version of Living Reviews in Relativity 21, 3 (2018); available from LIGO-P1200087

Advanced LIGO Upgrade: A+

- Reaches 325 Mpc with coating improvement and frequency dependent squeezing

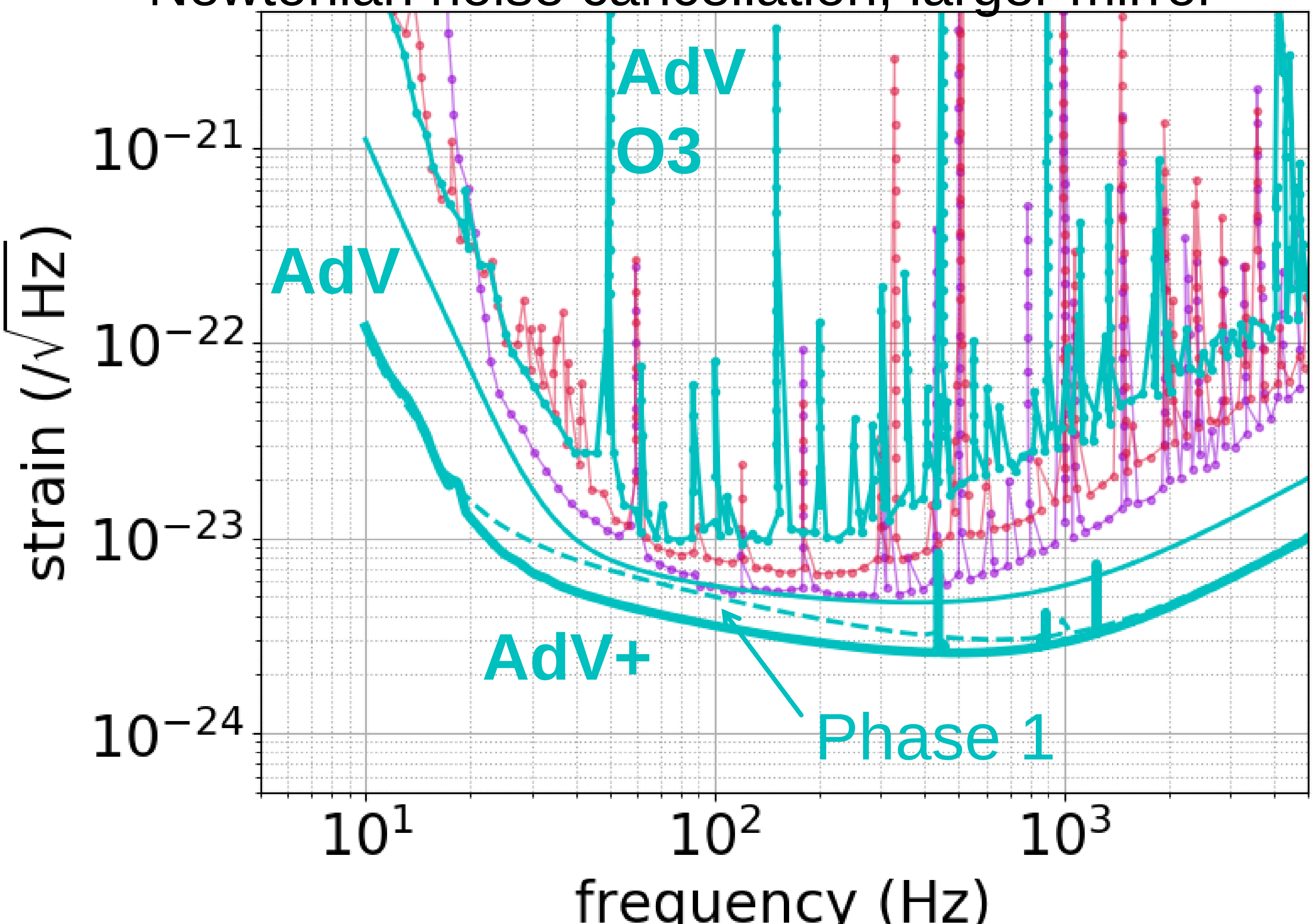


4 km arm
40 kg mirror
Fused silica

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

Advanced Virgo Upgrade: AdV+

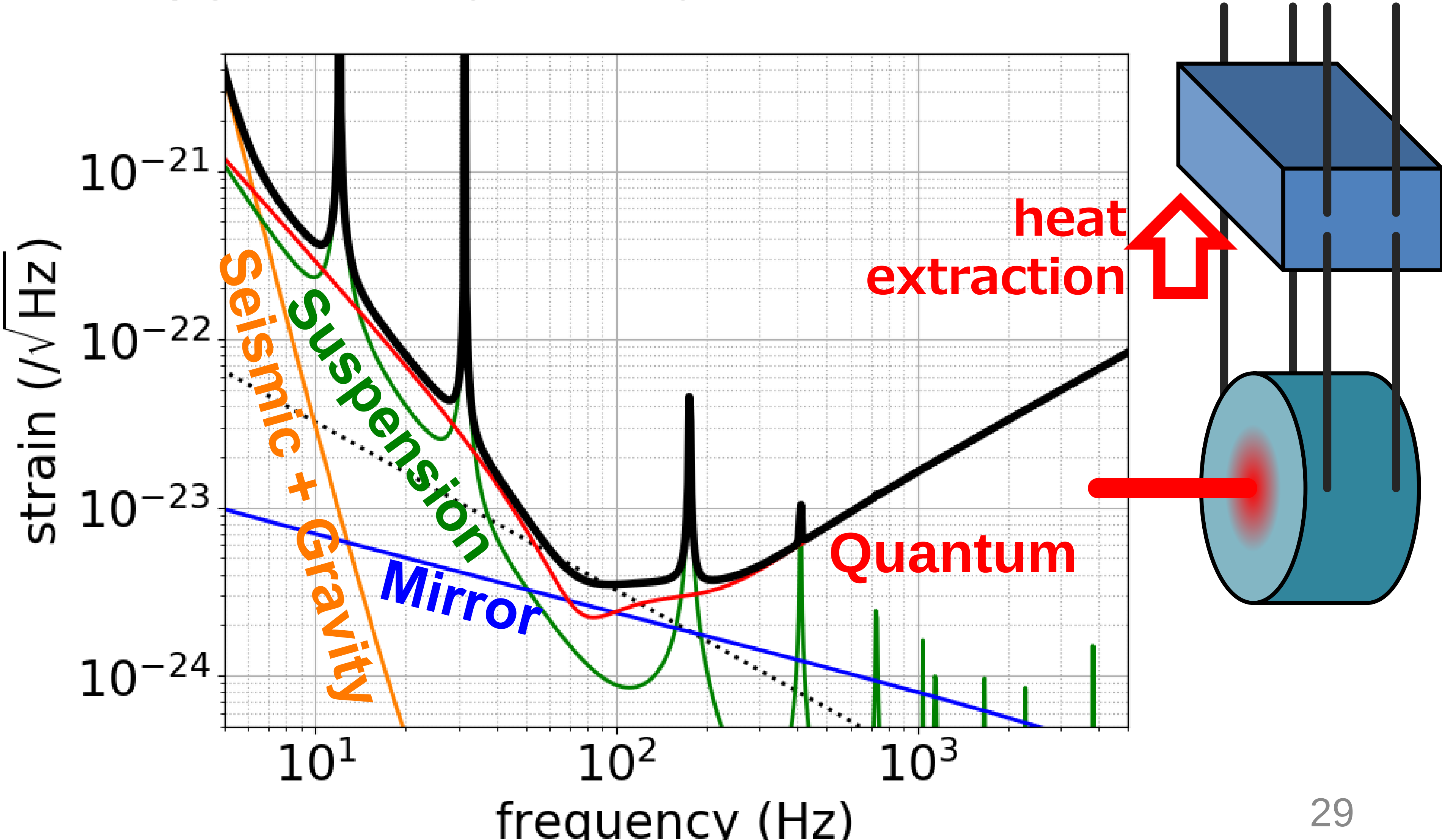
- Reaches 300 Mpc with frequency dependent squeezing, Newtonian noise cancellation, larger mirror



3 km arm
42 kg mirror
Fused silica

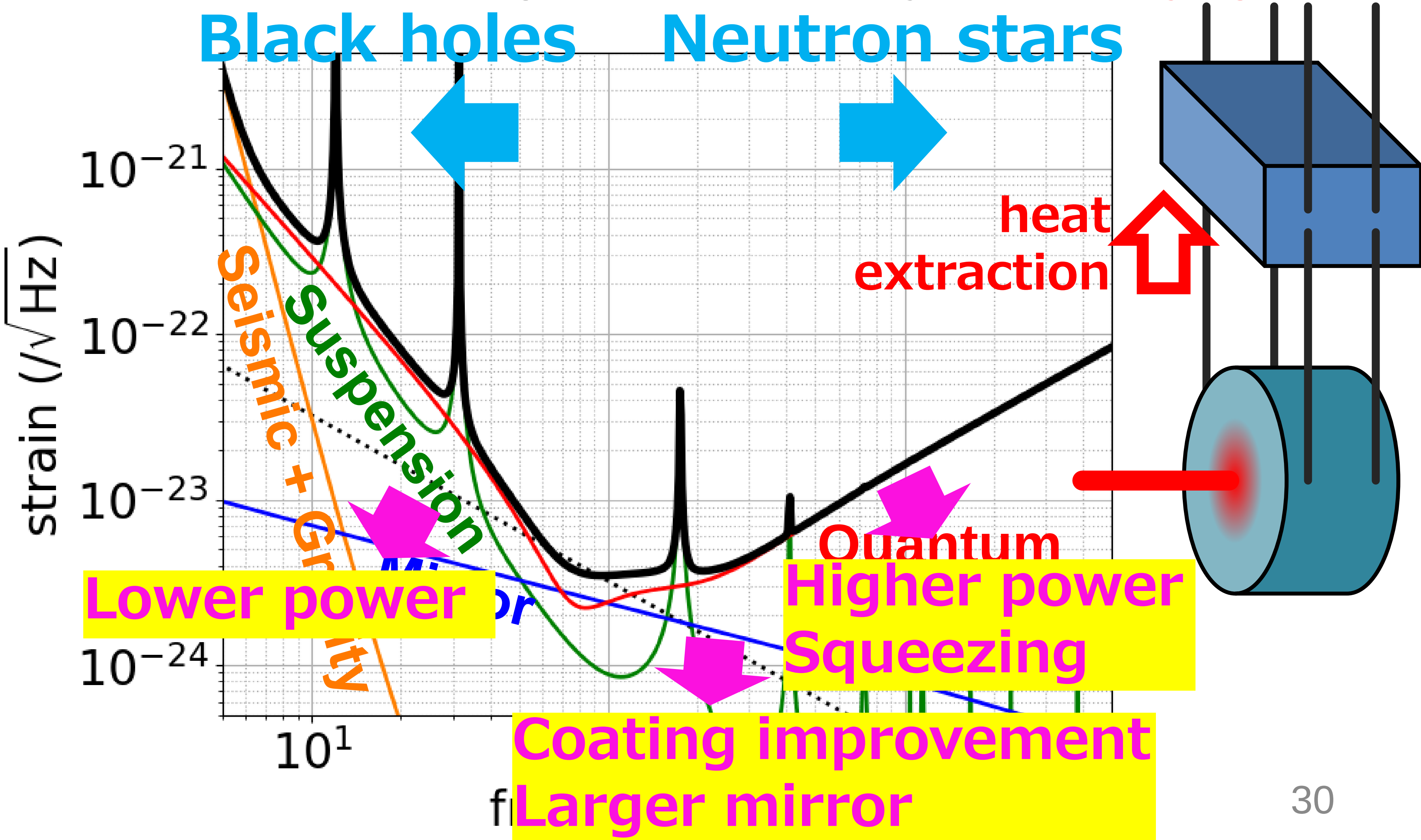
How about KAGRA?

- Upgrade study *formally* started in December 2018



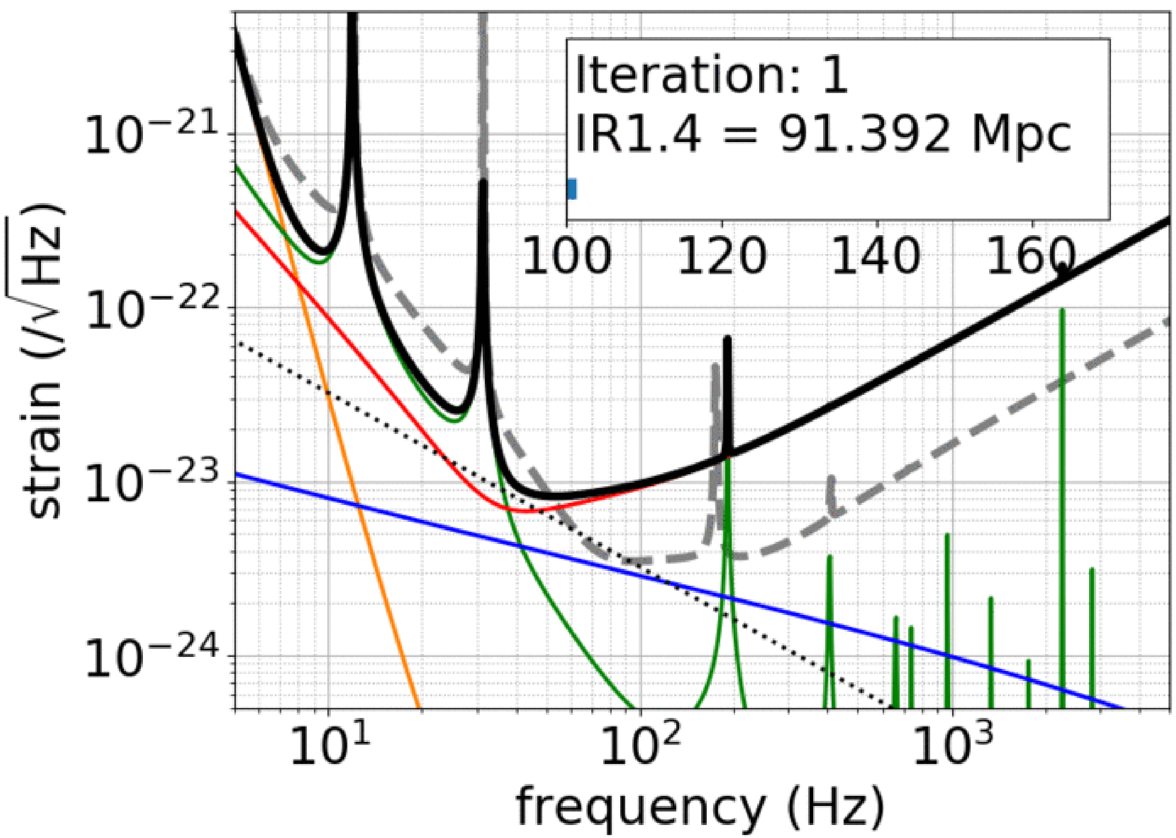
How about KAGRA?

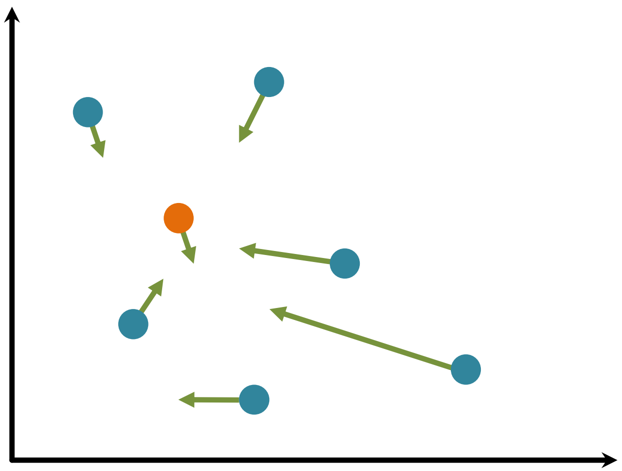
- Different investigation necessary due to cryogenic



Sensitivity Optimization

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

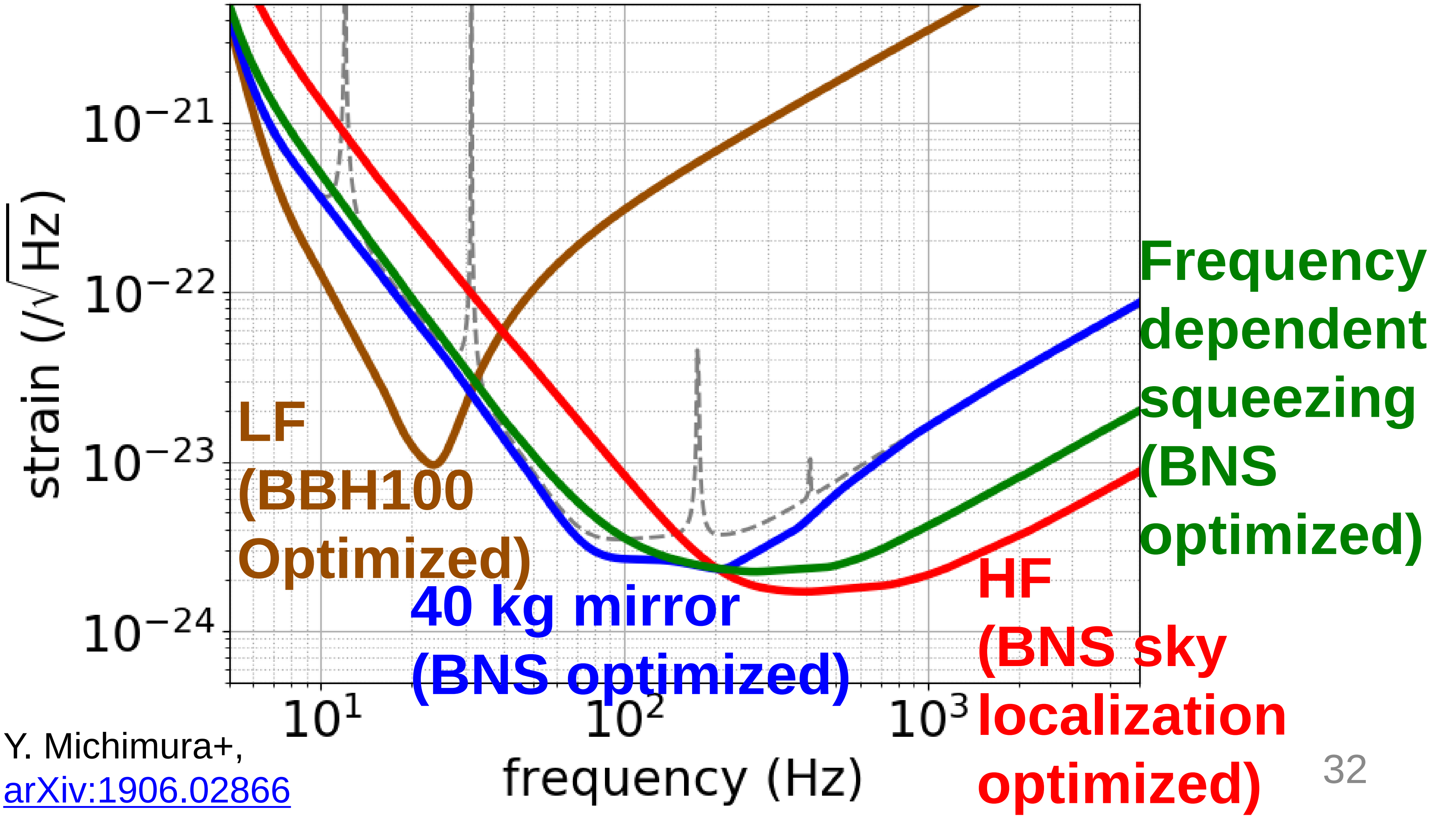




Y. Michimura+,
[PRD 97, 122003 (2018)]

Possible Near Term Upgrade Plans

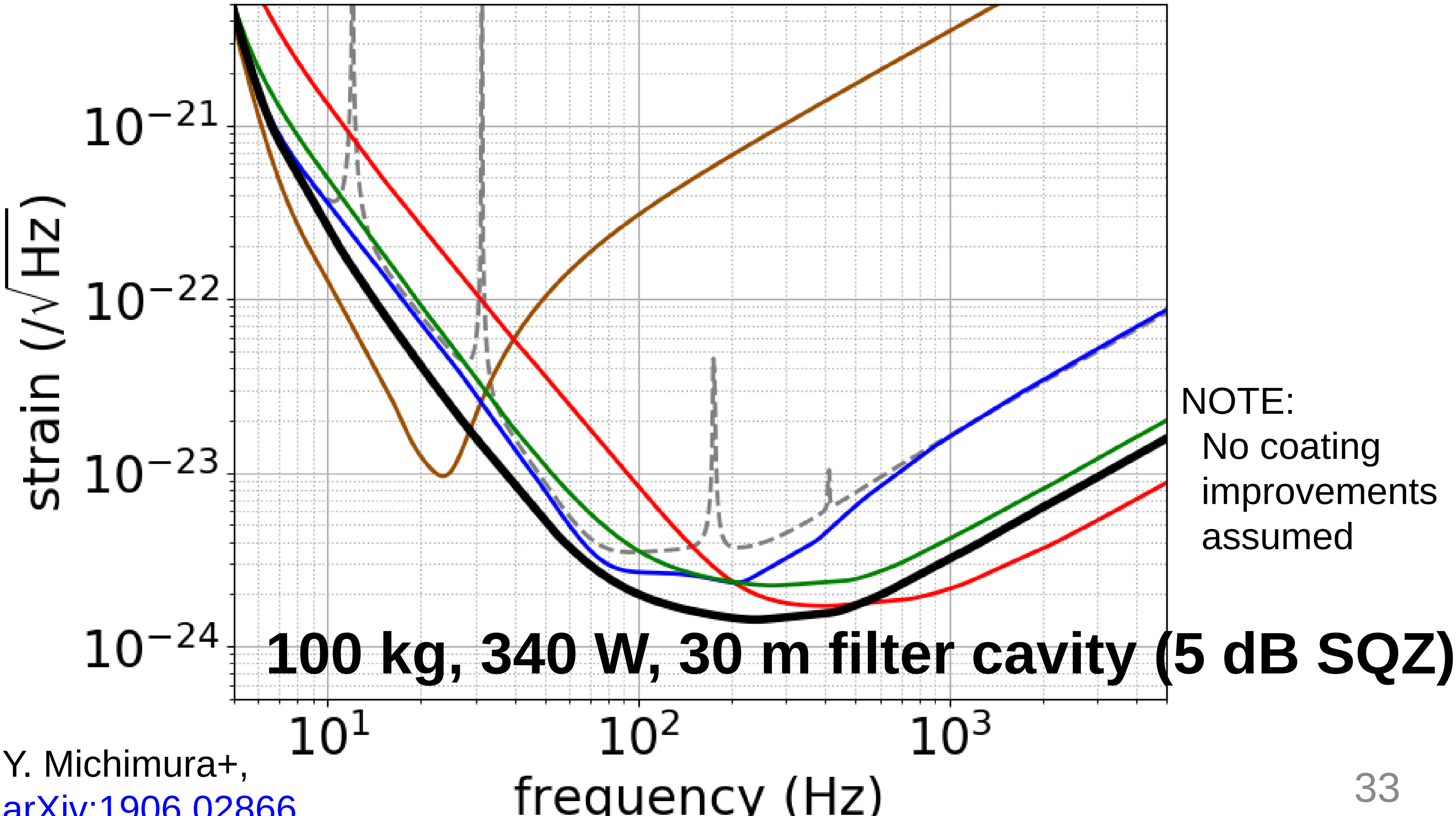
- Based on technical feasibility, facility and budget constraints (~5M USD)



Y. Michimura+, arXiv:1906.02866

Possible Longer Term Upgrade

- Reaches BNS range of 300 Mpc by combining technologies (~20M USD)

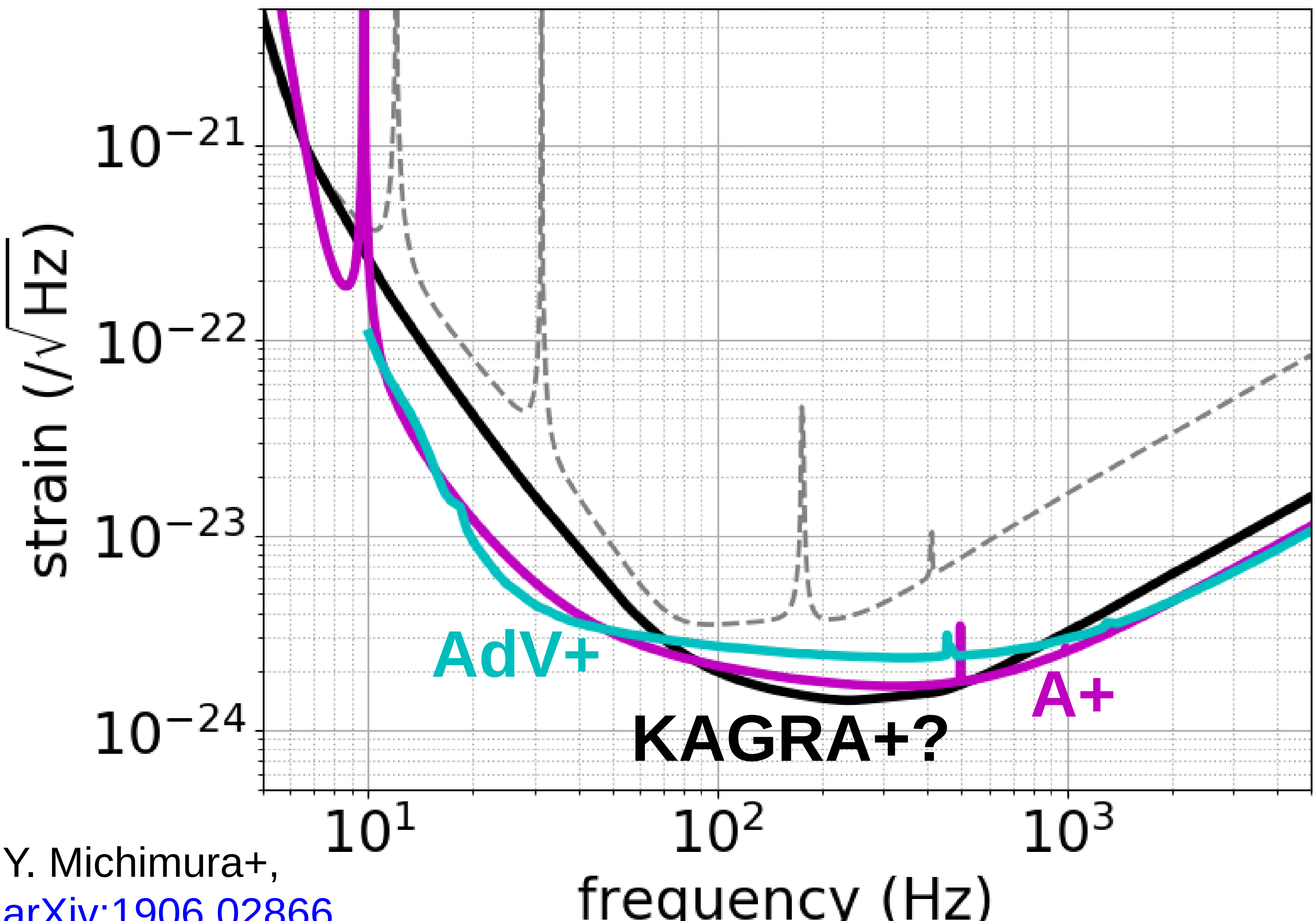


NOTE:
No coating improvements assumed

Y. Michimura+, arXiv:1906.02866

Possible Longer Term Upgrade

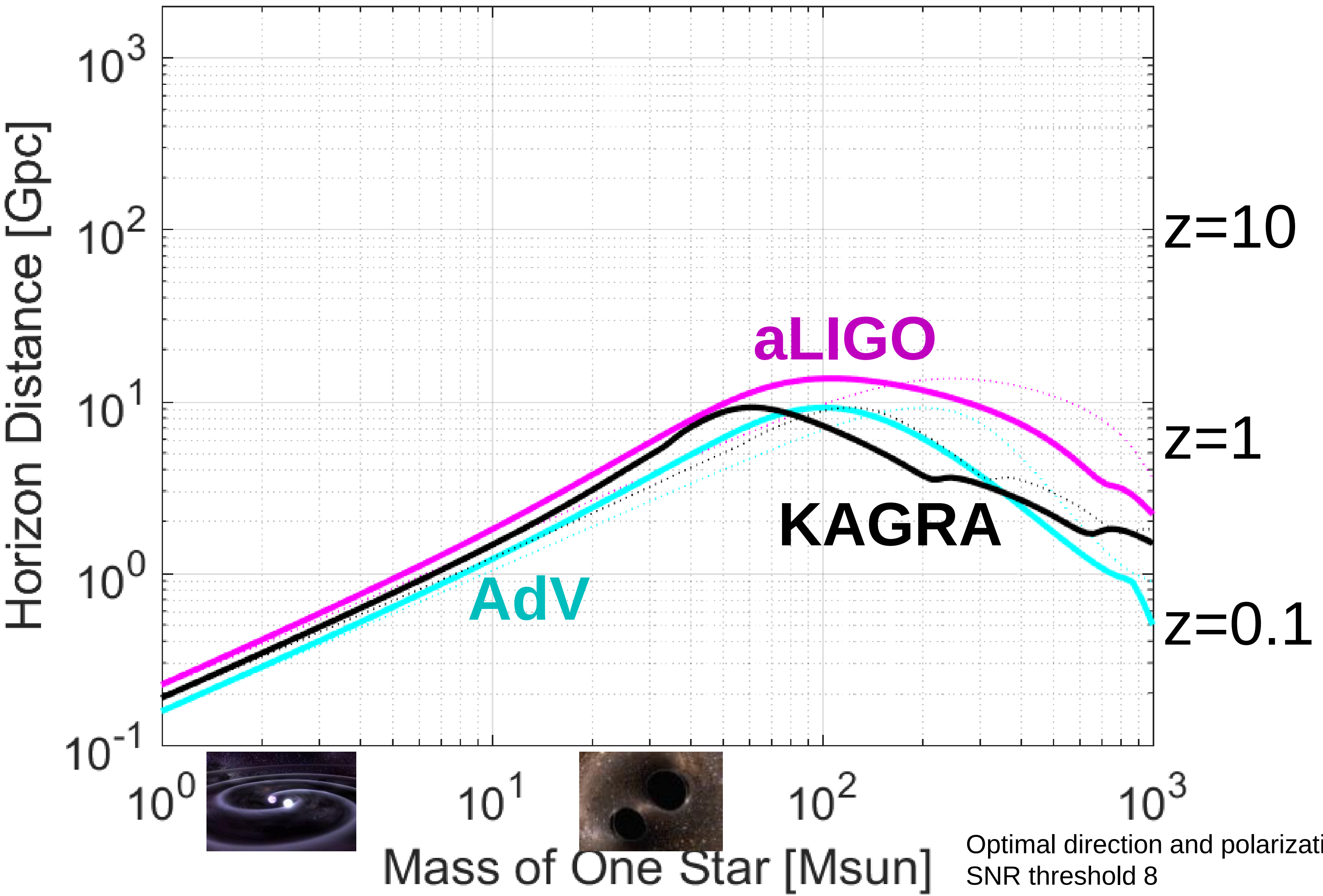
- Comparable to A+ (325 Mpc) and AdV+ (300 Mpc)



Y. Michimura+, arXiv:1906.02866

Horizon Distance Comparison

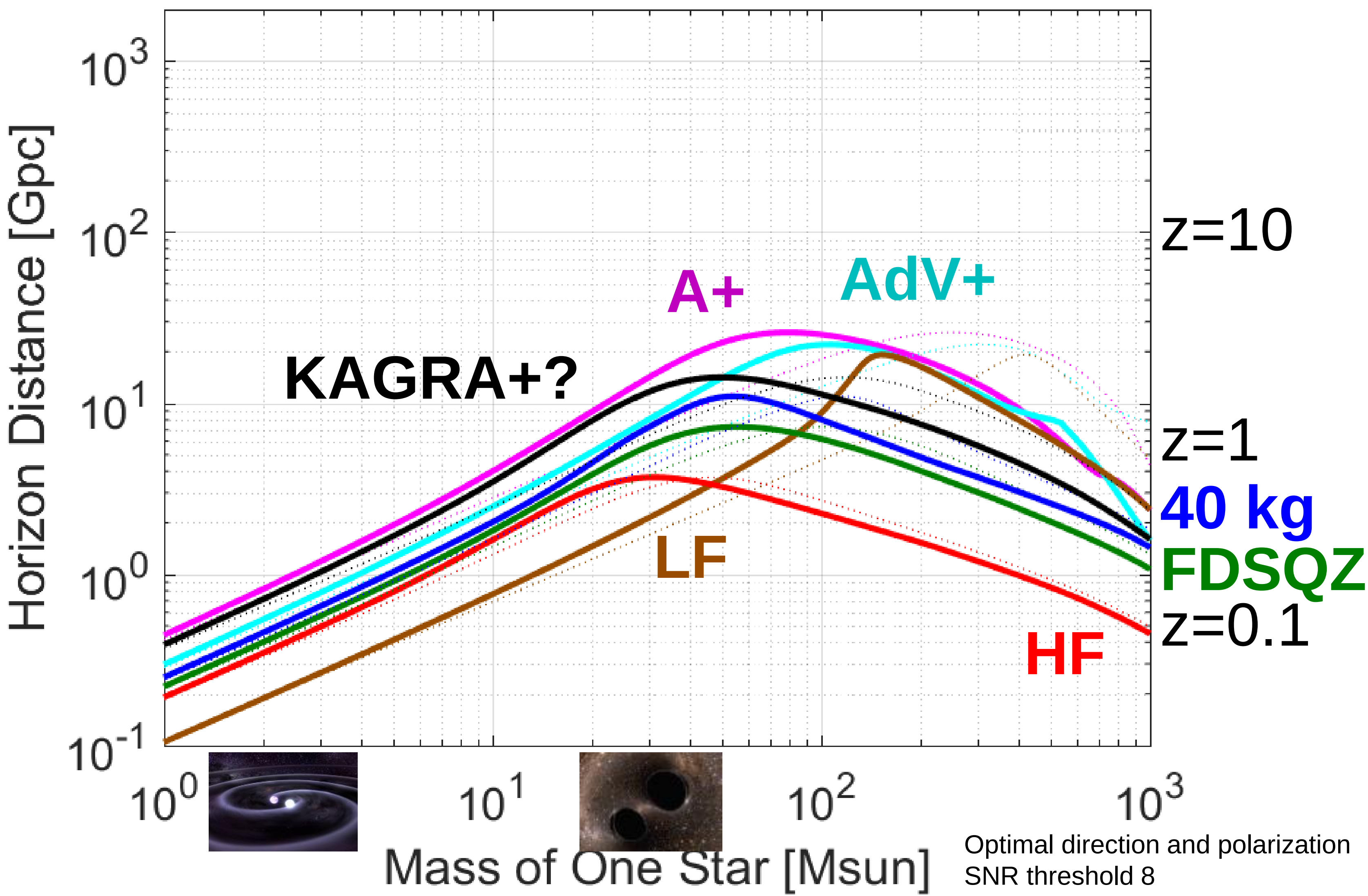
- O(10^2) events/year with designed sensitivity (~2021)



Optimal direction and polarization
SNR threshold 8

Horizon Distance Comparison

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



Science Targets for Each Bands

- Low frequency

  IMBHs and their spectroscopy

  (Stochastic GW background, cosmic string)

- Broadband

  Test of gravity

  Formation scenario of stellar-mass BBHs

  Multi-messenger observations

  Hubble constant

  (Supernovae and X-ray binaries)

- High frequency

  NS physics (EOS, post-merger, ejecta)

  Multi-messenger observations

  Hubble constant

  BH spectroscopy with stellar-mass BBHs

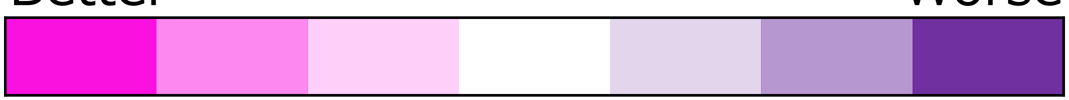
  (Isolated pulsars and magnetors)

(Selected) Science Comparison

- Sensitivity improvement in different bands give different science cases

	LF	40kg	FDSQZ	HF	Longer
IMBH event rate					
NS event rate					
NS tidal deformability					
Hubble constant by BBH					
Hubble constant by BNS					
GW polarization test					
Stellar-mass BH spectroscopy					
IMBH spectroscopy					

Better Worse



+100% +50% +15% -15% -50% -100%

* Compared with bKAGRA, assumed A+ and AdV+ Network

* Summarized by A. Nishizawa *et al.* JGW-G1909934

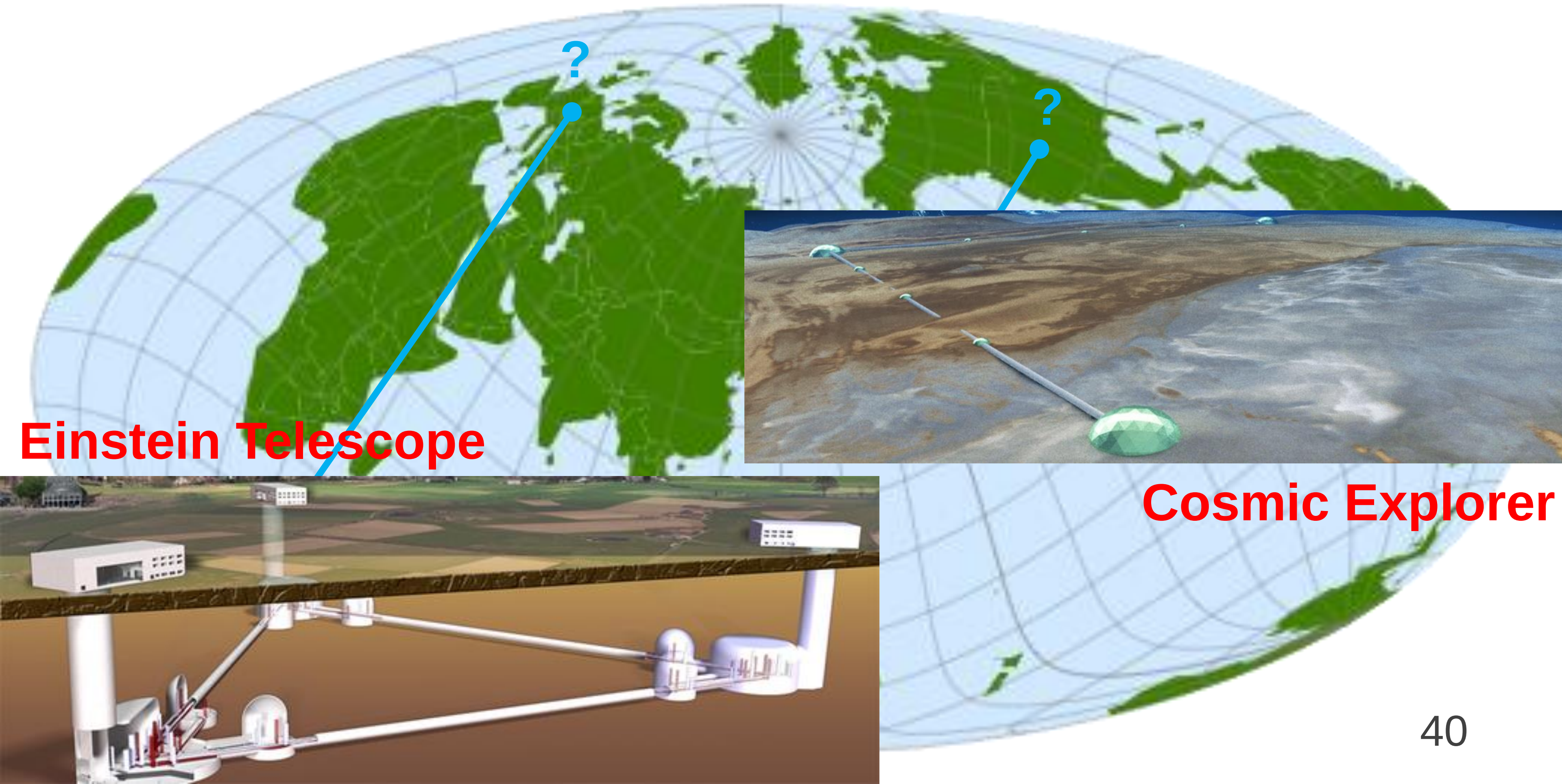
Effective Progression of Upgrades?

- **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

Next Generation Detectors

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



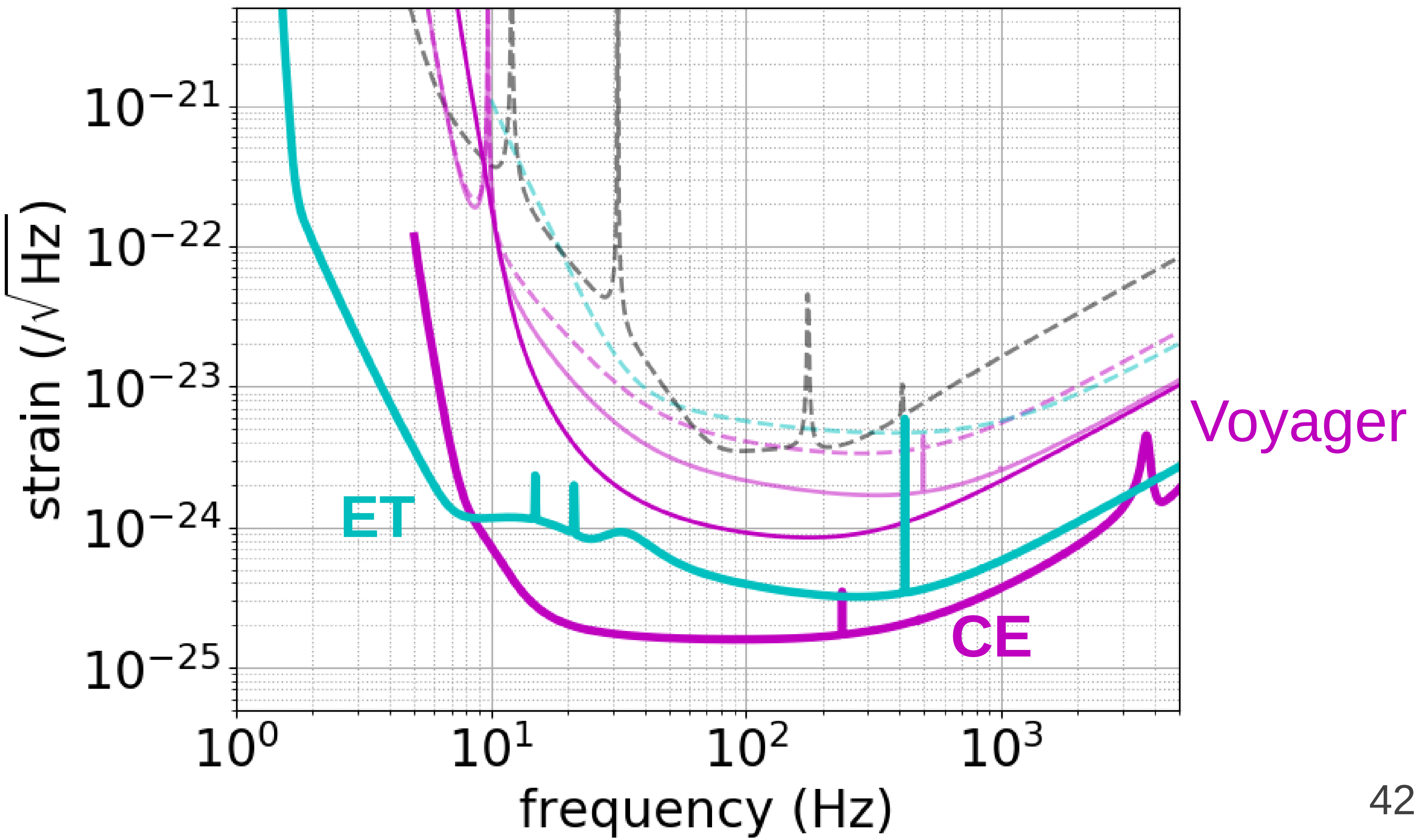
Next Generation Detectors

- 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

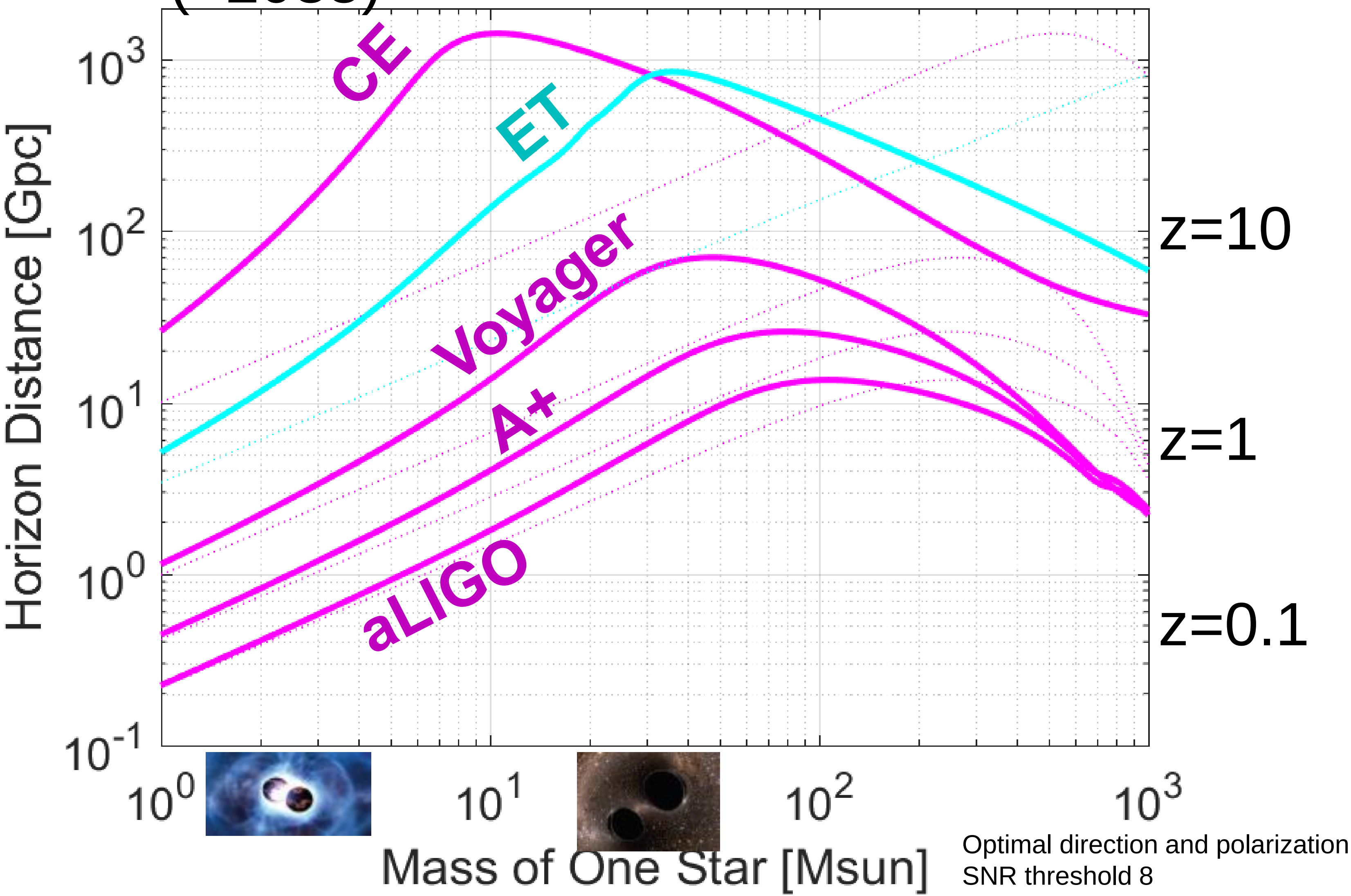
Sensitivity of Next Generations

- An order of magnitude improvement



Horizon Distance

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



Summary

- KAGRA is an underground cryogenic GW detector pioneering technologies for 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 (300 Mpc in BNS range) is feasible for KAGRA

Slides Available Online

1. Laser Interferometers (July 25 PM)
   https://tinyurl.com/YM20190725-1
2. Quantum Noise (July 25 PM)
   https://tinyurl.com/YM20190725-2
3. Sensitivity Design (July 26 AM)
   https://tinyurl.com/YM20190725-3
4. Status of KAGRA (July 26 AM)
   https://tinyurl.com/YM20190725-4

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)

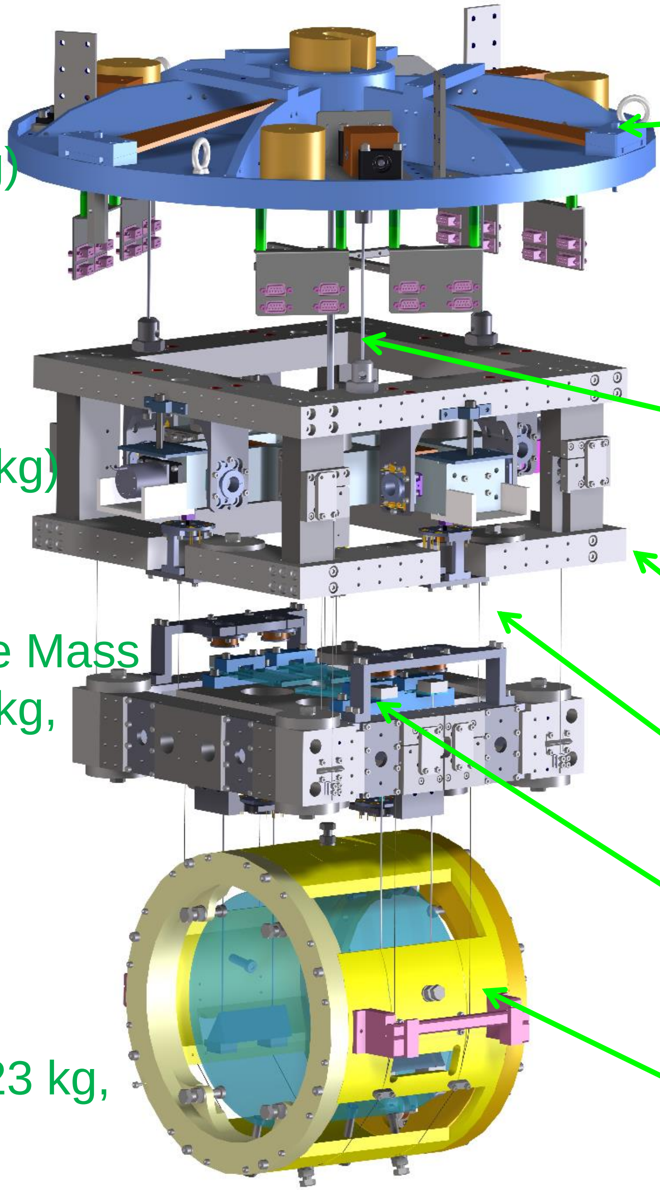
KAGRA Detailed Parameters

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)

Marionette
(SUS, 22.5 kg)

Intermediate Mass
(SUS, 20.1 kg,
16 K)

Test Mass
(Sapphire, 23 kg,
22 K)

3 CuBe blade springs

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

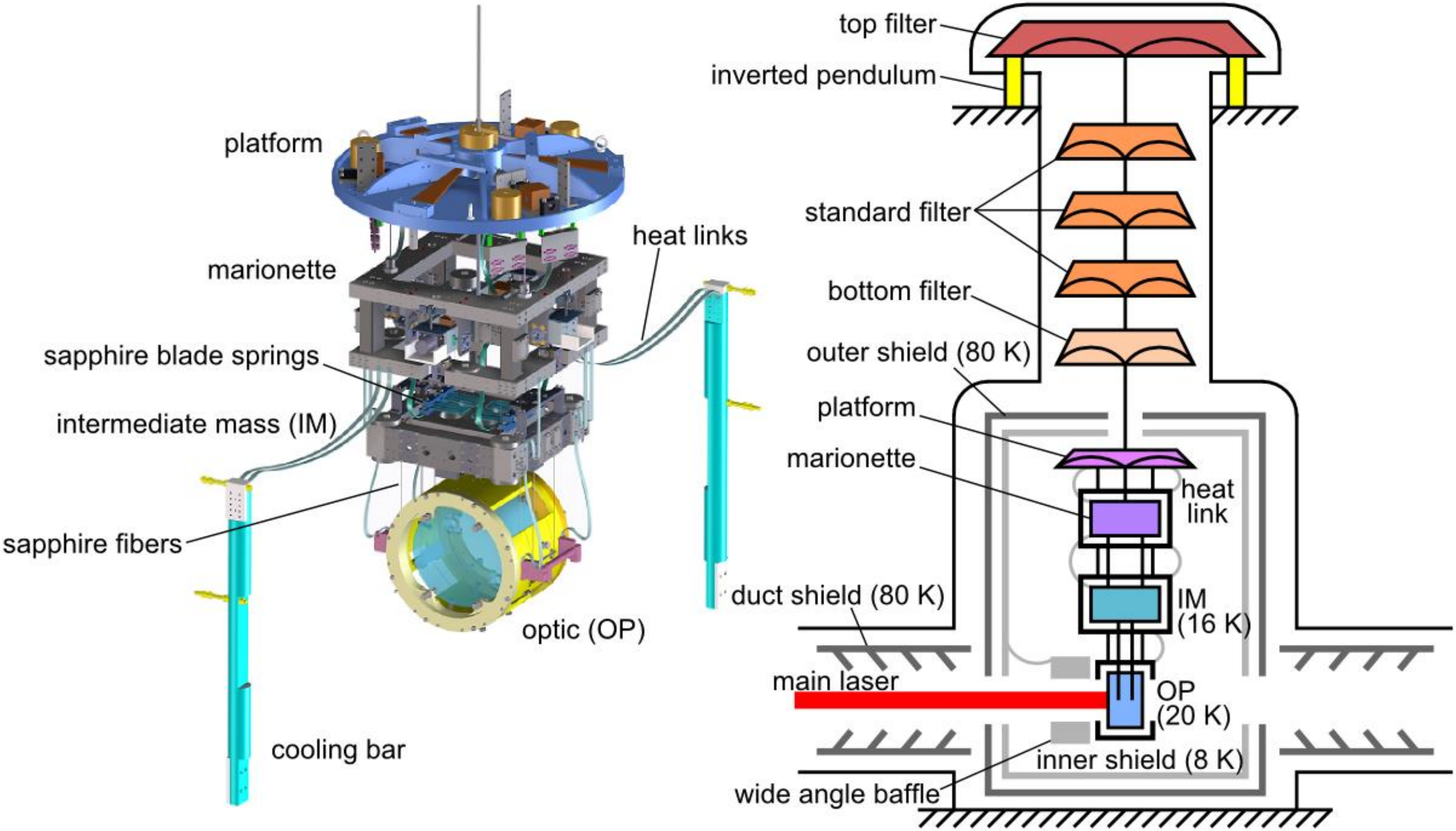
Heat link attached to MN

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

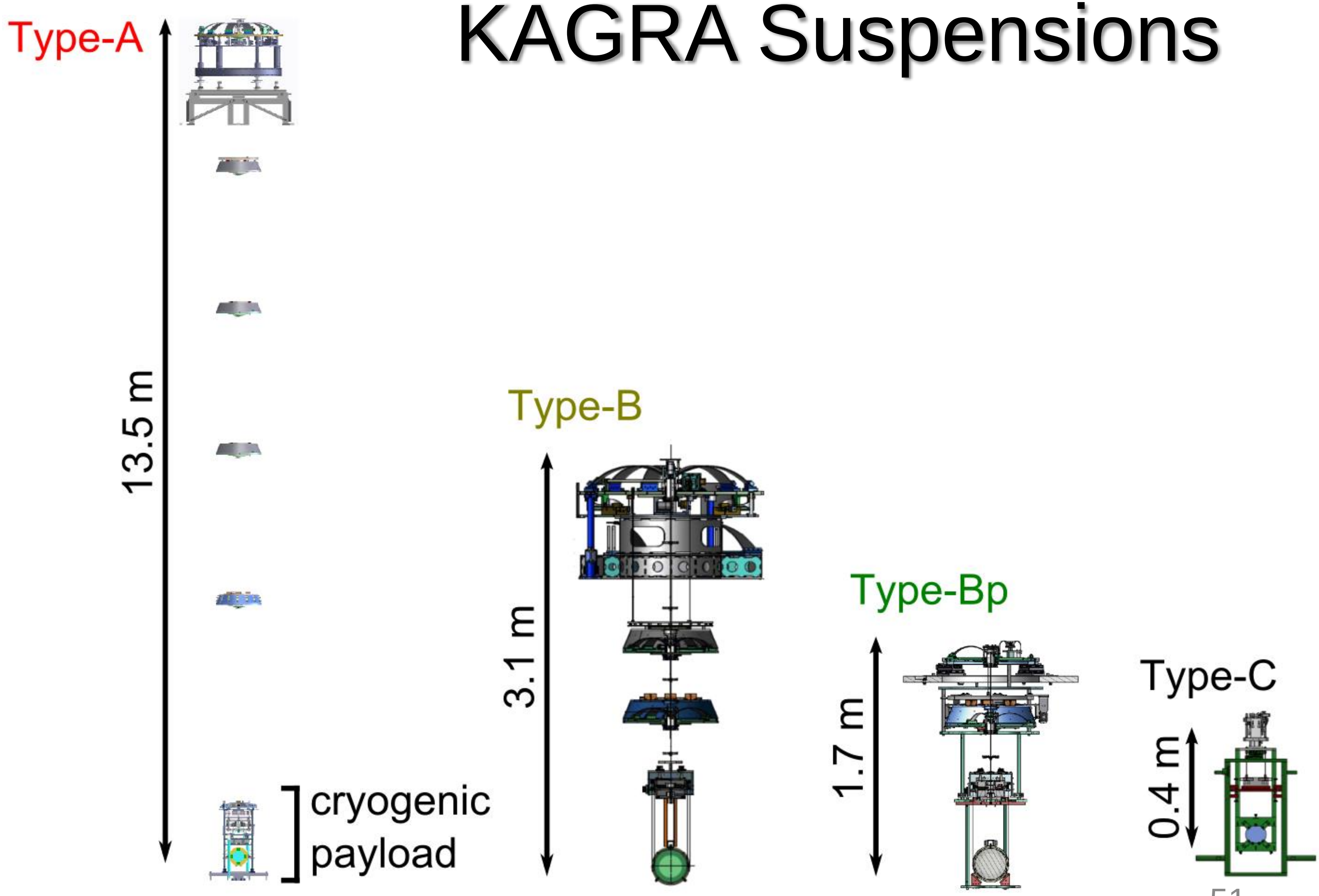
4 sapphire blades

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

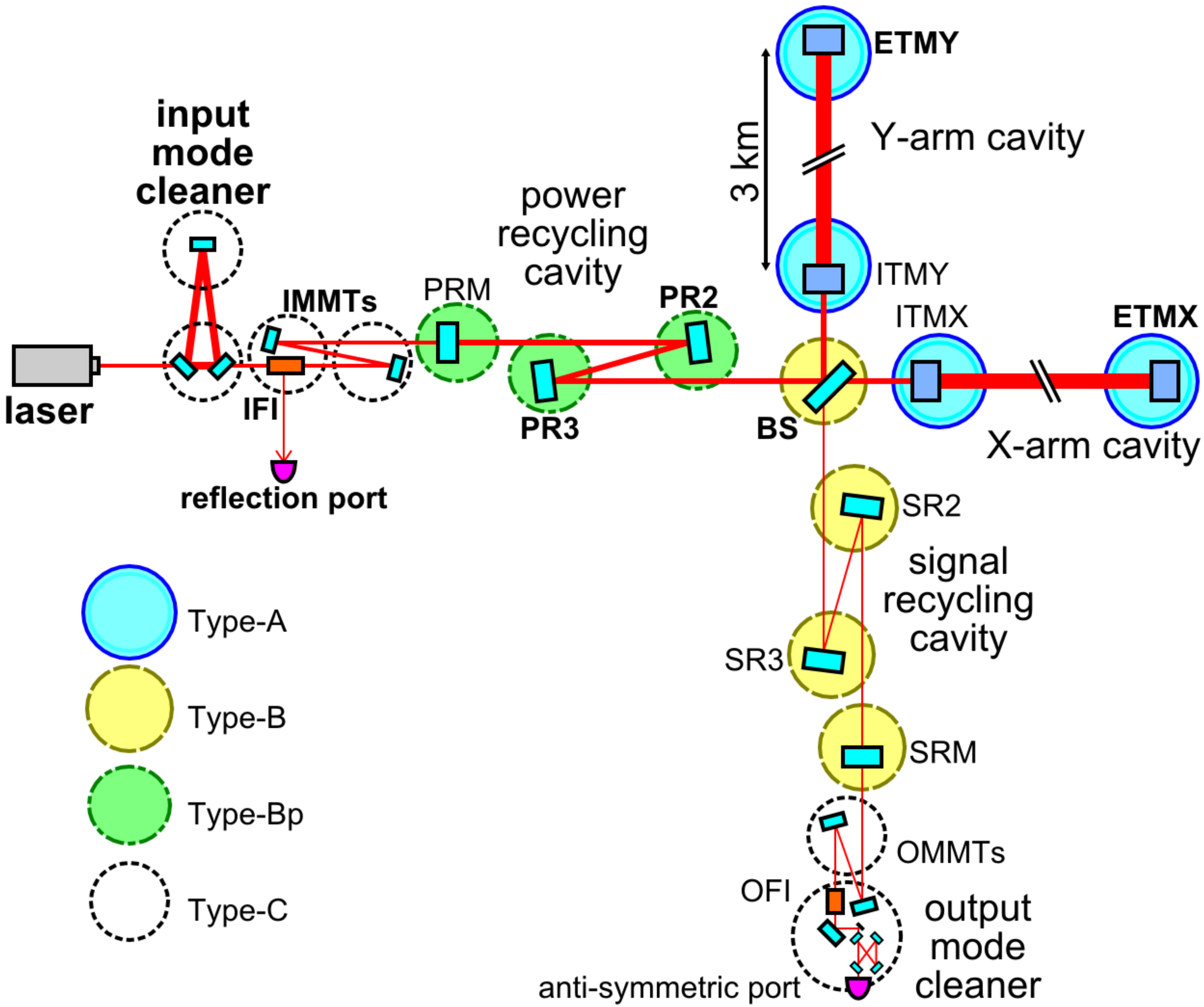
KAGRA Cryostat Schematic



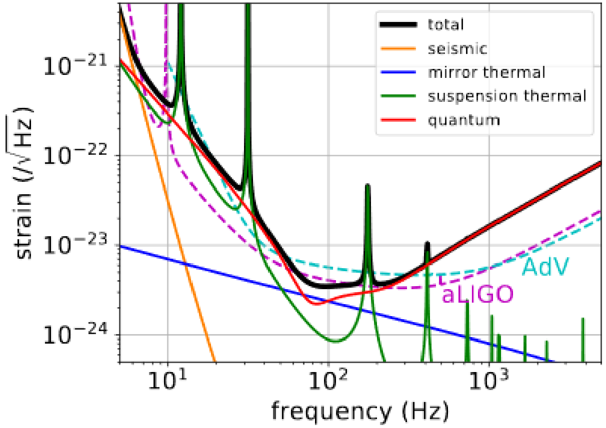
KAGRA Suspensions



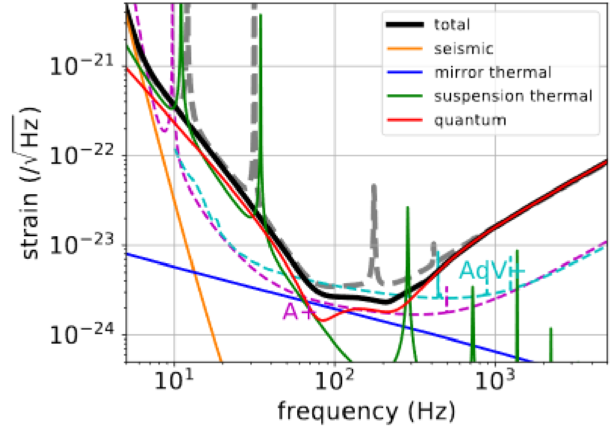
KAGRA Interferometer



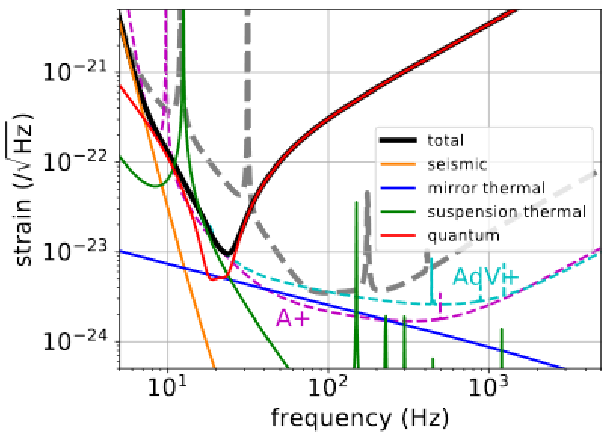
Possible KAGRA Upgrade Plans



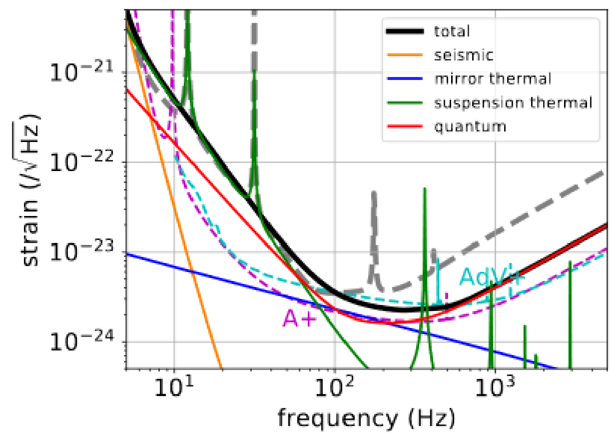
(a) bKAGRA



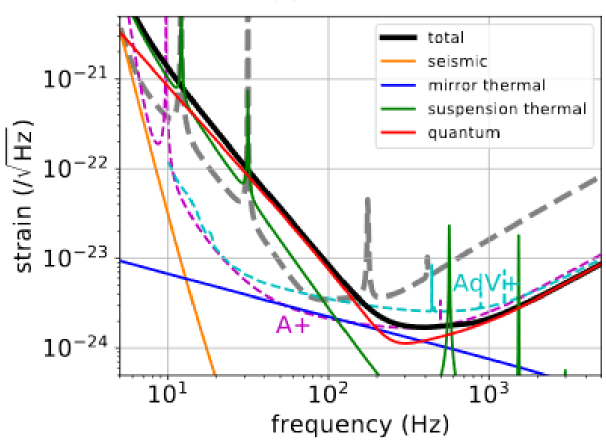
(d) 40kg



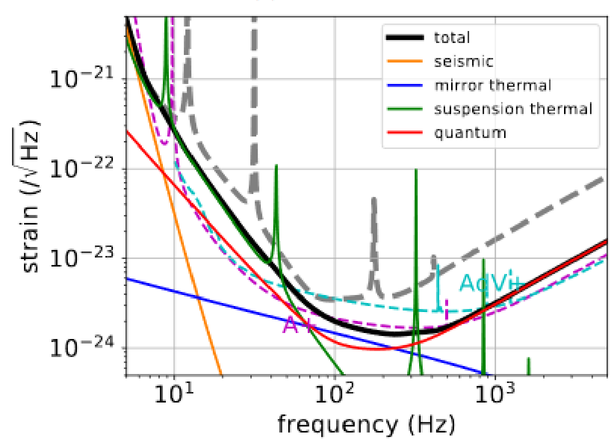
(b) LF



(e) FDSQZ



(c) HF



(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