Amaldi 13 @ Valencia, Spain

July 10, 2019

Prospects for upgrading the KAGRA gravitational wave telescope

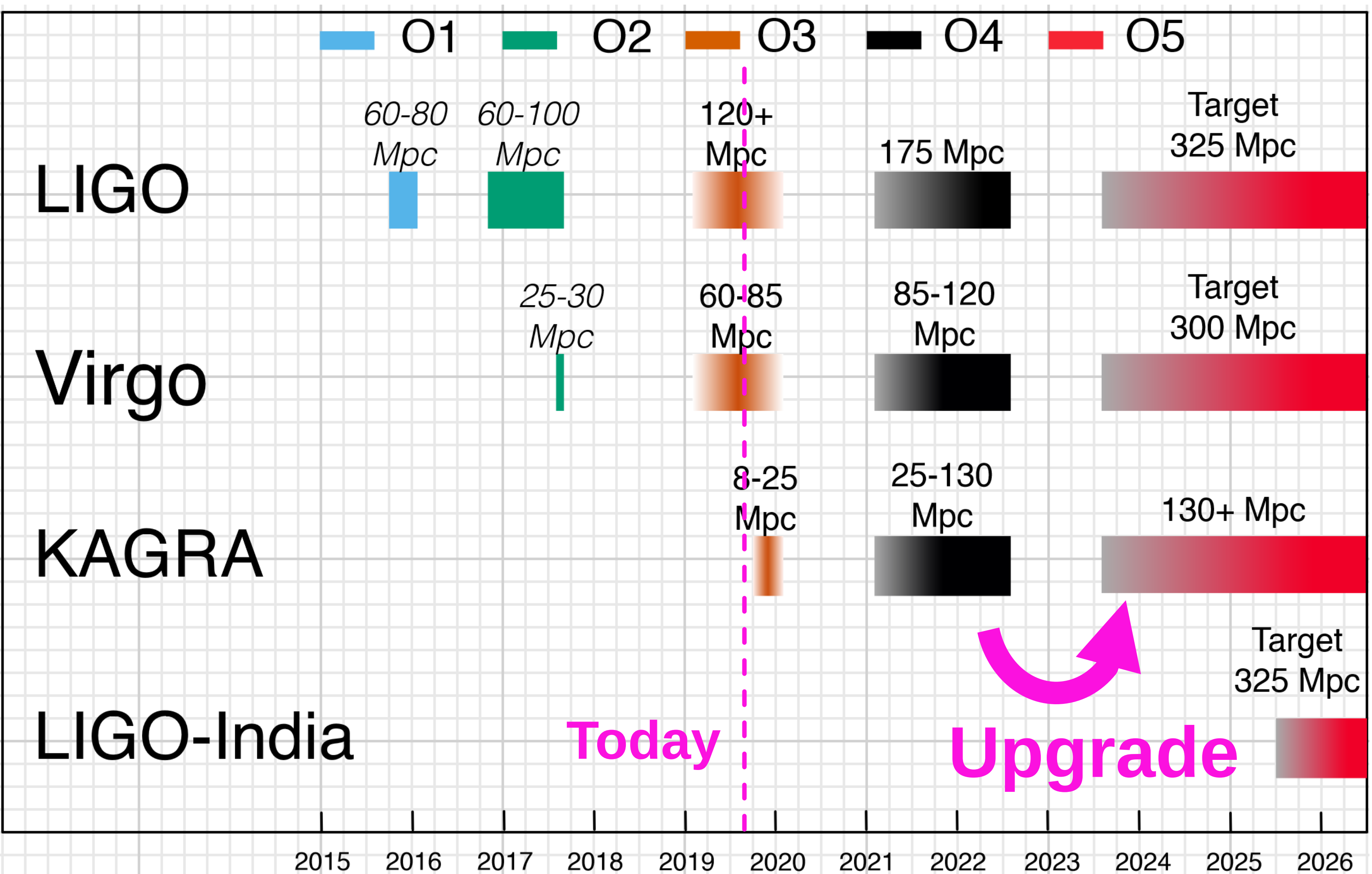
Yuta Michimura

Department of Physics, University of Tokyo

for the KAGRA Collaboration

Upgrading Current GW Detectors

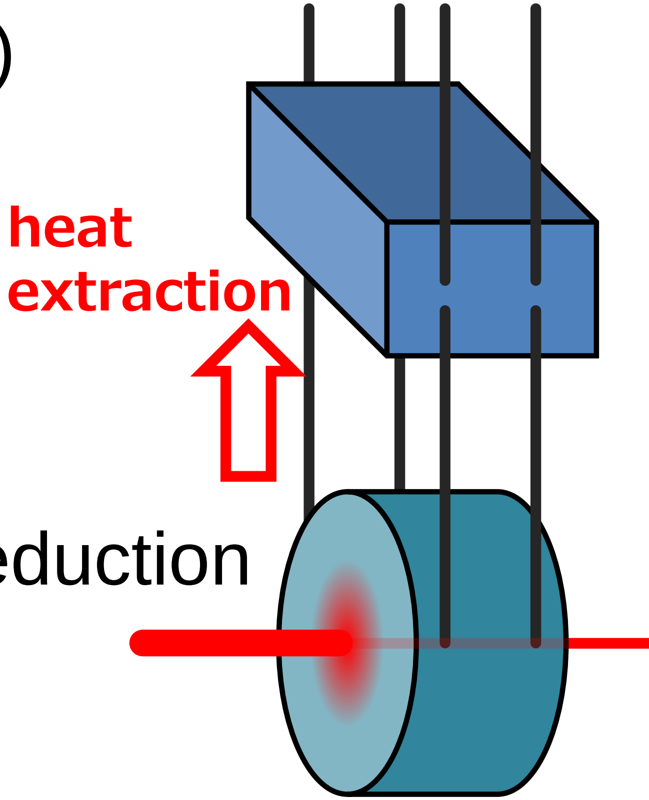
- Sensitivity improvements allow more detections and more precise source parameter estimation



NOTE that this scenario is to be updated (extend O3, ~1year delay of O4 and O5)

Upgrading KAGRA is Tricky

- Only cryogenic interferometer among 2G
- Not trivial to do both
  - high power (400 kW on mirror)
  - low temperature (20 K)



- Sapphire fibers to extract heat

  thinner and longer
  for suspension thermal noise reduction

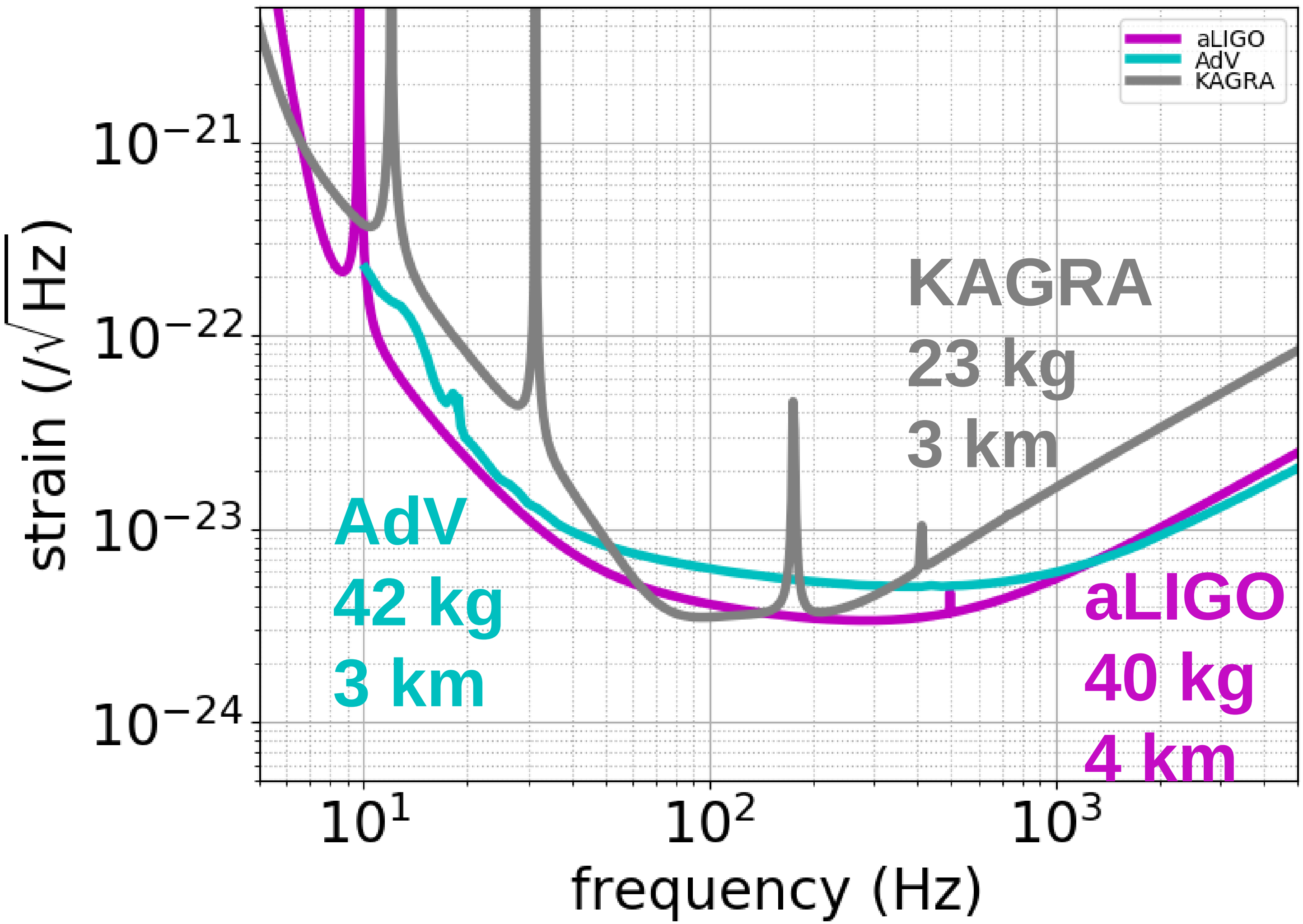
  ↕ **Dilemma**

  thicker and shorter
  for heat extraction

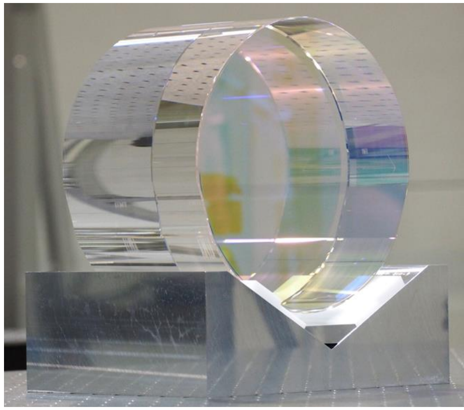
Y. Michimura+, PRD **97**, 122003 (2018)

2G Sensitivity Comparison

- Not good at low freq. because of thick and short fiber (35 cm, φ1.6 mm) to extract heat, and lower mass

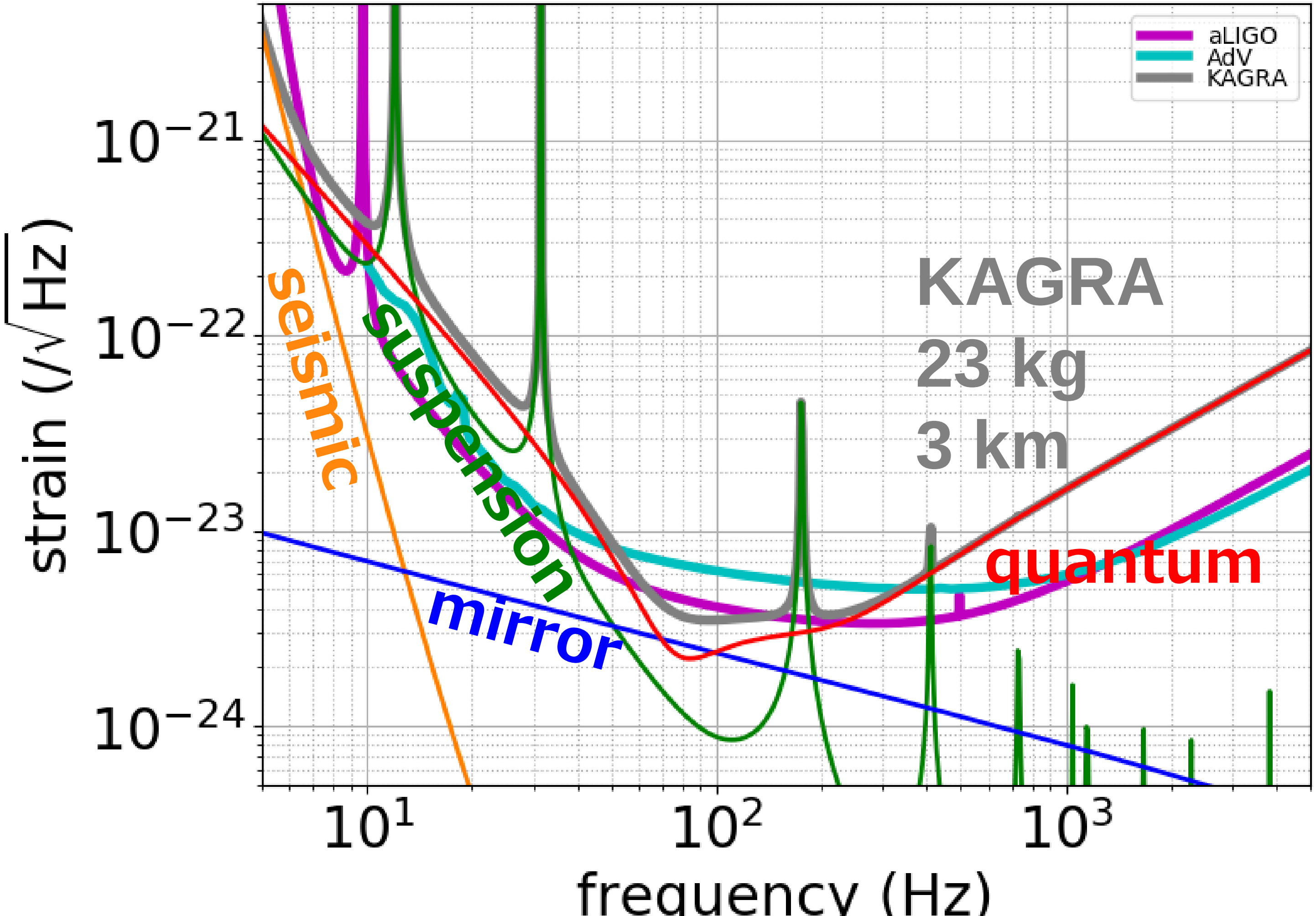


23 kg was the largest available sapphire mirror

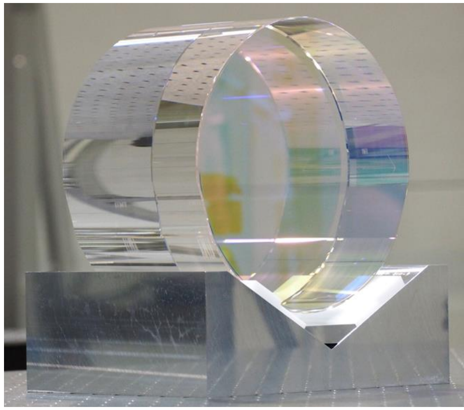


2G Sensitivity Comparison

- Not good at low freq. because of thick and short fiber (35 cm, φ1.6 mm) to extract heat, and lower mass

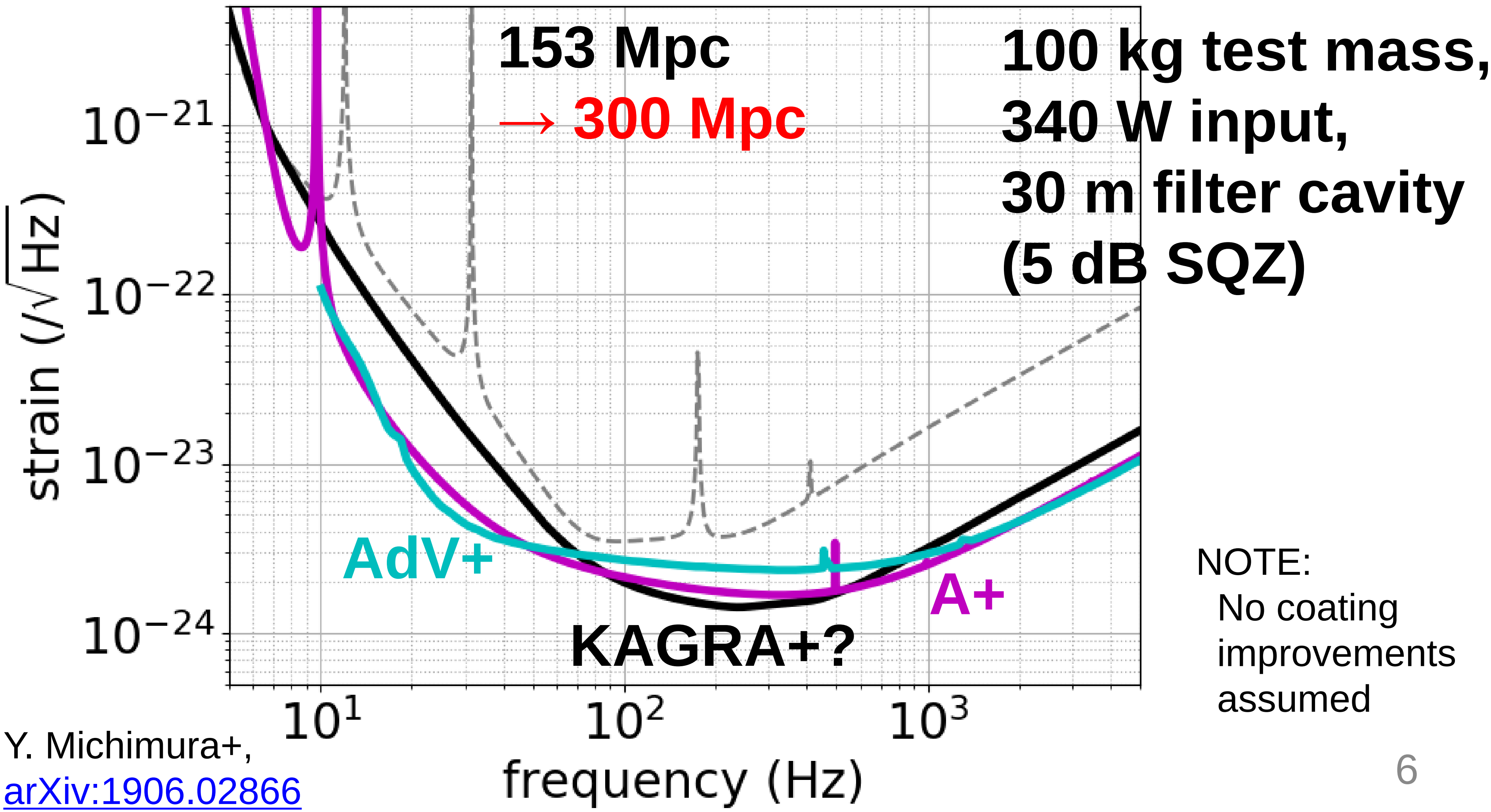


23 kg was the largest available sapphire mirror



Upgrade Plan for KAGRA?

- Twofold broadband sensitivity improvement possible with multiple upgrade technology



NOTE:
No coating improvements assumed

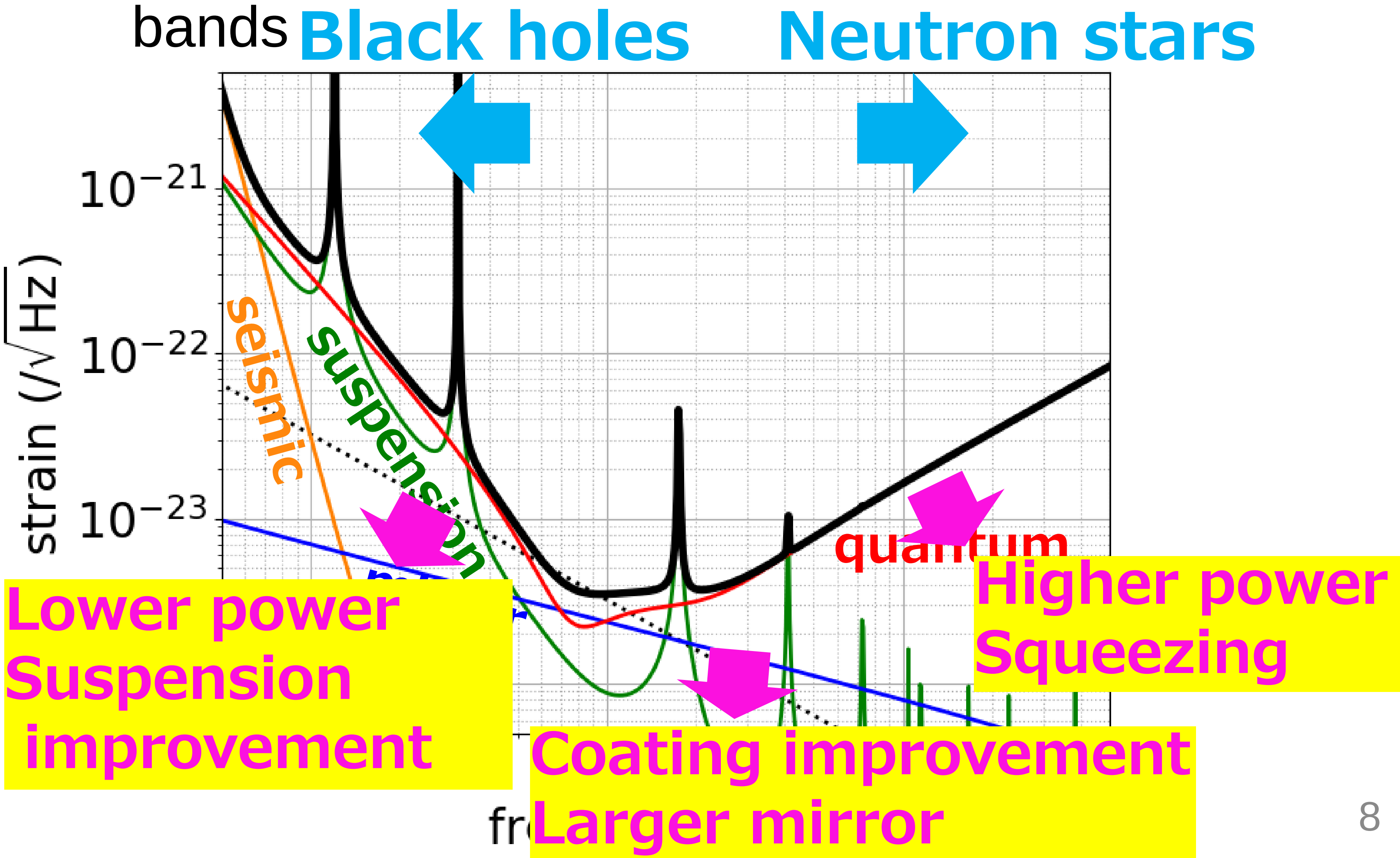
Y. Michimura+, arXiv:1906.02866

Technologies for the Upgrade

- Broadband improvement is favorable so that we don’t miss any science
- Combination of multiple technologies necessary to do broadband improvement
  - Larger sapphire test mass and its suspension
  - Higher power laser
  - Frequency dependent squeezing
- What to implement first depends on scientific scenarios and technical feasibility

Options for Near Term Upgrade

- Different technology improve sensitivity in different bands



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

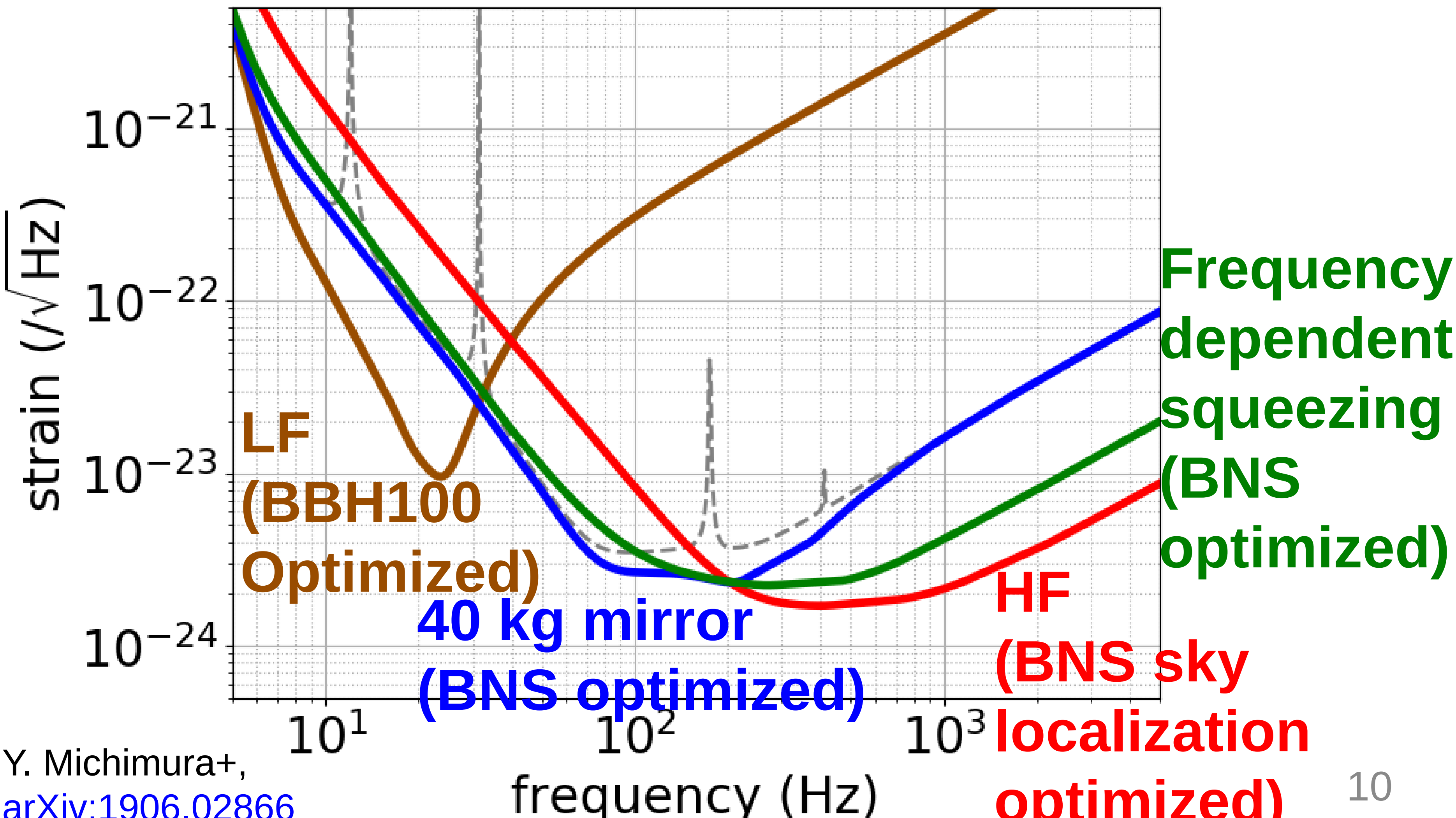
  Hubble constant

  BH spectroscopy with stellar-mass BBHs

  (Isolated pulsars and magnetors)

Possible Near Term Upgrade Plans

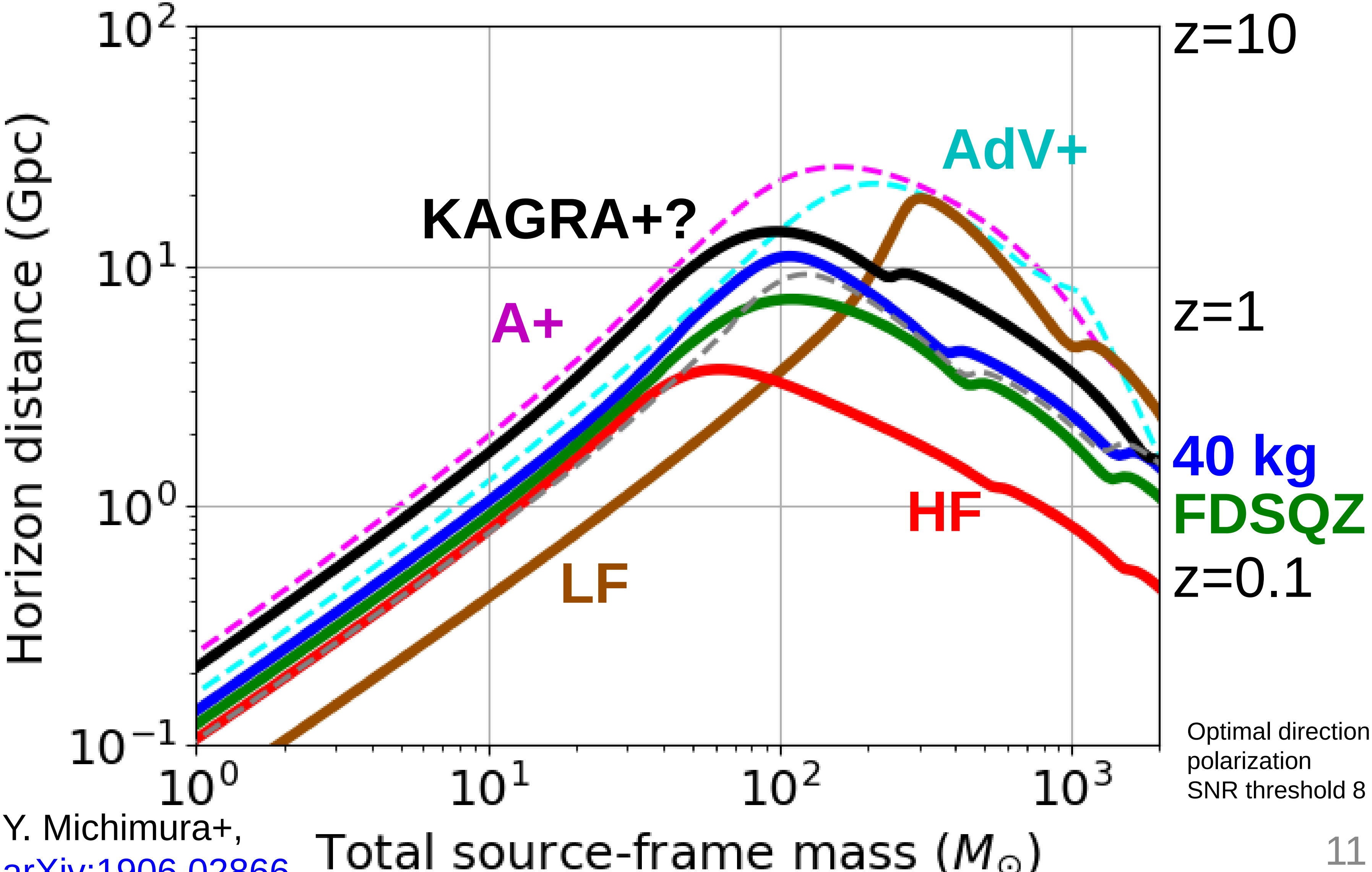
- Based on technical feasibility, facility and budget constraints (~5 years, ~$5M)



Y. Michimura+, arXiv:1906.02866

Horizon Distance Comparison

- Hard to beat A+ with horizon distance



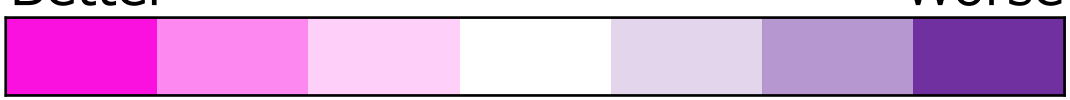
Optimal direction and polarization
SNR threshold 8

Y. Michimura+, arXiv:1906.02866

(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					



* Compared with bKAGRA, assumed A+ and AdV+ Network
* Summarized by A. Nishizawa *et al.* JGW-G1909934

Effective Progression of Upgrades?

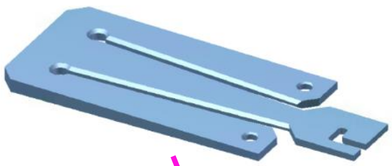
- **Low frequency** is uncertain since many low frequency excess noises exist
- **40 kg mirror** would be feasible but even larger mirror is required for longer term
- **Higher power laser** and **frequency dependent squeezing** are attractive in terms of feasibility
- **HF** plan has better sensitivity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

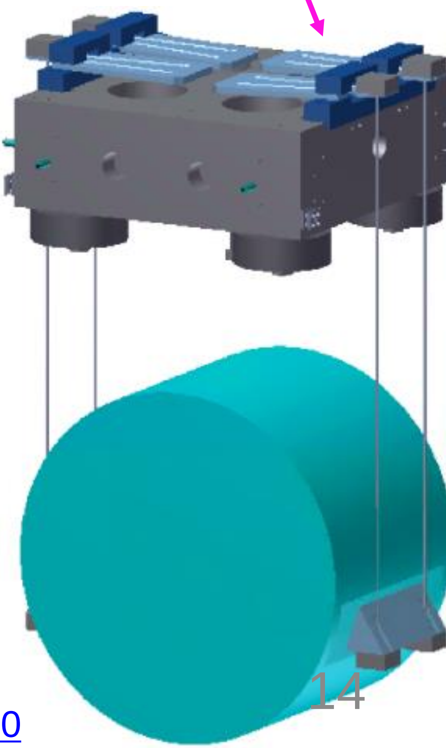
- **Higher power laser** → **Squeezing** → **Frequency dependent squeezing** → **Larger mirror** might be an effective progression

Still Many Other Challenges

- Many other challenges still remain to be overcame to achieve design sensitivity
  - Detuning of signal recycling cavity
  - Homodyne detection
  - Local sensors of cryogenic suspensions
  - Mechanical loss of sapphire blades
    3.6e-5 measured, while 7e-7 required
  - No sapphire mirror spares
    2 out of 12 met absorption requirement
    - measured ~30 ppm/cm
    - requirement for ITM was 50 ppm/cm
  - Inhomogeneity of sapphire ITM refractive index
  - ITM birefringence

NEW



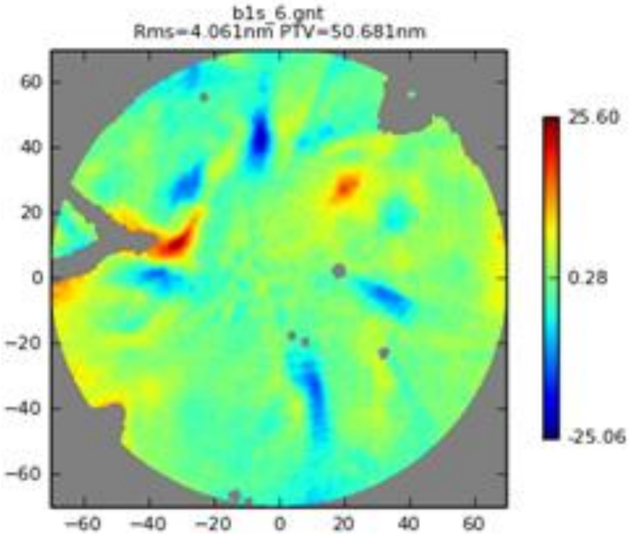


T. Yamada
JGW-G1910180

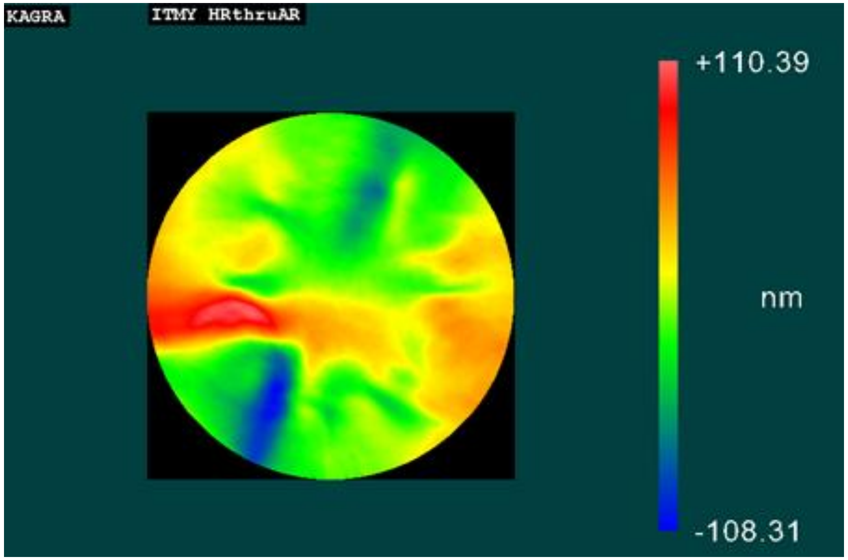
ITM Birefringence

- Found to have ~10% power loss on ITM reflection due to polarization rotation (June 22)
- Consistent with measured inhomogeneous birefringence

p-pol beam shape when PRX locked
klog #9393



Transmission wavefront error measured with circular polarization (4.07 nm RMS)



Transmission wavefront error measured with liner polarization (30.1 nm RMS)

E. Hirose, JGW-T1808715

Future Planning Committee

- Formulated inside KAGRA Collaboration in December 2018 to make a collaboration-wide agreement in upgrade plans

  Sadakazu Haino (chair)

  Chunglee Kim, Kentaro Komori, Matteo Leonardi, Yuta Michimura, Atsushi Nishizawa, Kentaro Somiya
- Coherent plans for achieving the design sensitivity and upgrades necessary
- White paper on KAGRA upgrade work in progress (to be finalized by August 2019) JGW-M1909590
  - Available technology survey
  - Science case study
  - Necessary R&Ds

Summary

- KAGRA requires different approach for the upgrade due to its cryogenic operation
- Twofold sensitivity improvement (300 Mpc) is feasible by combining multiple technologies
- What to implement first depends on scientific scenarios and technical feasibility
- We are proposing to focus on high frequencies first
- HF upgrade enables better source sky localization and to probe neutron star physics

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)

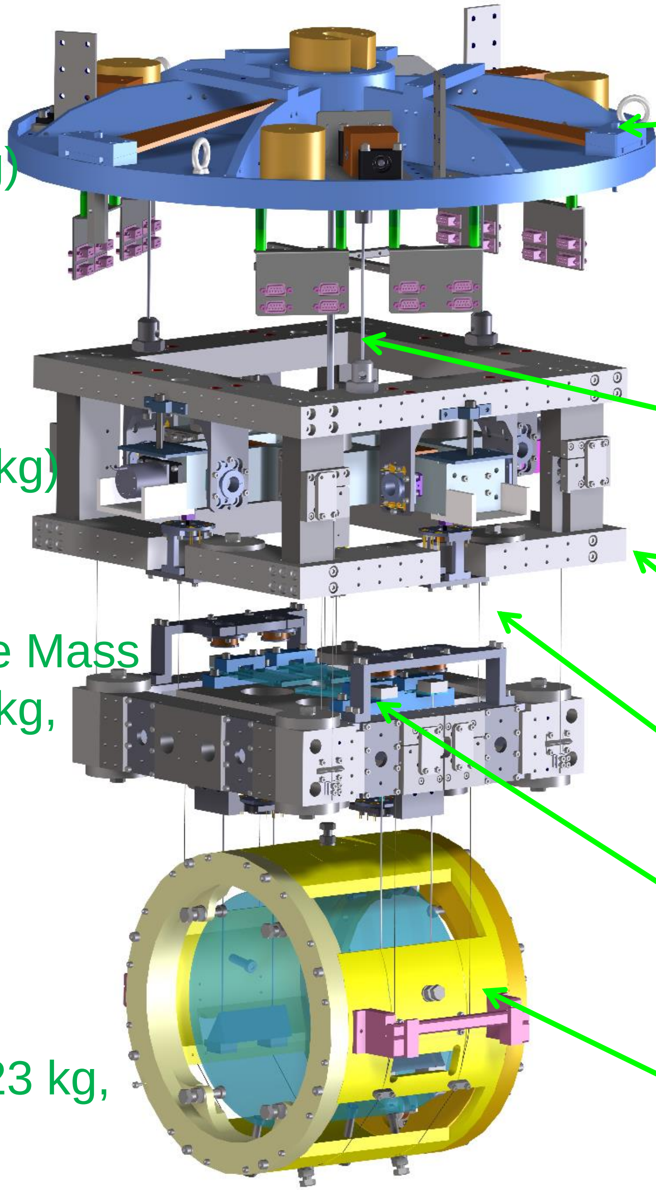
KAGRA Detailed Parameters

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

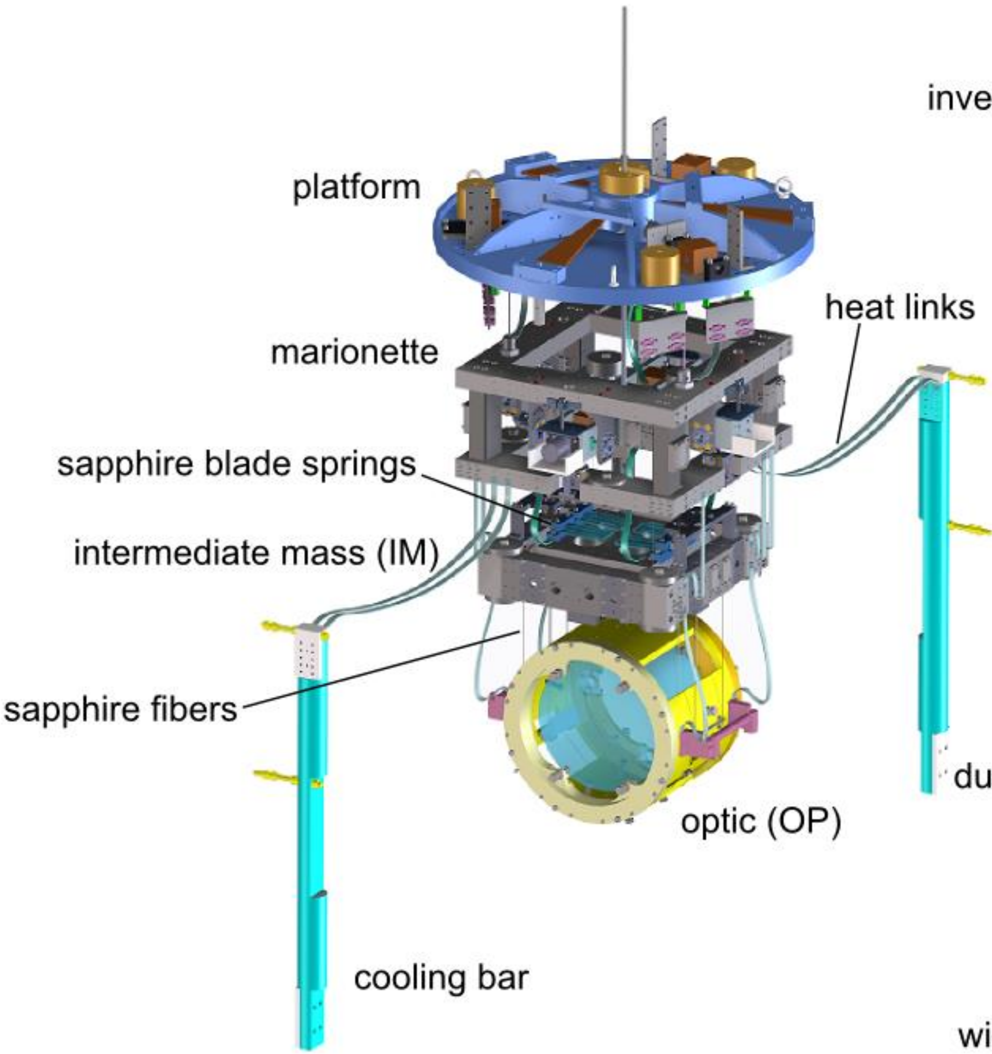
Heat link attached to MN

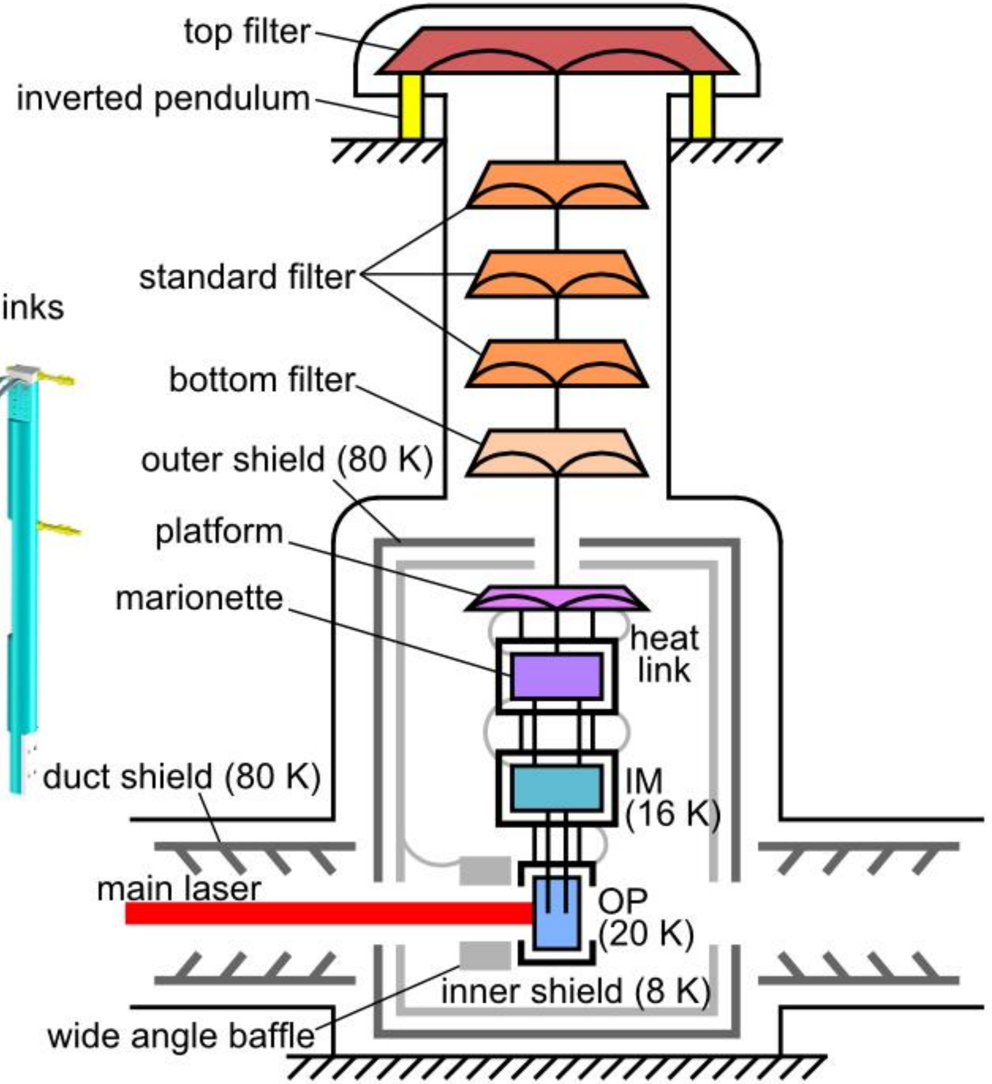
IM suspended by 4 CuBe fibers
(24 cm long, 0.6 mm dia)
IRM suspended by 4 CuBe fibers

4 sapphire blades

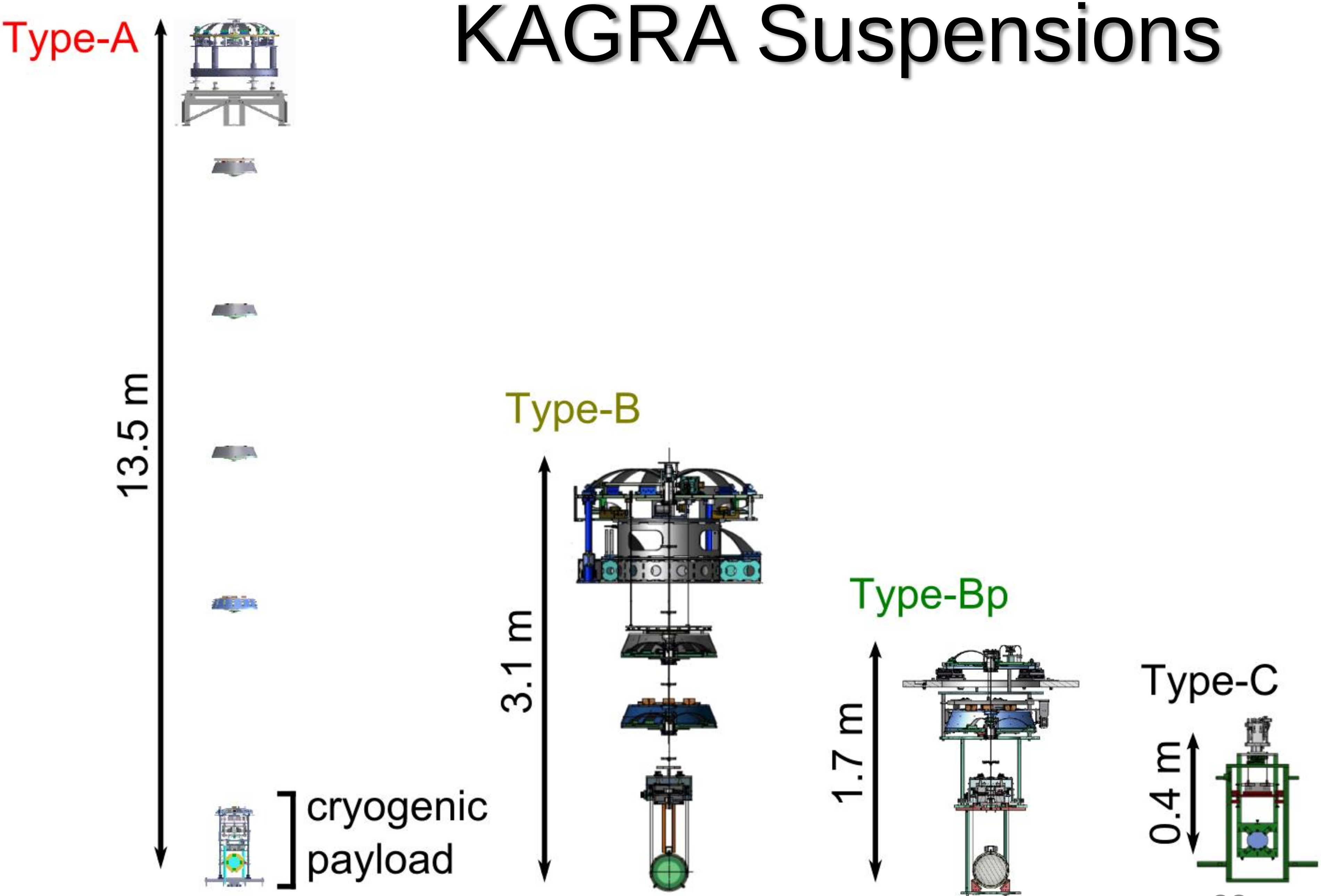
TM suspended by 4 sapphire fibers
(35 cm long, 1.6 mm dia.)
RM suspended by 4 CuBe fibers

KAGRA Cryostat Schematic

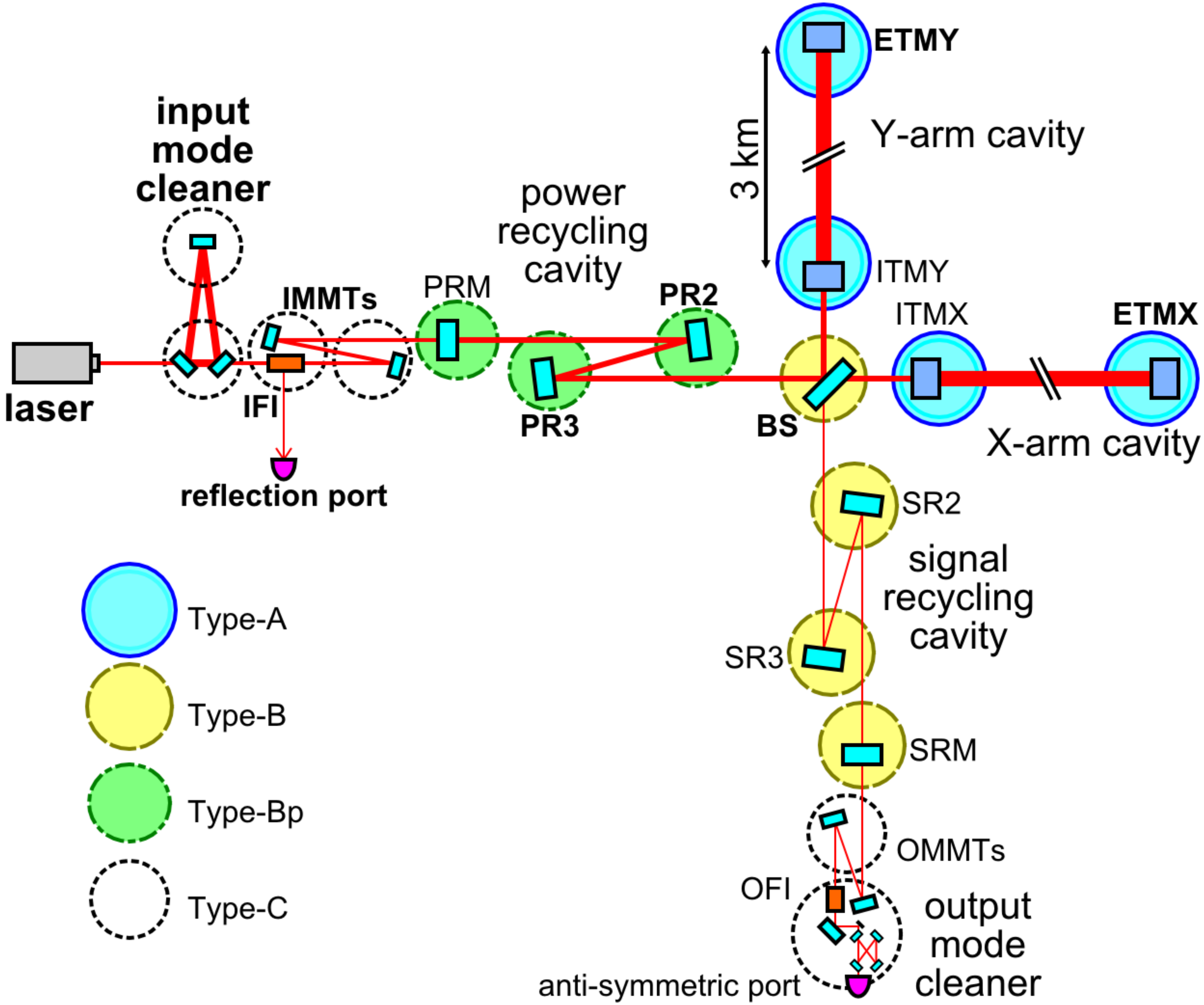




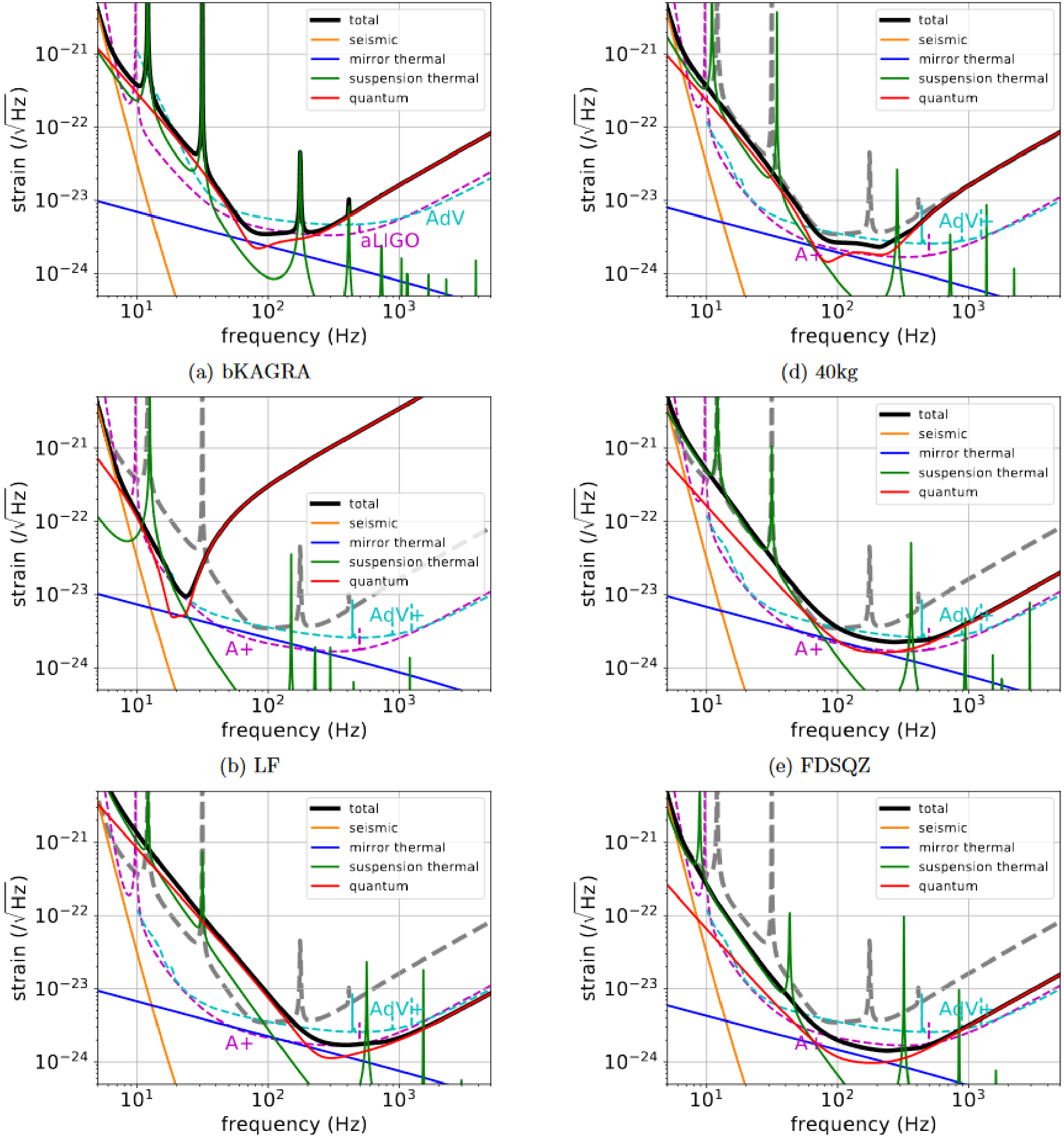
KAGRA Suspensions



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]()

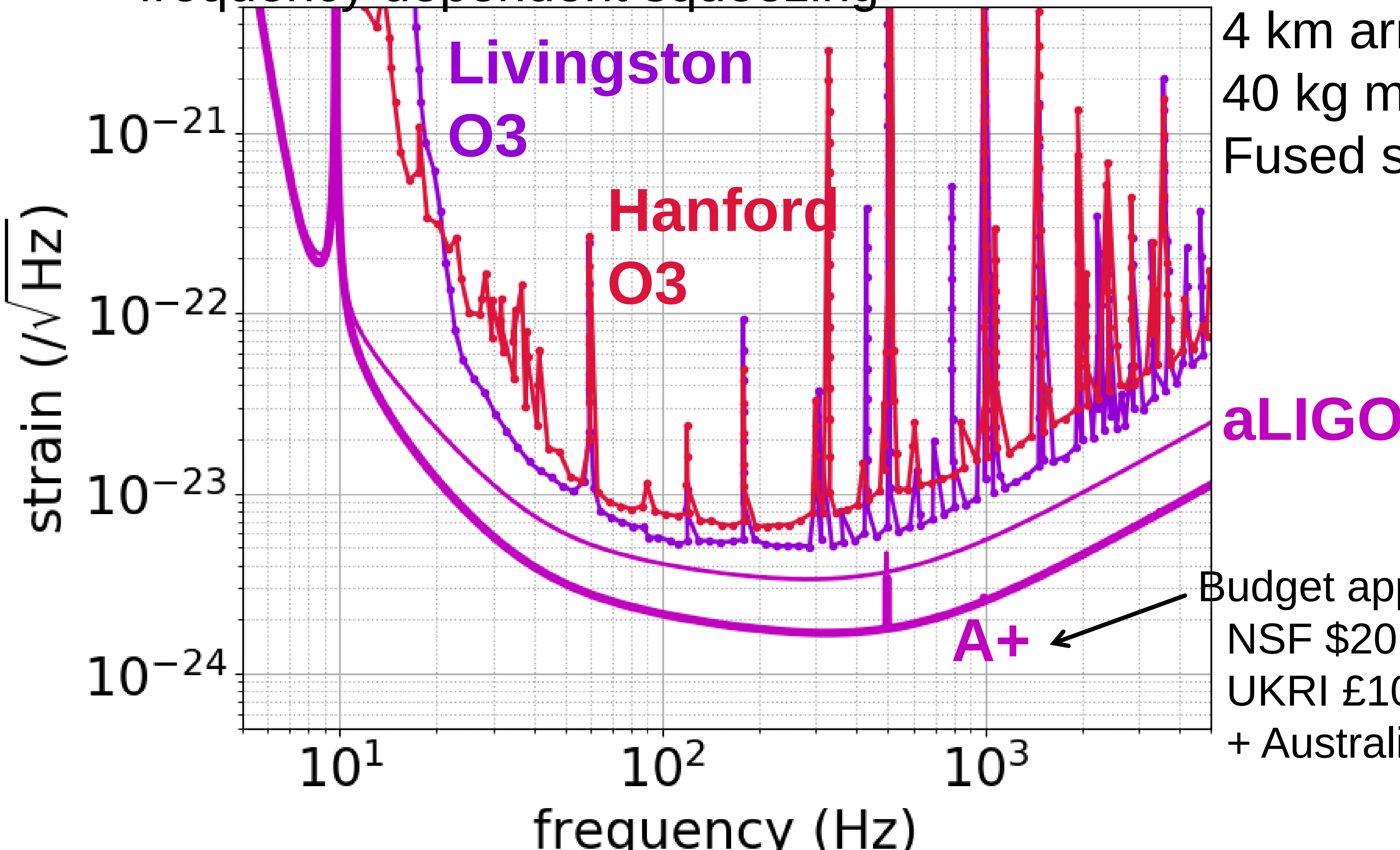
Possible KAGRA Upgrade Plans

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

Advanced LIGO Upgrade: A+

- Reaches 325 Mpc with coating improvement and frequency dependent squeezing

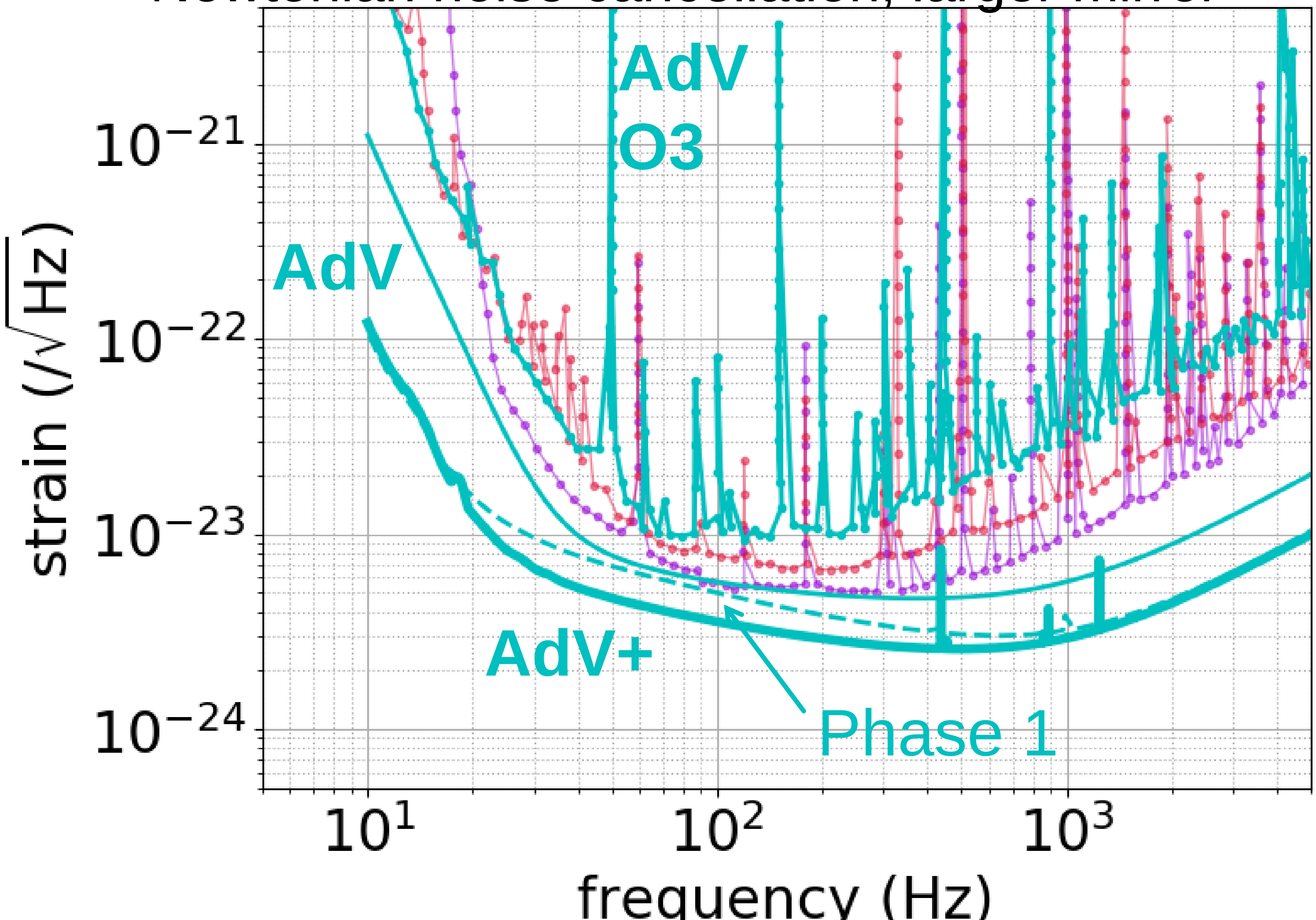


4 km arm
40 kg mirror
Fused silica

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