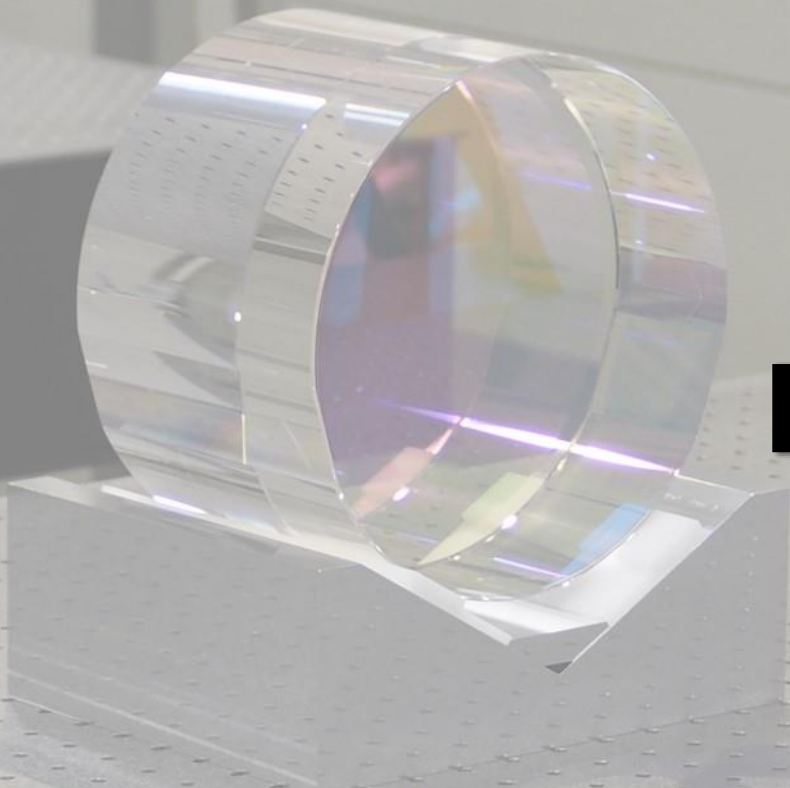
KAGRA-OzGrav Meeting

November 17, 2020



# Future Plans for KAGRA Facility

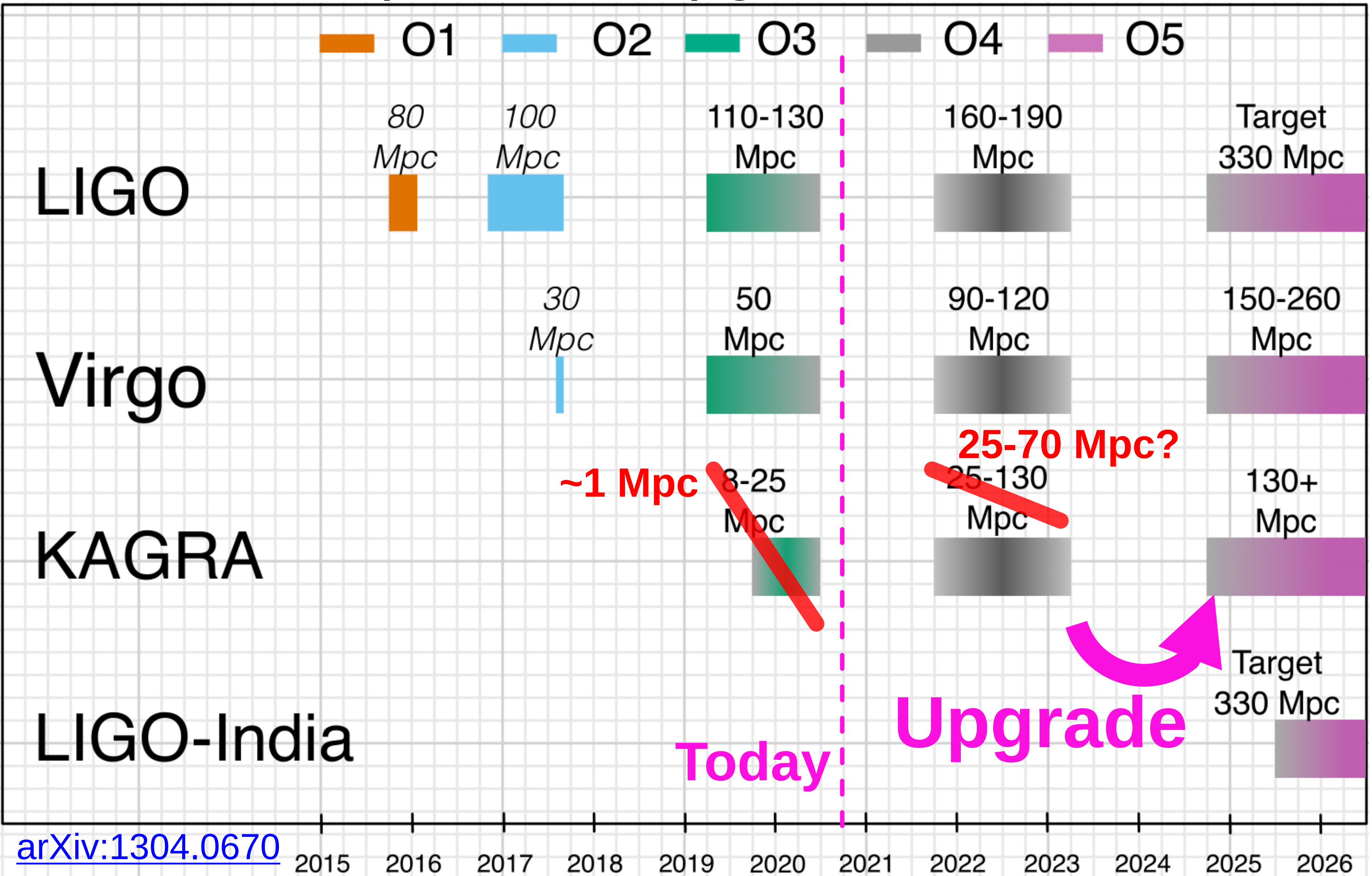

Yuta Michimura

Department of Physics, University of Tokyo

for the KAGRA Collaboration

# Observing Scenario

- Achieving the designed sensitivity is already tough
- But the plan is to upgrade KAGRA for O5




arXiv:1304.0670

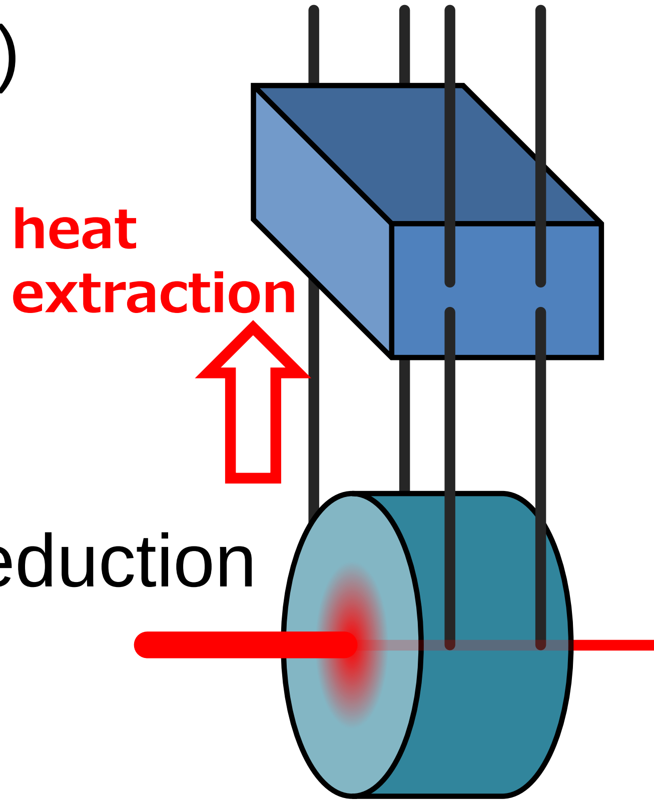
# Upgrading KAGRA is Tricky

- 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

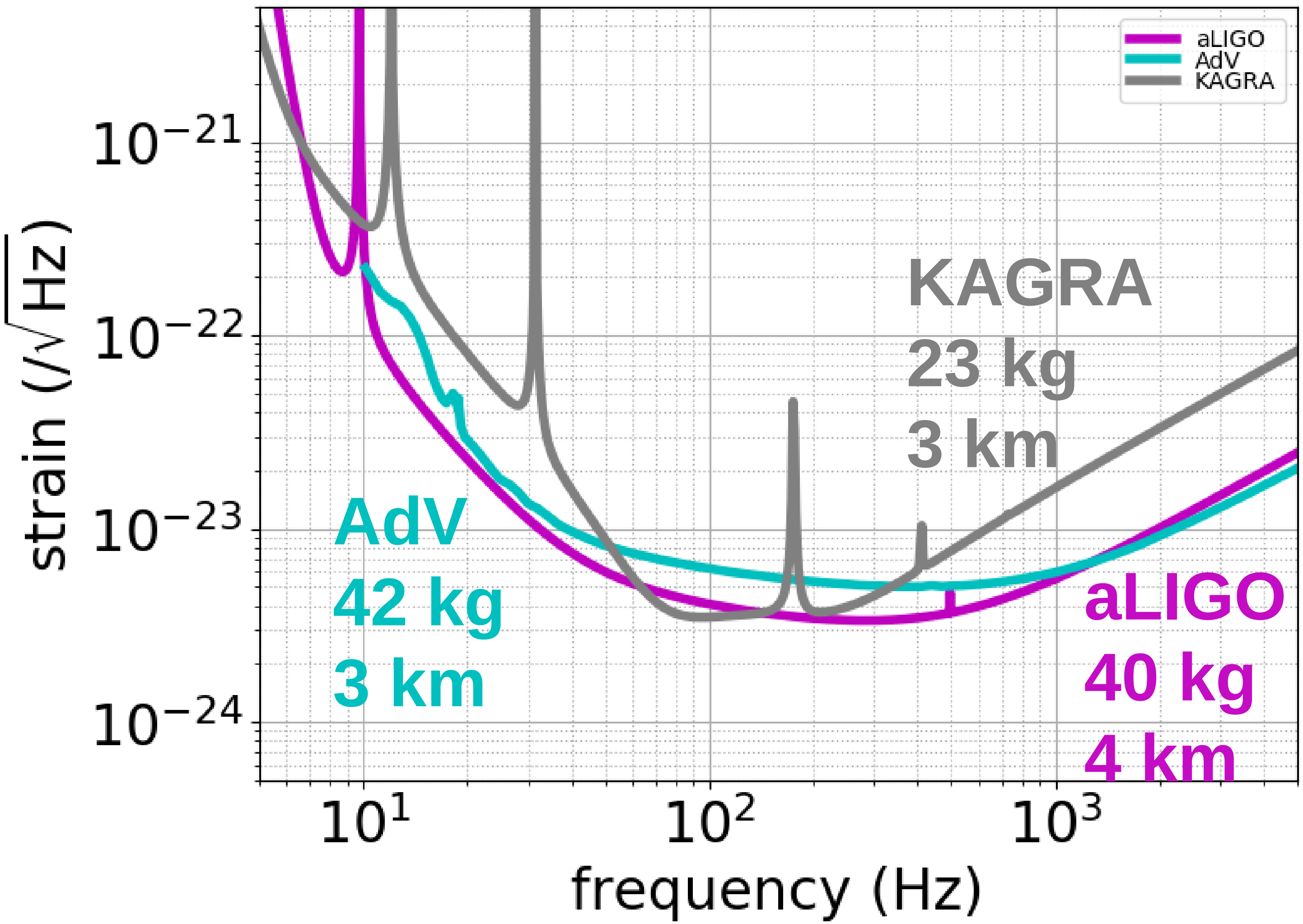
thicker and shorter
for heat extraction



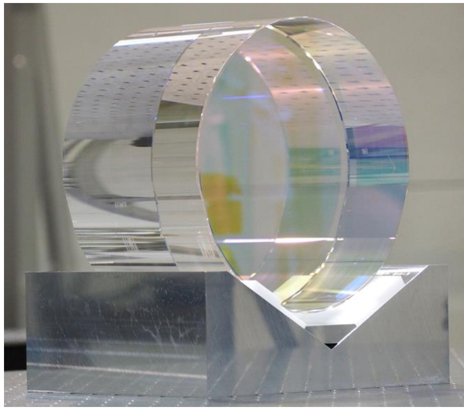

Y. Michimura+, PRD **97**, 122003 (2018)

# 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

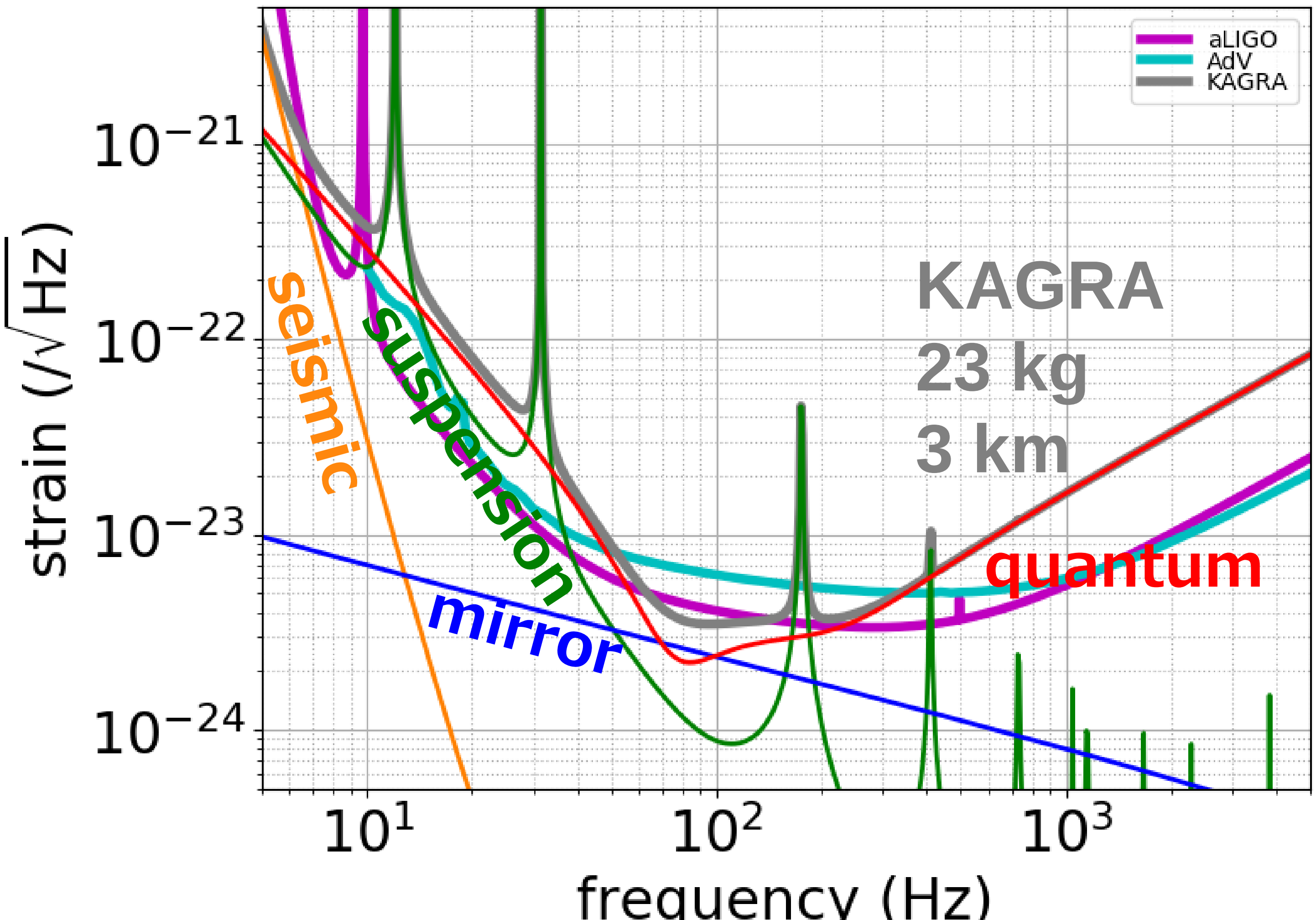



23 kg was the largest available sapphire mirror

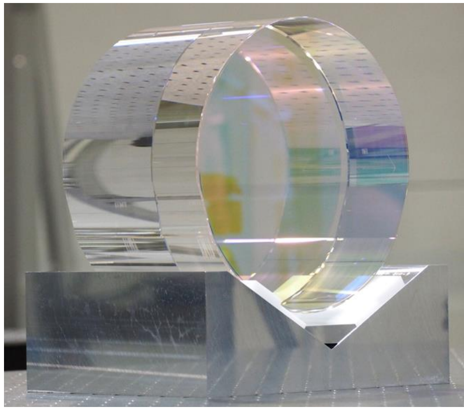


# 2G Sensitivity Comparison

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

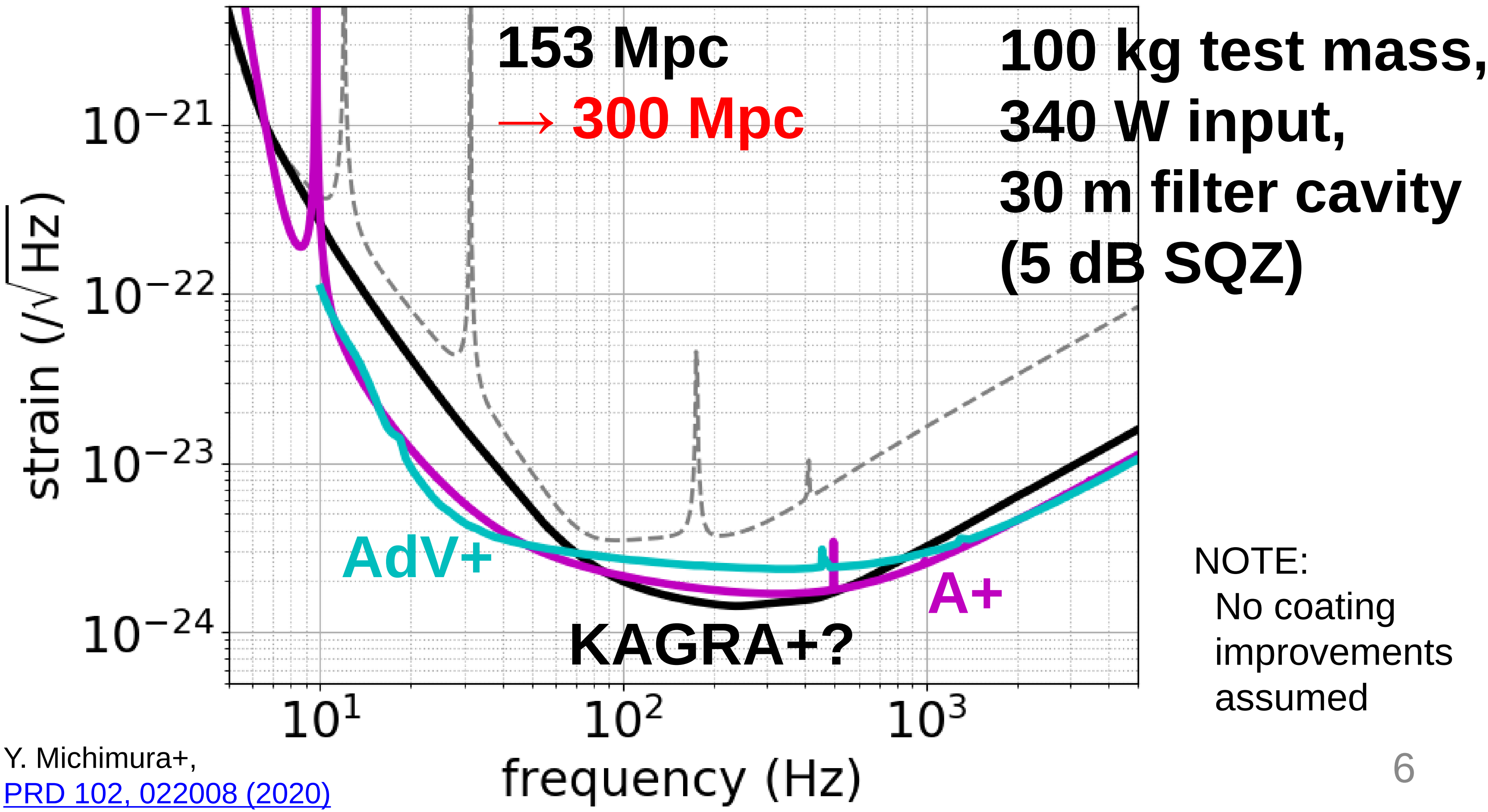



23 kg was the largest available sapphire mirror



# Upgrade Plan for KAGRA?

- Twofold broadband sensitivity improvement possible with multiple upgrade technology




NOTE:
No coating improvements assumed

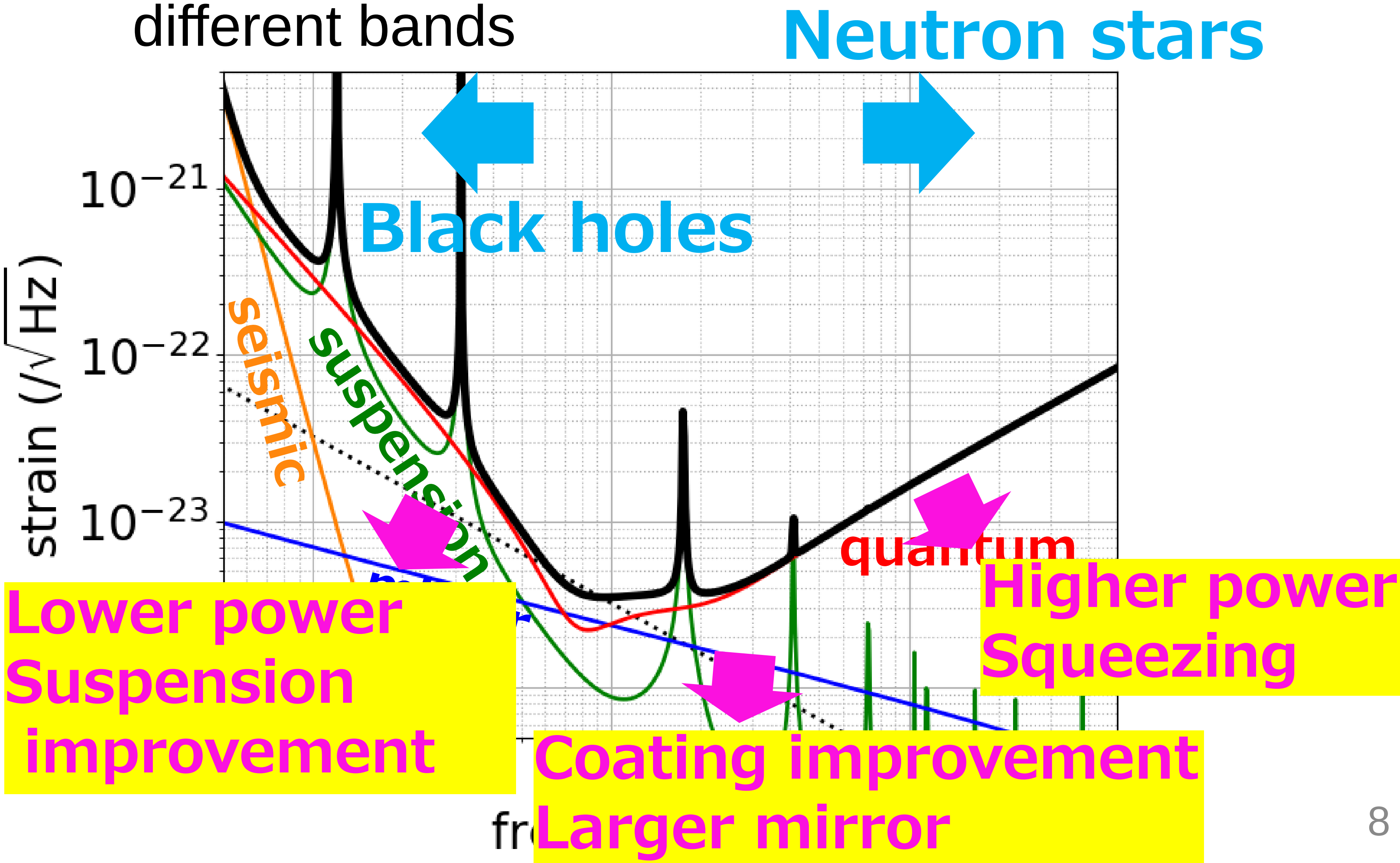
Y. Michimura+, PRD 102, 022008 (2020)

# 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
- Upgrade should be done in steps
- What to implement first depends on scientific scenarios and technical feasibility

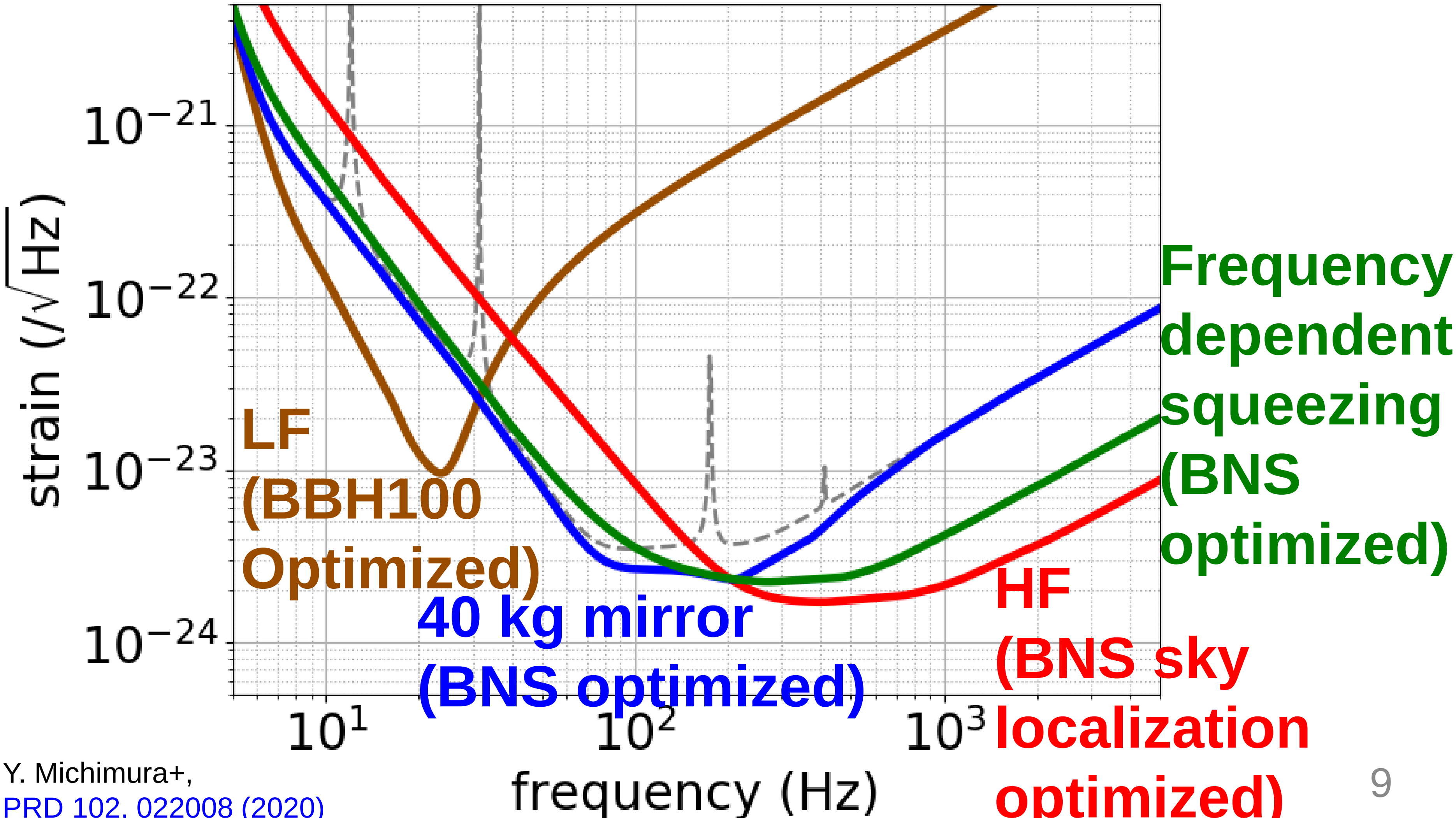
# Options for Near Term Upgrade

- Different technologies improve sensitivity in different bands



# Possible Near Term Upgrade Plans

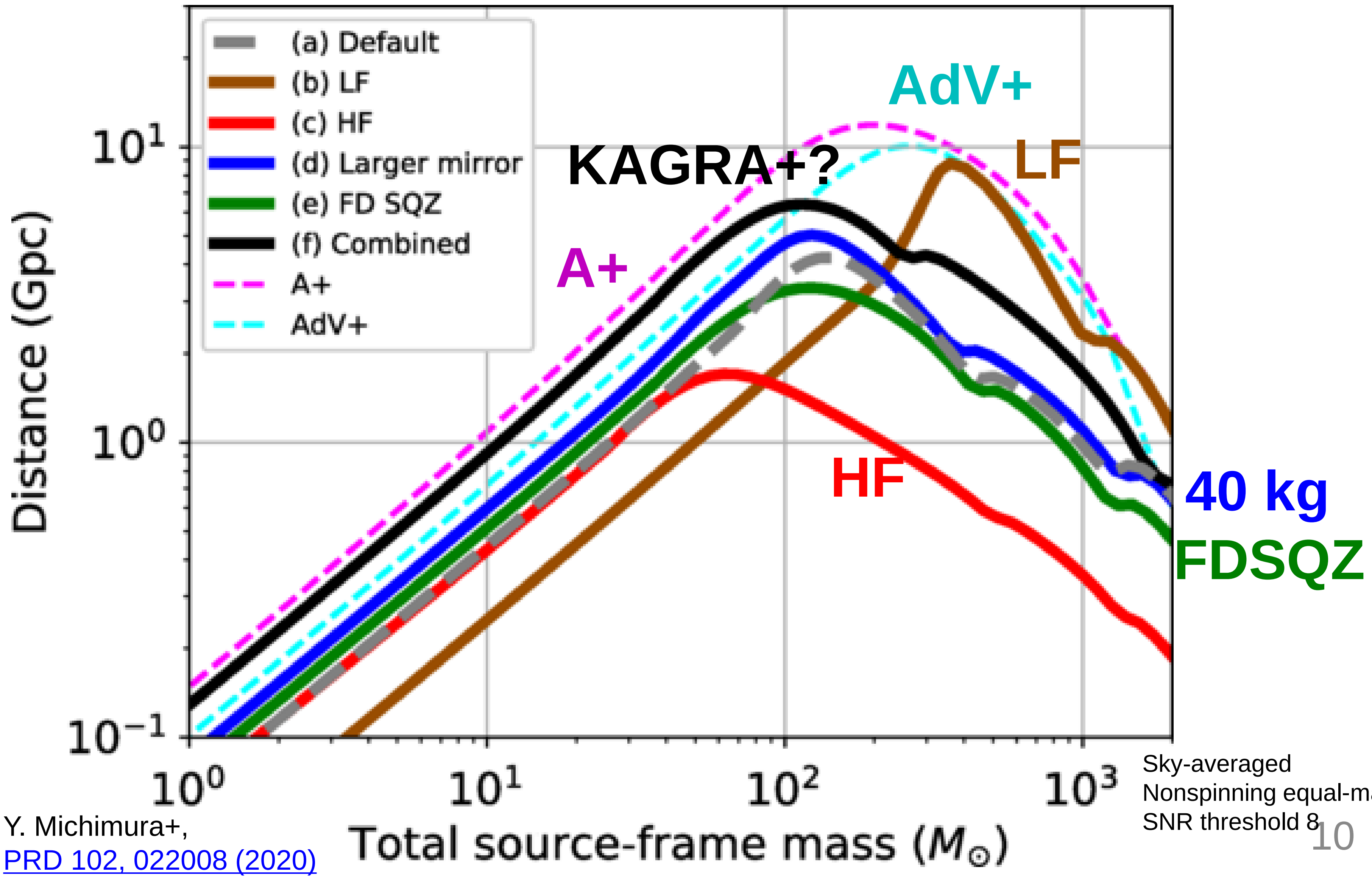
- Based on technical feasibility, facility and budget constraints (~5 years, ~$5M)




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

# Detection Ranges

- Hard to beat A+ with horizon distance




Sky-averaged
Nonspinning equal-mass
SNR threshold 8

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

# (Selected) Science Comparison

- Sensitivity improvement in different bands give different science cases

| | LF | 40kg | FDSQZ | HF | K+? |
|---|---|---|---|---|---|
| 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.* arXiv:2008.02921

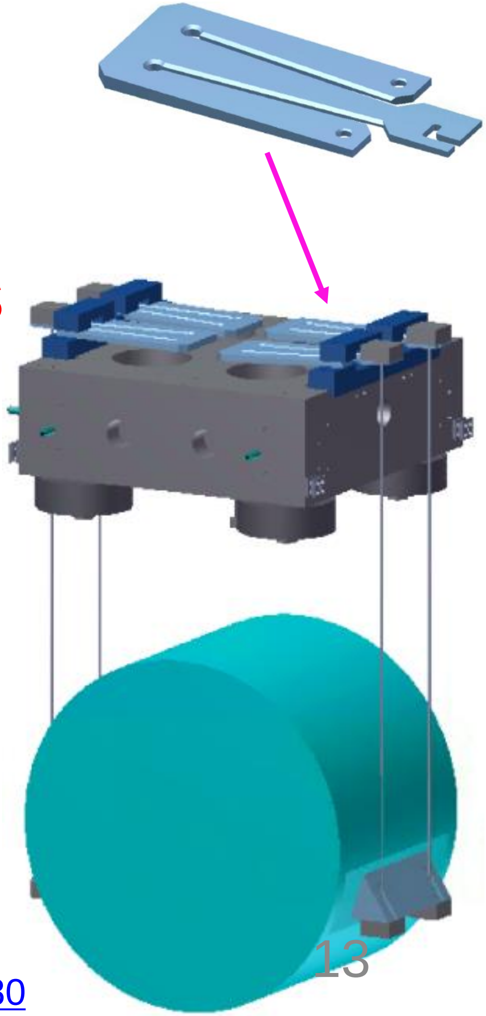
# Effective Progression of Upgrades?

- **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
  - Larger thermal resistance
  - 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



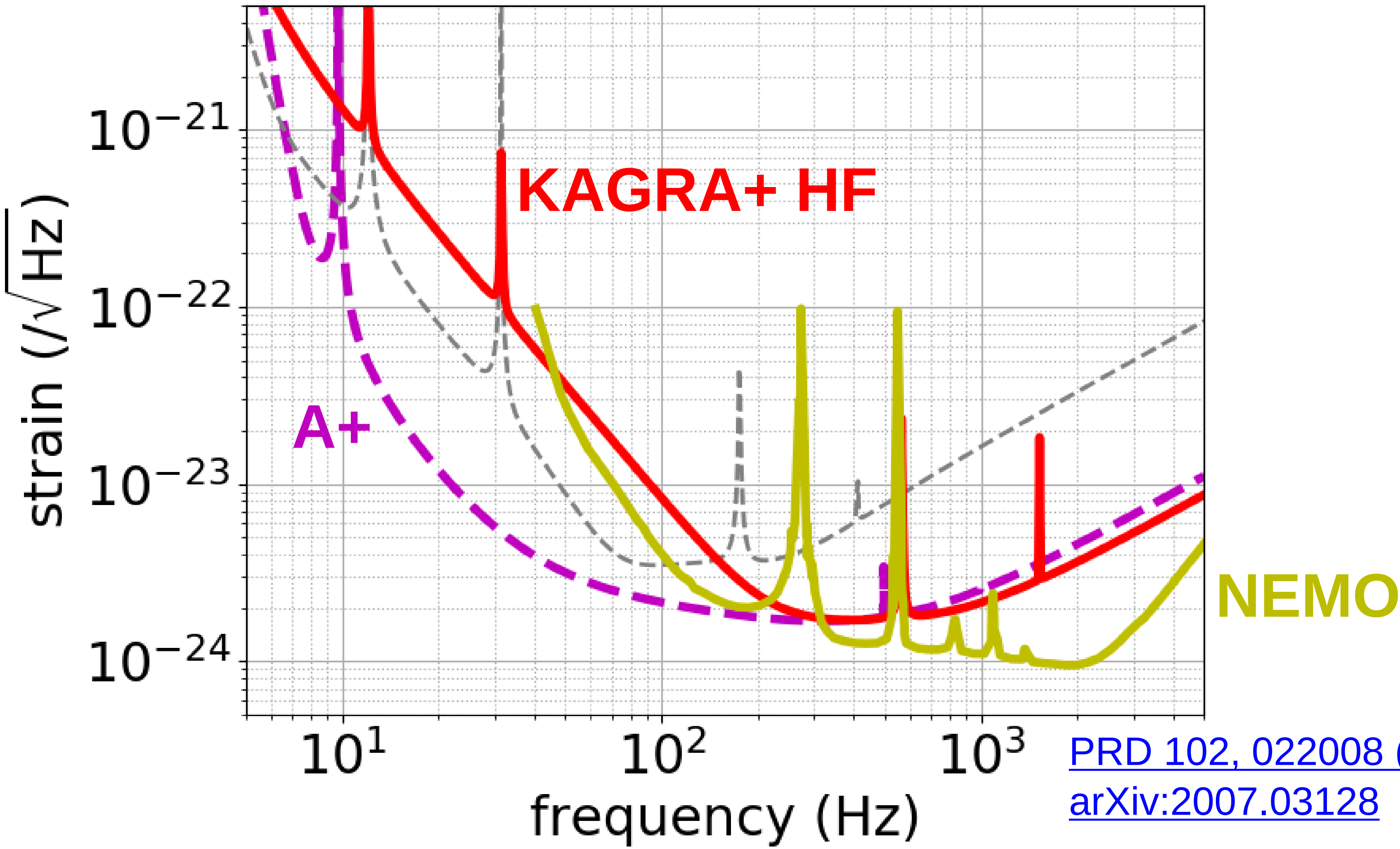
T. Yamada
JGW-G1910180

# Discussion History

- **March 2017**: Semi-officially started the discussion
- **May 2017**: Upgrade plans first presented outside of KAGRA at GWADW2017 at Hamilton Island (JGW-G1706485)
- **December 2018**: Future Planning Committee formulated (Chair: Sadakazu Haino)
- **June 2019**: Birefringence observed
- **August 2019**: First version of the white paper summarized (JGW-M1909590)
- **April 2020:** O3GK Observation run
- **2020**: Discussions to establish Future Strategy Committee to further organize the activities for upgrade implementation

# KAGRA+ HF and NEMO

- What KAGRA can do with ~5years, ~$5M, within current 3 km facility (NEMO: 4 km, ~$100M)




[PRD 102, 022008 (2020)](#)
[arXiv:2007.03128](#)

# 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
- KAGRA HF upgrade seems to be most attractive for the first step
- But there are still many practical challenges

- Other options is to do HF upgrade with extreme RSE and long SRC scheme (next Kentaro's talk)

# Supplemental 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

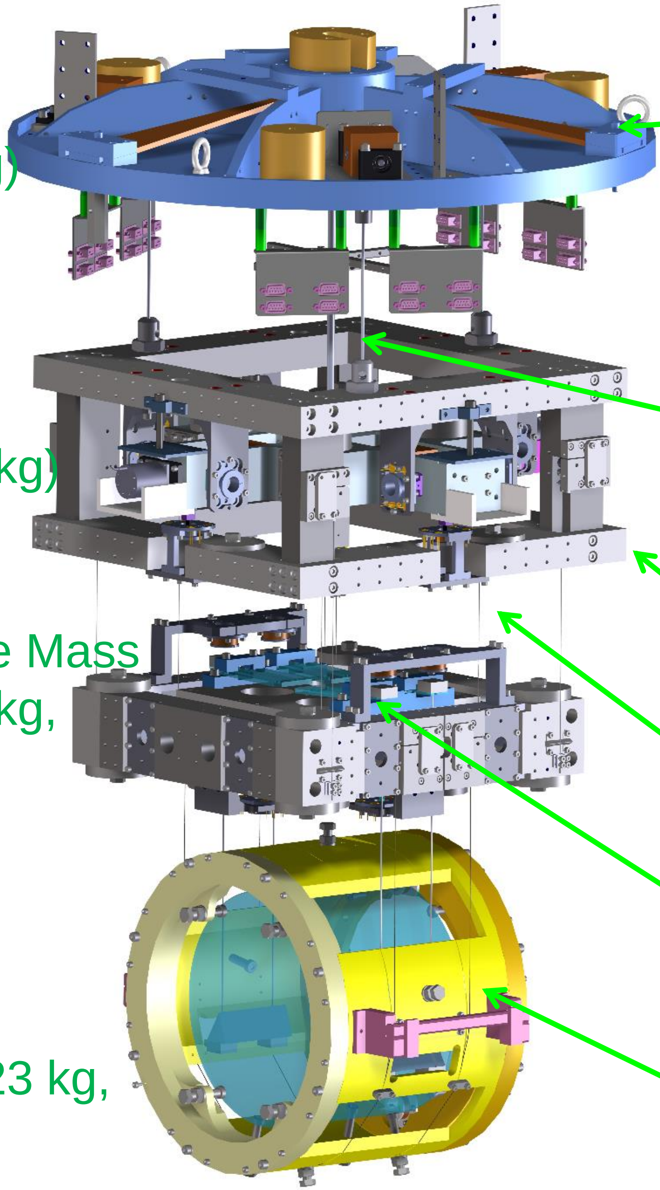
Figure by T. Ushiba and A. Hagiwara

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

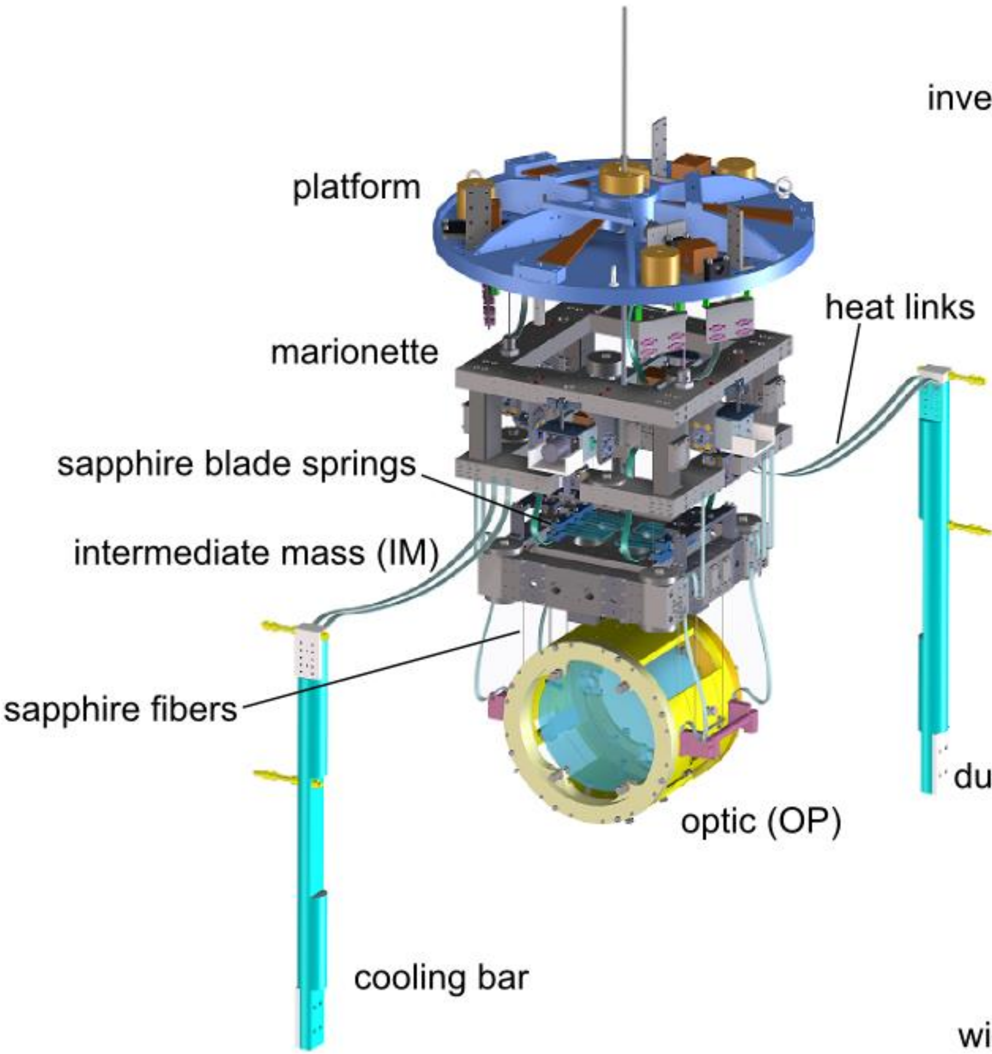
Heat link attached to MN

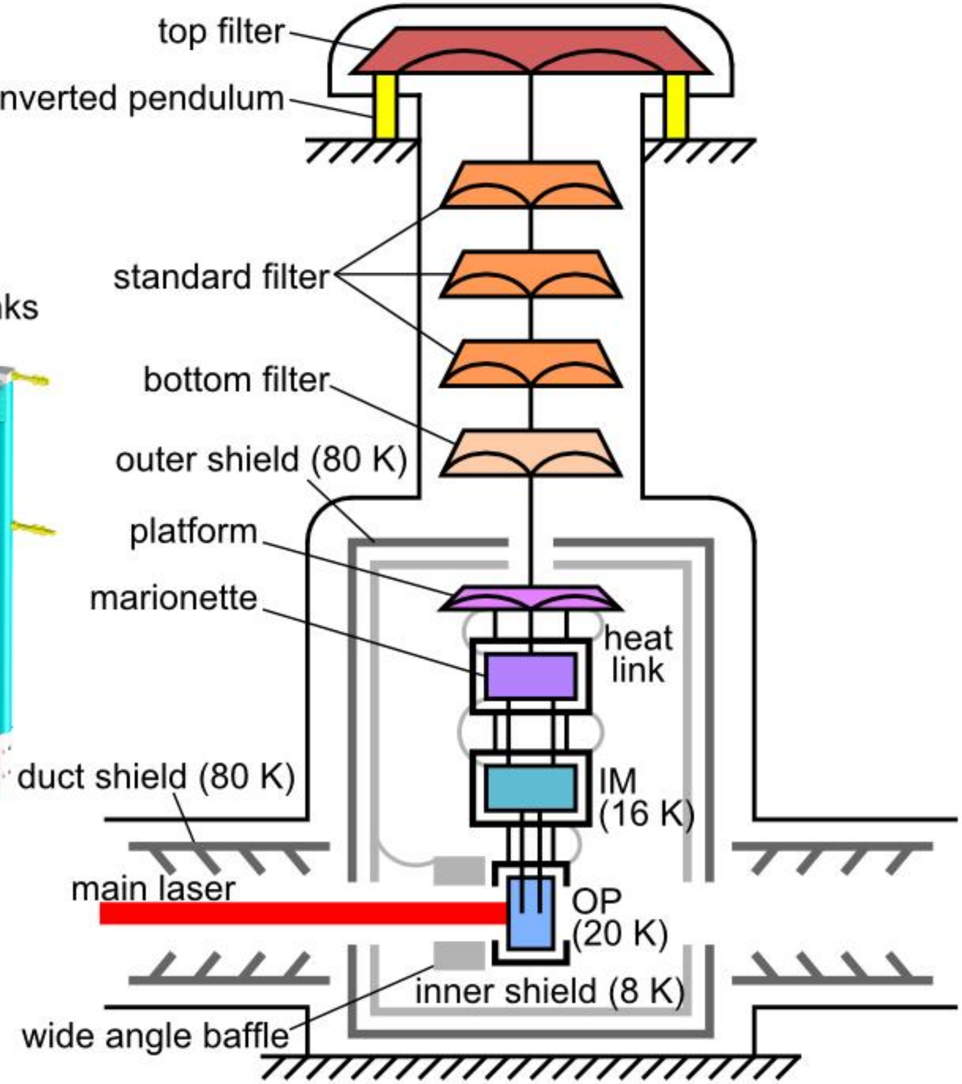
IM suspended by 4 CuBe fibers
(24 cm long, 0.6 mm dia)
IRM suspended by 4 CuBe fibers

4 sapphire blades

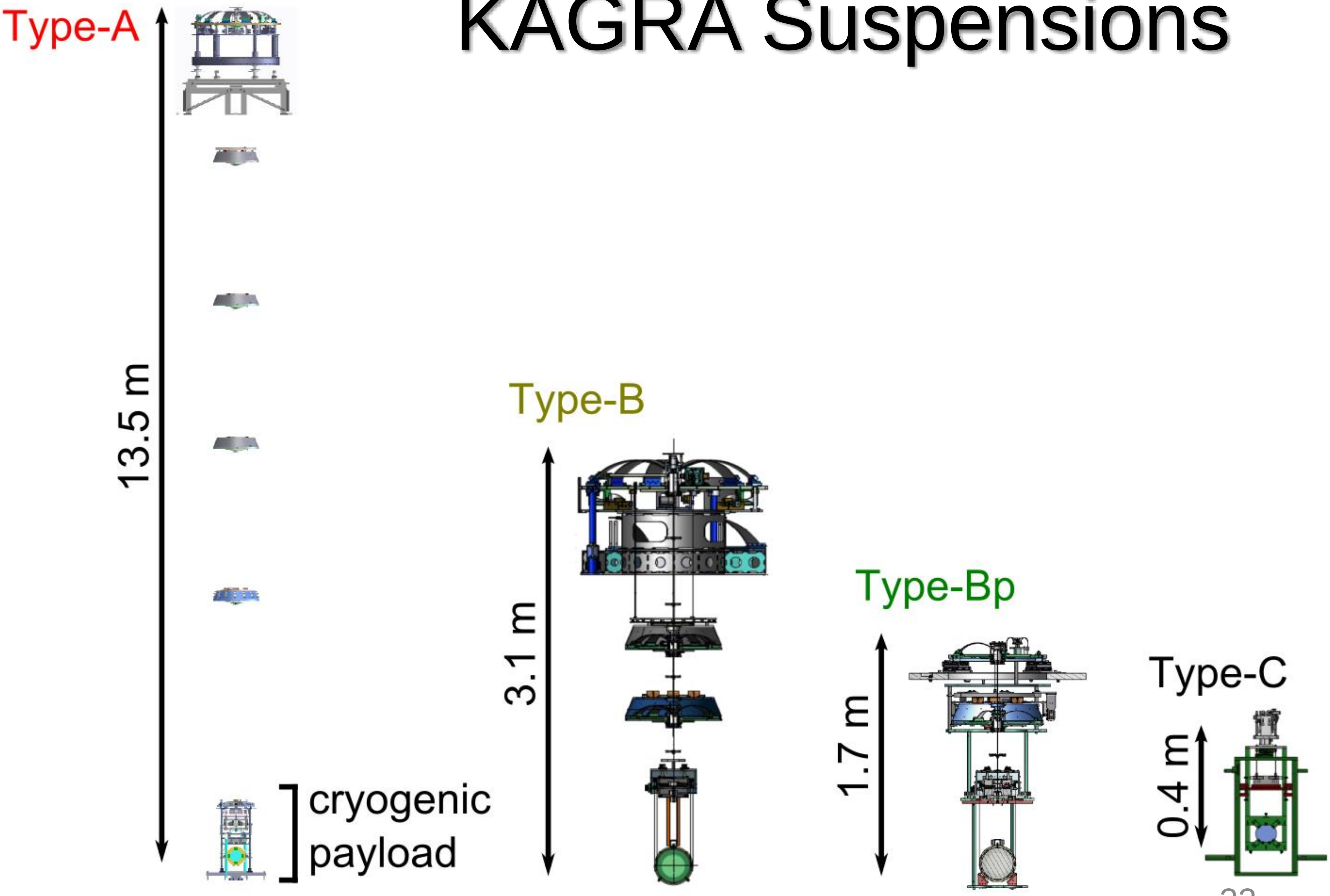
TM suspended by 4 sapphire fibers
(35 cm long, 1.6 mm dia.)
RM suspended by 4 CuBe fibers

# KAGRA Cryostat Schematic

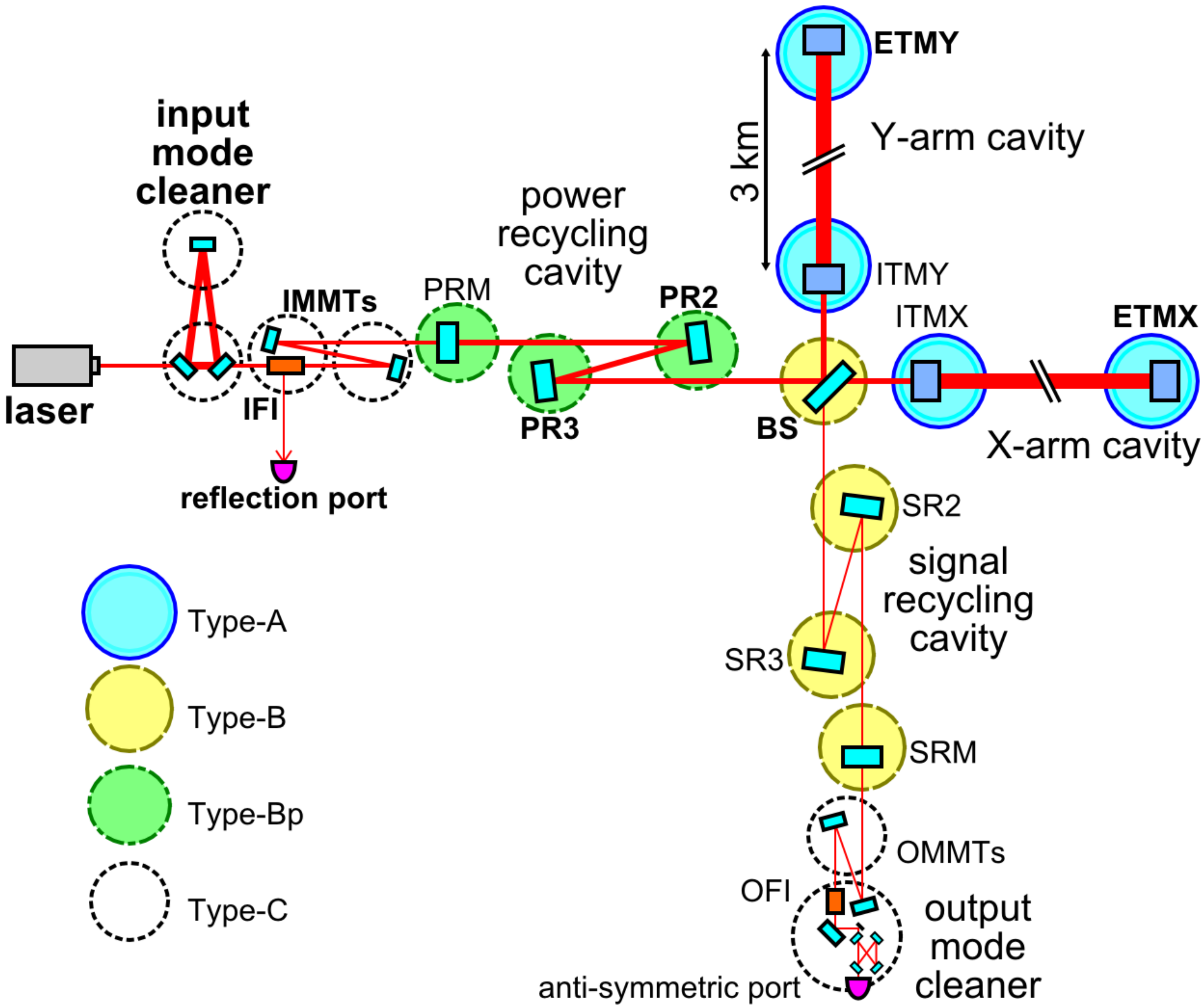


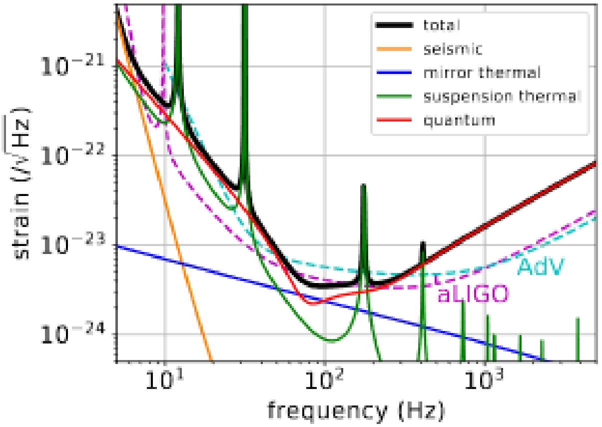
# KAGRA Suspensions



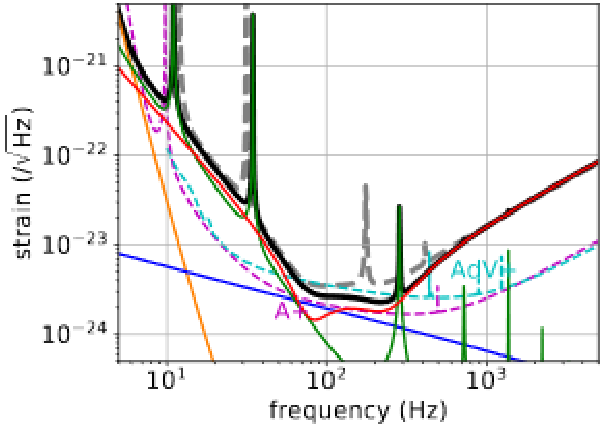
# KAGRA Interferometer



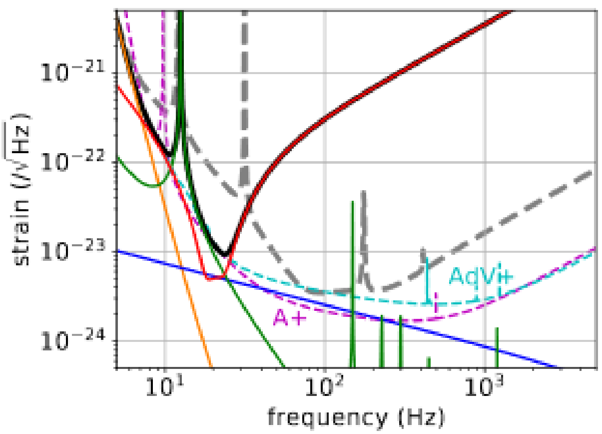
# KAGRA+ Noise Budget



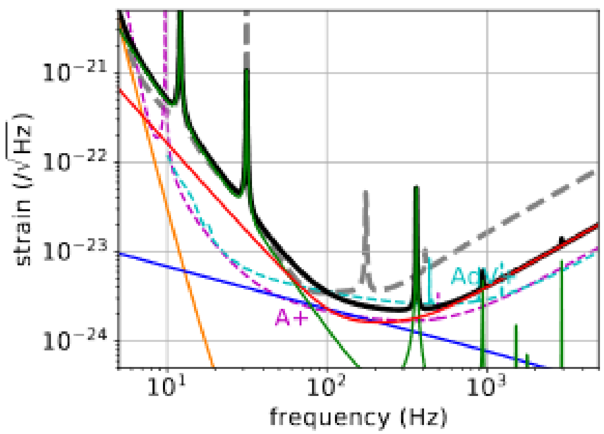

(a) Default



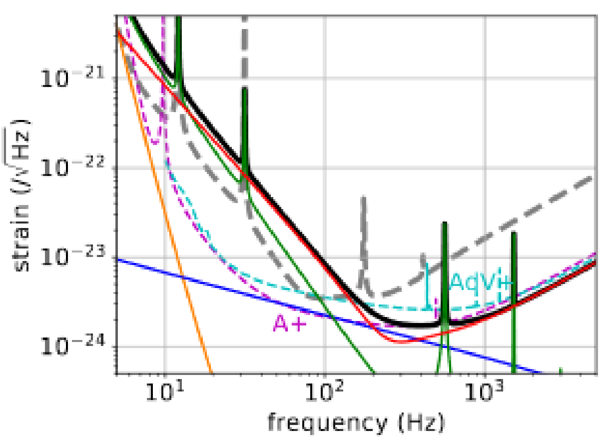

(d) Larger mirror



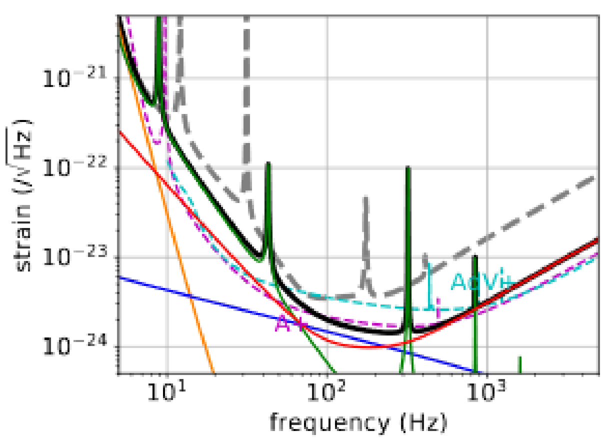

(b) Low frequency




(e) Frequency dependent squeezing




(c) High frequency




(f) Combined

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

# KAGRA+ Parameters

- No coating improvement
- 30 m filter cavity for FD SQZ and Combined

| | | 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) | $\zeta$ | 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) |
| $100M_\odot$-$100M_\odot$ inspiral range (Mpc) | | 353 | **2019** | 112 | 400 | 306 | 707 |
| $30M_\odot$-$30M_\odot$ inspiral range (Mpc) | | 1095 | 1088 | 270 | 1250 | 843 | 1687 |
| $1.4M_\odot$-$1.4M_\odot$ 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 |

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