Example sensitivity curves for the KAGRA upgrade

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I. SENSITIVITY DATA IN THE ZIP FILE

In the zip file, there are 5 sensitivity data files for KAGRA:

- bKAGRA.txt: Latest estimated KAGRA sensitivity, DRSE [1]
- KAGRAplusLF.txt: Upgrade plan candidate focused on low frequencies (near term upgrade)
- KAGRAplusHF.txt: Upgrade plan candidate focused on high frequencies (near term upgrade)
- KAGRAplus40kg.txt: Upgrade plan candidate to use heavier mirror to improve mid-frequencies (near term upgrade)
- KAGRAplusFDSQZ.txt: Upgrade plan candidate to inject frequency dependent squeezing (filter cavity) to improve both low and high frequencies (near term upgrade)
- KAGRAplusCombined.txt: Upgrade plan candidate to combine technologies for broadband twofold improvement (longer term upgrade)

For comparison and network sensitivity calculations, LIGO and Virgo data are also included in the zip file:

- aLIGO.txt: Design sensivity for Advanced LIGO with coating thermal noise update [2]
- Aplus.txt: Design sensitivity for the upgrade of Advanced LIGO, A+ [3]
- AdV.txt: Design sensitivity for Advanced Virgo (official data used in the Observation Scenario Paper v20190122 [4])
- AdVplus.txt: Design sensitivity for the upgrade of Advanced Virgo (official data used in the Observation Scenario Paper v20190122 [4]; details described in Ref. [5])

For network sensitivity calculations, we suggest to use the following network configuration

- aLIGO, AdV, and bKAGRA
- A+, AdV+, and KAGRA near term upgrade candidates (*LF*, *HF*, *40kg*, or *FDSQZ*)
- A+, AdV+, and KAGRA longer term upgrade candidate (*Combined*)

The first column in the text file is the frequency in Hz, and the second column is the strain sensitivity in $/\sqrt{\mathrm{Hz}}$. Note that thermal noise peaks in the sensitivities for KAGRA upgrade plans are ommited to generate smooth curves.

II. DETAILS OF THE SENSITIVITY CALCULATION

Details of the sensitivity calculation for KAGRA is described in Ref. [6], and the original MATLAB code for the sensitivity calculation lives in Ref. [1].

Parameters used for the sensitivity calculations and the sensitivities for bKAGRA and upgrade candidates are summarized in Table I and Fig. 1.

A. Suspension for LF

For *LF* sensitivity, some of the parameters related to suspensions are modified to reduce suspension thermal noise. First, the mass of the intermediate mass is increased from 20.5 kg to 82 kg. Second, the diameter and length of the wire suspending the intermediate mass from the marionette is changed from 0.6 mm dia. 26.1 cm long to 0.2 mm dia. 78.3 cm long. Also, ambient radiation absorbed to the test mass are reduced from 50 mW to ~~0.3 mW~~ 3 mW (typo fixed on June 16, 2020).

B. Mirror mass and coating

40 kg test mass is the maximum test mass size considering the space available inside the current cryostat, and therefore used in the near term upgrade candidate *40kg*. 100 kg mirror is under development, but suspending 100 kg mirror requires the changes in the suspension system and the cryostat, and therefore used in the longer term upgrade candidate *Combined*.

No coating improvements from bKAGRA design are assumed in the upgrade candidates, but the beam radius

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at the test masses are proportionally increased with respect to the radius of the test masses, keeping the aspect ratio the same, in *40kg* and *Combined* plans.

C. Laser power

Stable 400 W laser might be available in near future. Assuming the power recylcing gain to be the same as bKAGRA, 10, and assuming some losses in the input optics, the input power at BS is set to be 3500 W at maximum for *HF* and *Combined*. For other plans, we optimized the sensitivity with the condition that the input power at BS is less than 1500 W.

D. Filter cavity and squeezing

Filter cavity quantum noise calculations are based on the calculation by Y. Enomoto [7]. Filter cavity parameters used for *FDSQZ* and *Combined* sensitivities are summarized in Table II. Filter cavity length is assumed to be 30 m, considering the space restrictions around signal recycling cavity and OMC chambers for KAGRA.

The half bandwidth and detuning of the filter cavity were determined with [8]

$$\gamma_{\rm fc} = \sqrt{\frac{2}{(2-\epsilon)\sqrt{1-\epsilon}}}\frac{\omega_{\rm SQL}}{\sqrt{2}} \tag{1}$$

and

$$\Delta\omega_{\rm fc} = \sqrt{1-\epsilon}\gamma_{\rm fc}, \tag{2}$$

where ϵ is the loss parameter given by

$$\epsilon = \frac{4}{2+\sqrt{2+2\sqrt{1+\left(\frac{4L_{\rm fc}\omega_{\rm SQL}}{c\Lambda_{\rm rt}^2}\right)^4}}}. \tag{3}$$

$\omega_{\rm SQL}$ is the frequency at which the quantum noise equals the standard quantum limit. For a tuned interferometer without losses, $\omega_{\rm SQL}$ can be obtained by solving $\mathcal{K} = 1$, where

$$\mathcal{K} = \frac{16\pi c I_{\rm RSE}}{m\lambda L_{\rm arm}^2\omega^2(\gamma_{\rm RSE}^2+\omega^2)} \tag{4}$$

is the optomechanical coupling constant (a.k.a *Kimble factor*) [9], and is given by

$$\omega_{\rm SQL} = \sqrt{\frac{-\gamma_{\rm RSE}^2+\sqrt{\gamma_{\rm RSE}^4+\frac{64\pi c I_{\rm RSE}}{m\lambda L_{\rm arm}^2}}}{2}} \tag{5}$$

Here,

$$I_{\rm RSE} = \frac{1+r_{\rm SRM}}{1-r_{\rm SRM}}I_0 \tag{6}$$

and

$$\gamma_{\rm RSE} = \frac{1+r_{\rm SRM}}{1-r_{\rm SRM}}\gamma_{\rm arm}. \tag{7}$$

m is the mass of the test mass, λ is the laser wavelength, $L_{\rm arm}$ is the arm length, $r_{\rm SRM}$ ($t_{\rm SRM}$) is the amplitude reflectivity (transmissivity) of the SRM, I_0 is the laser power at BS, and $\gamma_{\rm arm}$ is the arm cavity half bandwidth.

The input mirror transmissivity of the filter cavity is tuned by

$$T_{\rm fc} = \frac{4L_{\rm fc}\gamma_{\rm fc}}{c} - \Lambda_{\rm rt}^2, \tag{8}$$

to obtain the required filter cavity bandwidth.

We remind here that optimal filter cavity bandwidth and detuning for tuned RSE is used for our calculations, even if *FDSQZ* and *Combined* has slight SRC detuning to maximize BNS inspiral range.

For *HF*, frequency independent squeezing is assumed. The injected squeezing is set to 10 dB, and injection loss is assumed to be 5%. In all the sensitivity calculations, the losses at the SRM and at the detection photodiode are assumed to be 0.2% and 10%, respectively. The arm cavity round trip loss is assumed to be 100 ppm.

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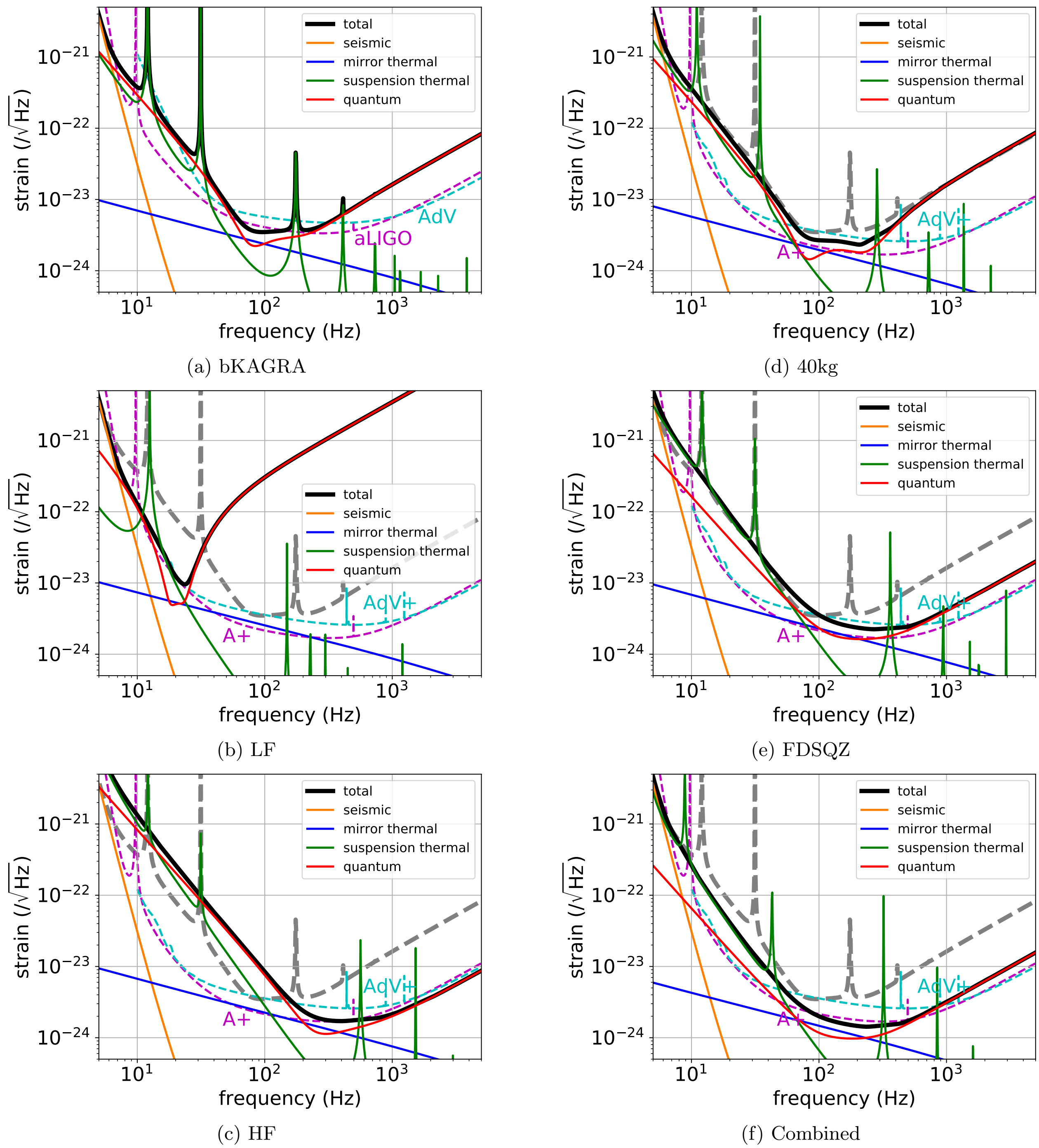
TABLE I. Interferometer parameter values, inspiral ranges and median of sky localization error for GW17817-like binary for bKAGRA and upgrade candidates. Note that inspiral ranges and sky localization errors for upgrade candidates are calculated with smoothened curves. The figure of merit used for the parameter optimization is shown in bold. *LF* sensitivity is optimized with $100M_\odot$-$100M_\odot$ inspiral range upto ISCO at ~ 20 Hz to focus the sensitivity at low frequencies. Details of the parameter optimization and the inspiral range and sky localization calculations are given in Ref. [6]. aLIGO sensitivity and AdV sensitivity are used for the sky localization calculations.

		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

TABLE II. Filter cavity parameters used for the sensitivity calculation of *FDSQZ* and *Combined* sensitivities. Values in parentheses correspond to the parameters for *Combined*. Injected squeezing is also 10 dB for *HF*, and $\Lambda_{\rm in}^2 + \Lambda_{\rm out}^2$ is set to 5% for *HF*. Note that $\Lambda_{\rm in}^2 + \Lambda_{\rm out}^2$ equals to $\Lambda_{\rm inj}^2$ in Ref. [8].

Parameter	Symbol	Value
filter cavity length	$L_{\rm fc}$	30 m
filter cavity input mirror transmissivity	$T_{\rm fc}$	189 ppm (148) ppm
filter cavity half bandwidth	$\gamma_{\rm fc}/(2\pi)$	87 Hz (71) Hz
filter cavity detuning	$\Delta\omega_{\rm fc}/(2\pi)$	74 Hz (58) Hz
filter cavity losses	$\Lambda_{\rm rt}^2$	30 ppm
losses between squeezer and filter cavity	$\Lambda_{\rm in}^2$	5%
losses between filter cavity and SRM	$\Lambda_{\rm out}^2$	5%
injected squeezing	$\sigma_{\rm dB}$	10 dB



(a) bKAGRA

(d) 40kg

(b) LF

(e) FDSQZ

(c) HF

(f) Combined

FIG. 1. Sensitivity curves for bKAGRA and upgrade candidates. Sensitivity curves for Advanced LIGO (aLIGO) and Advanced Virgo (AdV) are also shown for comparison in (a). For other plots, sensitivity curves for their upgrades A+ and AdV+, and bKAGRA are shown for comparison. Note that thermal noise peaks in the sensitivities for KAGRA upgrade plans are ommited to generate smooth curves.