Estimating the sensitivity for KAGRA in O4a

Yuta Michimura[1, *]

[1] *Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*

(Dated: December 10, 2021)

JGW-T2113287 2021.12.10: Fixed a typo in Eq. (2).

I. SCOPE

This document describes how to estimate the sensitivity for KAGRA in O4a. Here, we assumed the room temperature operation. Low frequency noise and high frequency noise are estimated from the fitting of the best sensitivity curve achieved in the O3 era. This noise model, dubbed O3GK noise model, is described in the next section, and the estimation method for O4a sensitivity is described in the subsequent section.

II. KARA O3GK MODEL

The O3GK noise model is given by

$$S_{\rm O3GK}(f) = S_{\rm LF}(f) + S_{\rm thermal}(f) + S_{\rm HF}(f), \quad (1)$$

where f is the Fourier frequency, $S_{\rm LF}(f)$ is the power spectral density of the low frequency excess noise, $S_{\rm thermal}(f)$ is the sum of suspension thermal and mirror thermal noises, and $S_{\rm HF}(f)$ is the high frequency noise mainly from the shot noise. $S_{\rm LF}(f)$ and $S_{\rm HF}(f)$ are given by the fitting of the best sensitivity curve achieved on March 26, 2021. The noise curves are given in Fig. 1. The noise data is given in `O3GKSensitivityModel.txt` of JGW-T2113287.

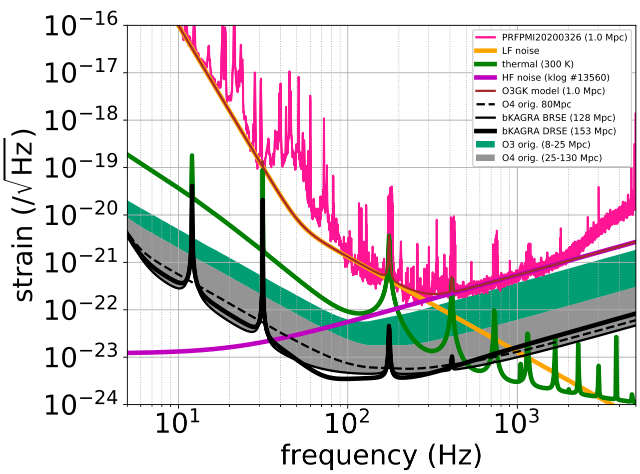

FIG. 1. The O3GK noise model and the best sensitivity curve achieved on March 26, 2021. Orignal target sensitivity in O3 and O4 from the observing scenario paper [1] are also plotted.

A. Low frequency noise

The low frequency noise $S_{\rm LF}(f)$ is from the fitting of the best sensitivity and is given by

$$S_{\rm LF}(f) = \left[1.3 \times 10^{-17} \left(f/1~{\rm Hz}\right)^{-2}\right]^2 + \left[1.0 \times 10^{-10} \left(f/1~{\rm Hz}\right)^{-6}\right]^2 ~/\sqrt{\rm Hz}. \quad (2)$$

B. Thermal noise

Thermal noise for the O3GK model $S_{\rm thermal}(f)$ is the sum of suspension thermal and mirror thermal noise at 300 K calculated in Ref. [2]. Note that, in O3GK, mirror temperature was actually at around 250 K. The difference is only about 5 % in amplitude at 100 Hz [3].

C. High frequency noise

The high frequency noise $S_{\rm HF}(f)$ is from the fitting of the best sensitivity and is given by

$$\sqrt{S_{\rm HF}(f)} = 1.2 \times 10^{-23} ~/\sqrt{\rm Hz} \times \sqrt{1 + (f/f_{\rm c})^2}, \quad (3)$$

where $f_{\rm c} = 22.2$ Hz is the cavity pole frequency [4]. Here, it is assumed that the high frequency noise is dominated by the shot noise in PRFPMI configuration. The shot noise with various input laser power and optical losses will be roughly proportional to $\sqrt{S_{\rm HF}(f)}$, if the interferometer configuration is PRFPMI or FPMI. For example, $\sqrt{S_{\rm HF}(f)}$ scales with $1/\sqrt{P_{\rm in}}$, where $P_{\rm in}$ is the input laser power. For DRFPMI, the cavity pole frequency and effective input laser power will change.

III. ESTIMATING THE SENSISITVITY FOR O4A

The estimated sensitivity for O4a can be written as

$$S_{\rm O4a}(f) = k_{\rm LF}^2 S_{\rm LF}(f) + S_{\rm thermal}(f) + k_{\rm HF}^2 S_{\rm HF}(f). \quad (4)$$

Here, the following assumptions are made:

* michimura@phys.s.u-tokyo.ac.jp

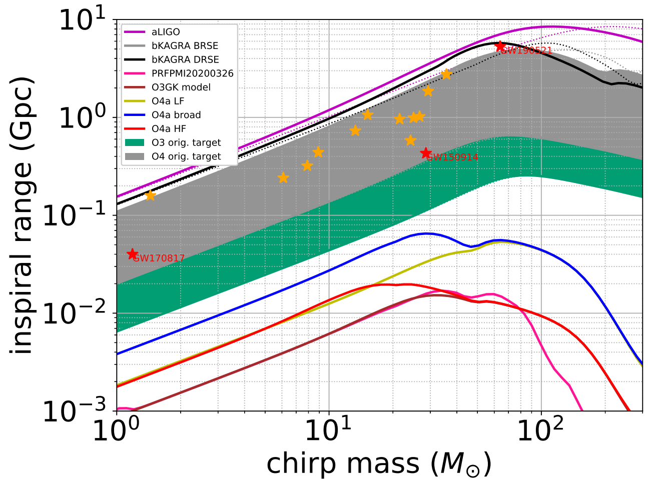

FIG. 2. The detection ranges of example KAGRA O4a sensitivity for non-spinning equal-mass binaries. The redshift corrected, sky averaged distance at which gravitational waves can be detected with signal-to-noise ratio of more than 8 is shown for each curve. O4a LF: $k_{\rm LF} = 1/5$ and $k_{\rm HF} = 1$, O4a broad: $k_{\rm LF} = 1/5$ and $k_{\rm HF} = 1/5$, O4a HF: $k_{\rm LF} = 1$ and $k_{\rm HF} = 1/5$

- The shape of the low frequency excess noise do not change and it is proportional to $S_{\rm LF}(f)$.

- The test mass for O4a is at room temperature

- The interferometer configuration is PRFPMI or FPMI, and the contribution of quantum radiation pressure noise is negligible.

Fig. 2 gives the sky averaged inspiral range for example O4a sensitivity curves. The inspiral range is calculated using the inspiral-merger-ringdown waveform compiled in Ref. [5]. O4a LF, broad and HF sensitivity curves are calculated by assuming $k_{\rm LF} = 1/5$ and/or $k_{\rm HF} = 1/5$. Note that, if the same interferometer configuration with the same noise level as O3GK is achieved, the shot noise can be reduced by a factor of $k_{\rm HF} = 1/\sqrt{2} \times \sqrt{0.3} \simeq 1/2.6$, just by replacing the SRM to $T = 0\%$ one and by fixing one of the OMC DC PD. The amount of $k_{\rm LF}$ is harder to estimate, but can be reduced by optimizing the suspension controls and interferometer controls.

[1] KAGRA Collaboration, LIGO Scientific Collaboration and Virgo Collaboration, Living Reviews in Relativity 23, 3 (2020).

[2] KAGRA Collaboration, Progress of Theoretical and Experimental Physics 2020, 05A101 (2020).

[3] Y. Michimura, *Summary of Sensitivity Estimate for O4 in Various Interferometer Configurations*, JGW-T2011662 (2020).

[4] Y. Michimura, *Comment to Noise budget for PRFPMI*, klog #13560 (2020).

[5] P. Ajith, M. Hannam, S. Husa, Y. Chen, B. Brügmann, N. Dorband, D. Müller, F. Ohme, D. Pollney, C. Reisswig, L. Santamaria, J. Seiler, Phys. Rev. Lett. 106, 241101 (2011).