

Prospects for improving the sensitivity of KAGRA gravitational wave detector

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Upgrades to improve the sensitivity of gravitational wave detectors are critical for enriching our understandings of the sources and for more precise tests of gravity theories and more precise astronomical observations. Unlike other state-of-the-art detectors such as Advanced LIGO and Advanced Virgo, KAGRA requires a different approach for the upgrade since it is the only detector which employs cryogenic cooling of the test mass mirrors. Here, we present possible KAGRA upgrade plans which can be realized by reducing or increasing the input laser power, increasing the mirror mass and injecting frequency dependent squeezed vacuum. We show that each upgrade is effective for different frequency bands and gives different impact on gravitational wave science. We then discuss an effective progression of upgrades based on technical feasibility and science cases.

Keywords: Gravitational waves; Cryogenics; Underground; Laser interferometer; Optimization

1. Introduction

The era of gravitational wave astronomy began with the first direct detections of gravitational waves from binary black holes and binary neutron star systems by Advanced LIGO and Advanced Virgo^{1,2}. Improving the sensitivity of these detectors enables more frequent detection and more precise source parameter estimation. To this end, there have been extensive studies to improve the sensitivity beyond the detector's original design sensitivity.

Within LIGO Scientific Collaboration and Virgo Collaboration, there are ongoing effort to upgrade Advanced LIGO and Advanced Virgo detectors to *A+*³ and *AdV+*⁴, respectively, by around 2024⁷. The designed sensitivities of *A+* and *AdV+* are improved over that of Advanced LIGO and Advanced Virgo by roughly a factor of two. The improvement is in part realized by the coating thermal noise reduction either from the mechanical loss reduction of the coating material or from larger beam size. Also, broadband quantum noise reduction is expected by using a 300-m filter cavity^{6,7} to generate frequency dependent squeezed vacuum.

KAGRA is another laser interferometric gravitational wave detector which is being built in Japan^{8,9}. Compared with Advanced LIGO and Advanced Virgo, KAGRA has two technologically unique features: it is constructed at a seismically quiet underground site, and it uses sapphire mirrors at cryogenic temperatures to reduce thermal noise. Therefore, KAGRA has unique potential to further improve its sensitivity and upgrading KAGRA will require different approach compared with other detectors.

In this paper, we discuss the prospects for the upgrade of KAGRA detector. We start by describing possible technologies that can be applied for upgrading KAGRA and show that different technologies will improve the sensitivity in different frequency bands. We then discuss science cases for each upgrades, and show possible strategy for the KAGRA upgrade.

2. Technologies for the KAGRA upgrade

The current design sensitivity of KAGRA is shown in Fig. 1. At low frequencies, the sensitivity is limited by the suspension thermal noise and the quantum radiation pressure noise. At high frequencies, the sensitivity is limited by the quantum shot noise. At the most sensitive band in the mid-frequencies, the sensitivity is limited by the mirror thermal noise, which mainly comes from coating Brownian noise. Thanks to cryogenic cooling of the test masses to 22 K, the mirror thermal noise is smaller than Advanced LIGO and Advanced Virgo although the size of the test mass is smaller. However, the suspension thermal noise is higher since the heat extraction is done by the fibers suspending the test mass and it requires thick and short fiber (1.6 mm diameter, 35 cm long) for efficient heat extraction. The quantum shot noise is also higher due to input laser power limitation for cryogenic cooling. Because of these features, KAGRA plans to use quantum non-demolition techniques such as the detuning of the signal recycling cavity and homodyne readout to reduce quantum

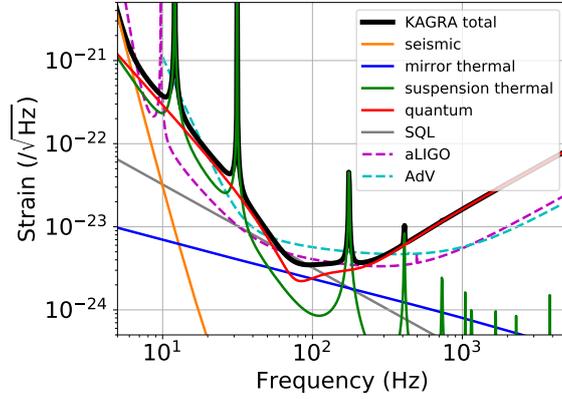


Fig. 1. The design sensitivity of KAGRA. The seismic noise shown includes the estimated Newtonian noise from the surface and bulk motion of the mountain containing KAGRA. The mirror thermal noise shown is the sum of the thermal noise from the test mass substrates and the coatings. Sensitivity curves for Advanced LIGO (aLIGO)¹² and Advanced Virgo (AdV)⁵ are also shown for comparison.

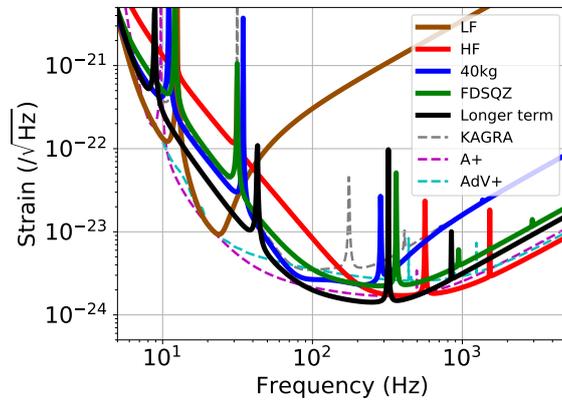


Fig. 2. Example sensitivity curves for the upgrade of KAGRA using different technologies. LF: Lower input power plan to focus on low frequency. HF: Higher power plan with frequency independent squeezing to focus on high frequency. 40kg: Sensitivity with the increased the mass of the test masses from 23 kg to 40 kg. FDSQZ: Sensitivity with the injection of frequency dependent squeezing generated with a 30-m filter cavity. Longer term: Example of longer term upgrade plan combining multiple technologies. Sensitivity curves for A+¹³ and AdV+⁵ are also shown for comparison.

noise in the most sensitive band at the cost of narrowing the detector bandwidth. Detailed discussion on the sensitivity optimization of KAGRA is given in Refs.^{10,11}

To improve the sensitivity of KAGRA, retuning of laser power and suspension parameters will help at certain frequency bands. Increasing the mirror mass and

injection of frequency dependent squeezing are also promising ways to improve the KAGRA sensitivity. In the following subsections, we will discuss the effect of each technology for the upgrade of KAGRA. We will then discuss longer term (~ 5 -10 years) prospects for the KAGRA upgrade which can be realized by combining multiple technologies.

Example sensitivity curves of KAGRA upgraded with different technologies discussed below are shown in Fig. 2. The interferometer parameters and dimensions of the suspension fibers to calculate these sensitivity curves are optimized with particle swarm optimization method¹¹.

2.1. *Laser power and heat extraction*

The input laser power and suspension thermal noise is closely related in KAGRA since heat extraction is done by the suspension fibers. To improve the sensitivity at low frequencies, reduction of suspension thermal noise is necessary, and this can be done by changing the suspension fibers to thinner and longer ones. However, this will result in larger shot noise because the heat extraction efficiency will be less and maximum input laser power allowed will be less. Similarly, higher laser power to reduce shot noise at high frequencies require thicker and shorter suspension fibers, which will result in larger suspension thermal noise.

The *LF* curve shown in Fig. 2 is an example curve which the sensitivity at low frequencies is improved by lowering the laser power at the beam splitter from 673 W to 5 W. This plan requires higher detuning of the signal recycling cavity to reduce quantum noise at 20-30 Hz. The suspension thermal noise peak at 31 Hz in the original KAGRA design sensitivity comes from the vertical motion of the intermediate mass suspension. Therefore, to remove this peak from the low frequency band, the LF plan also requires heavier intermediate mass with thinner and longer suspension wires. The interferometer parameters are optimized to maximize the inspiral range of $100 M_{\odot} - 100 M_{\odot}$ binaries.

The *HF* curve shown in Fig. 2 on the other hand focuses on the high frequencies by increasing the laser power at the beam splitter to 3400 W. It also assumes the injection of frequency independent squeezing (6 dB of detected squeezing at high frequencies) to further reduce the shot noise. The interferometer parameters are optimized to minimize the sky localization error of GW170814-like binary neutron stars¹¹.

2.2. *Increasing the mirror mass*

Increasing the mass of the test mass generally improves the sensitivity since the suspension thermal noise and quantum radiation pressure noise scales with $m^{-3/2}$ and m^{-1} , respectively. The coating thermal noise also can be reduced since larger mirror allows larger beam size on the mirror. Assuming both the aspect ratio of the mirror and the ratio of the beam diameter to the mirror diameter to be the same, the coating thermal noise scales with $m^{-1/3}$.

The *40kg* curve shown in Fig. 2 is an example sensitivity with the mirror mass increased from 22.8 kg to 40 kg. Considering the design of the current KAGRA cryostat, 40 kg would be the size limit without changing the design drastically. The interferometer parameters are optimized to maximize the inspiral range of $1.4 M_{\odot} - 1.4 M_{\odot}$ binaries. We note here that coating thermal noise reduction by larger beam size is assumed but smaller mechanical loss of the coating material is not assumed in the sensitivity calculation to show a feasible plan.

Interestingly, increasing the mirror mass result in the sensitivity improvement only at mid-frequencies where coating thermal noise dominates. This is because heavier mass requires higher laser power to keep the frequency f_{SQL} where quantum noise reaches the standard quantum limit. In case of KAGRA, f_{SQL} should be as high as possible until the quantum noise reaches the coating thermal noise, if we want to maximize the inspiral range since the frequency dependence of the standard quantum limit f^{-1} is steeper than that of the inspiral signal ($f^{-2/3}$). Therefore, the laser power I_0 scales with more than m . Higher laser power require thicker suspension fiber and in the end the suspension thermal noise is not much dependent on the mirror mass.

2.3. Frequency dependent squeezing

Injection of frequency dependent squeezed vacuum is a promising way to reduce both radiation pressure noise and shot noise, which can be done without increasing the mirror mass or the laser power. The *FDSQZ* curve shown in Fig. 2 is an example curve which can be realized with 30-m filter cavity and 5 dB of detected squeezing at high frequencies. 30-m filter cavity can be constructed along the vacuum tubes of the signal recycling cavity. The interferometer parameters are optimized to maximize the inspiral range of $1.4 M_{\odot} - 1.4 M_{\odot}$ binaries.

As discussed previously, the input laser power should be increased for higher f_{SQL} and this result in slightly worse suspension thermal noise. Also, injection of the squeezed vacuum prefers no detuning of the signal recycling cavity. Therefore, injection of frequency dependent squeezed vacuum result in a sensitivity improvement at high frequencies.

2.4. Longer term prospects

As we have shown, applying only one of these technologies give sensitivity improvement at certain frequency bands. Combination of multiple technologies is necessary for broadband sensitivity improvement. The *Longer term* curve shown in Fig. 2 is an example sensitivity for 5-10 year upgrade plan which can be realized with 100 kg mirror mass, 30-m filter cavity and 3500 W of the laser power at the beam splitter. The interferometer parameters are optimized to maximize the inspiral range of $1.4 M_{\odot} - 1.4 M_{\odot}$ binaries.

The situation is similar to *FDSQZ* plan, but because of larger test mass, suspension thermal noise and coating thermal noise are also reduced. In total, twofold

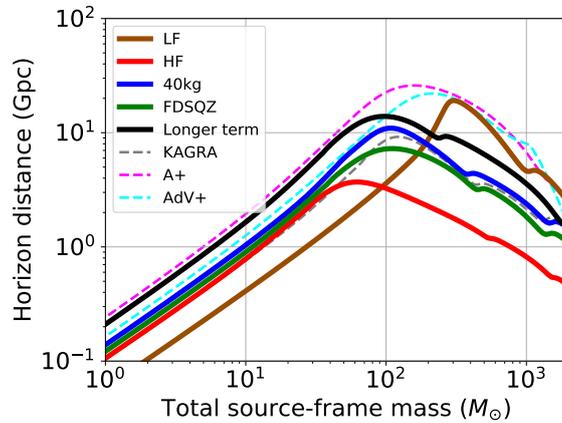


Fig. 3. The horizon distance of example KAGRA upgrades for equal-mass, nonspinning binaries. The horizon distance show the maximum distance at which gravitational waves can be detected with signal-to-noise ratio of more than 8.

broadband sensitivity improvement will be realized.

3. Science case study and disussion on strategic upgrade

As shown in the previous section, combination of multiple technologies is necessary for the broadband sensitivity improvement. Upgrades to the detector requires incremental implementation of the upgrade components and which to be implemented at earlier stages depend on the technological feasibility and impact on gravitational wave science.

Figure. 3 shows the horion distance of each example upgrade for compact binary coalescences. *LF* plan has the largest horizon distance above $200M_{\odot}$ in total mass, whereas *40kg* plan has the largest horizon distance for smaller masses. We can say that *LF* has the highest probability of detecting the intermediate mass black holes (IMBHs).

Although the horizon distance is not great, *HF* plan gives the smallest sky localization error for binary neutron stars. The median of the sky localization error for GW170817-like binaries calculated with the same method described in Ref. 11 for *LF*, *HF*, *40kg* and *FDSQZ* are 0.507 deg^2 , 0.105 deg^2 , 0.156 deg^2 and 0.119 deg^2 , respectively. For the sky localization of binary black holes, *40kg* gives the smallest error. For constraining neutron star equation of state and for search for continuous wave from pulsars, *HF* and *FDSQZ* will be the best choices since the sensitivity from 500 Hz to 4 kHz is important for these study.

From the technical feasibility point of view, *LF* has the largest uncertainty since reducing low frequency excess noises other than the fundamental noises discussed above is generally tough. 40 kg test mass would be feasible in next few years, but even larger mirror is required for longer term upgrade. Considering that higher

power laser source and squeezed vacuum source are required for longer term upgrade, implementing these as a first step to focus on high frequency sensitivity improvement for the upgrade would be a strategy. *HF* plan is also attractive in that it might be able to do original science because *HF* has better sensitivity at high frequencies than A+ and AdV+.

4. Summary

Upgrading KAGRA requires simultaneous tuning of the parameters related to thermal noise and those related to quantum noise since the heat extraction is done through the fibers suspending the test mass mirrors. We showed that shifting the detector frequency band of KAGRA is possible by changing the input laser power. We also showed that increasing the mirror mass and injection of frequency dependent squeezed vacuum will improve the sensitivity at mid-frequencies and high frequencies, respectively. Considering the technical feasibility and impact on the detection of gravitational waves, possible strategy for upgrading KAGRA would be to focus on high frequency improvement with higher laser power and squeezed vacuum injection for near term. In the longer term, broadband two improvement with frequency dependent squeezed vacuum injection and heavier mirror would be realized.

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