Interferometric Gravitational-Wave Detectors: Current Status and Future Plans

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Abstract.
Constructions of the first-generation interferometric gravitational-wave detectors, such as LIGO, VIRGO, GEO600, and TAMA300, have been finished, and long-term observation runs have been carried out as a global network. These data are analyzed in searches for gravitational-wave signals, and are starting to produce scientific results. In addition, next-generation detectors, which will have sufficient sensitivity to directly detect gravitational waves, are being proposed. In this article, the status of the current detectors, scientific results obtained form observation data, and future interferometric detector plans are reviewed.

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I. INTRODUCTION

Direct observations of gravitational waves (GWs) are expected to reveal new aspects of the universe [1]. Since GWs are emitted by the coherent bulk motion of matter, and are hardly absorbed or scattered, observations with GWs will provide complementary information to that with electromagnetic waves and, moreover, provide completely new information that cannot be obtained by other observations (Fig. 1).

Among various kind of gravitational-wave detectors, the largest efforts in the community are being put into the development, operation, and analysis of laser-interferometric detectors. Interferometric detectors have been investigated with many table-top and prototype experiments since the early 1970s [2, 3]. With the knowledge obtained from these experiments, several gravitational-wave detectors, called first-generation interferometric detectors, have started observation runs: LIGO in USA [4], VIRGO [5] and GEO600 [6] in Europe, and TAMA300 in Japan [7] (Table 1). The observation range of these detectors reaches 15 Mpc for gravitational-wave signals from neutron-star binary inspirals. The data collected by them are analyzed to look for gravitational-wave signals. Though no gravitational-wave signal has been found to date, results with scientific significance have been obtained.

In order to increase the chance of observation, and thus open a new window of gravitational-wave astronomy, several future plans have been proposed, or have already started. There are two ways to increase the detection possibility. One is to improve the sensitivity of the current ground-based detectors to watch distant galaxies. Another is to expand the observation frequency band, in particular to lower frequencies, to observe large scale and more stationary phenomena. The former will be realized by next-generation ground-based interferometers, and the latter by interferometers in space.

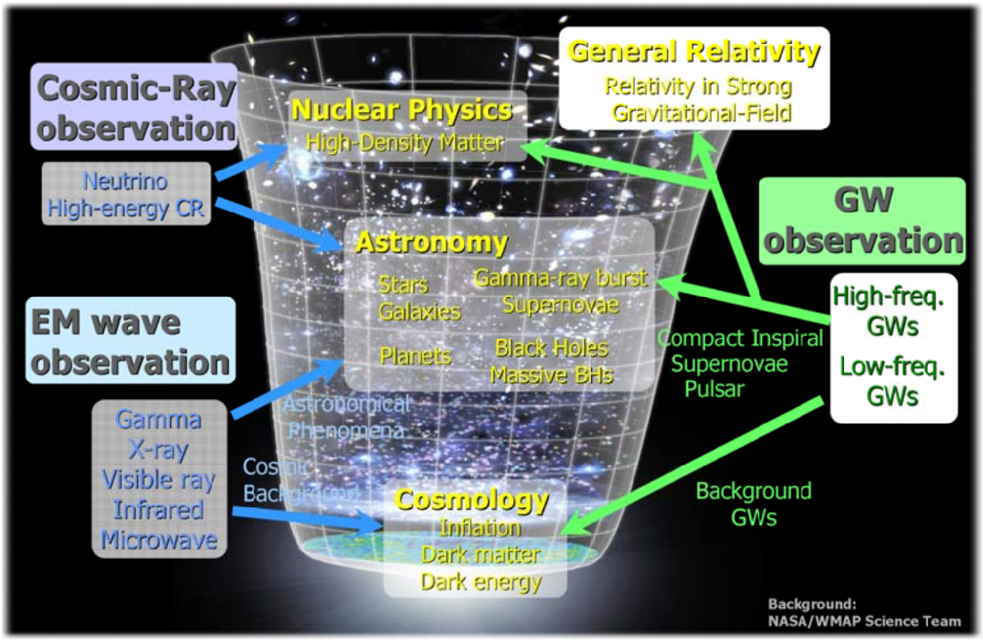

FIGURE 1. Gravitational-wave observation as a counterpart of other observations.

As future ground-based detectors, Advanced LIGO [8], Advanced VIRGO [9], and LCGT [10] are planed as second-generation detectors, and detailed designs are being refined. These detectors will have sufficient sensitivities to cover a few hundred Mpc range for neutron-star inspiral events, with which we expect a signal detection rate of more than several events per year. In the more distant future, ET (Einstein gravitational-wave Telescope) [11] is being considered as a third-generation interferometric detector, which will have sensitivity to observe throughout the universe by means of GWs. As for space detectors, LISA (Laser Interferometer Space Antenna) [12], DECIGO (DECI-hertz interferometer Gravitational wave Observatory) [13], and BBO (Big-Bang Observer) [14, 15] are proposed. They have guaranteed signal sources, and will be powerful detectors for gravitational-wave astronomy and cosmology.

In this article, I will review the status of current interferometric detectors, analysis results using observation data, and future plans of ground-based and space detectors [16, 17].

II. INTERFEROMETERS UNDER OPERATION

Interferometric gravitational-wave detectors are based on a Michelson interferometer. The quadrupole nature of a GW causes differential changes in the arm lengths of the Michelson interferometer, which are detected as changes in the interference fringe (Fig. 2). An interferometer is designed so as to have a sensitive frequency band between about 10 Hz to a few kHz, which is only limited by seismic noise, thermal noises, and shot noise. As a laser source, a Nd:YAG laser with an output power of 10-20 W and a wavelength of 1064 nm is used. Before being introduced to the main interferometer, the

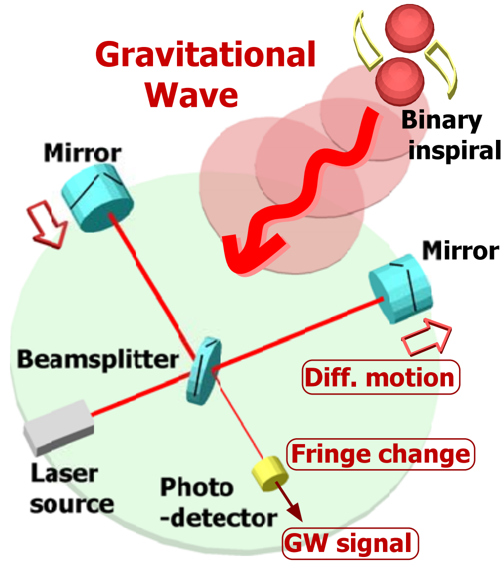

FIGURE 2. Principle of gravitational-wave observation with a Michelson interferometer.

laser beam is stabilized in frequency and amplitude, and passed through a cavity used as a spacial mode cleaner. The main mirrors of the interferometer are made of fused silica, and the surfaces are polished and coated as dielectric multi-layer mirrors. Each mirror is suspended by a pendulum to behave as a free test mass, and which is supported by a seismic isolation system. The interferometer is placed inside a vacuum tank so as to avoid any effect of acoustic disturbances and fluctuations in the optical paths. In order to keep the interferometer at its operational point, lengths between the optical components are controlled. The control system is designed to realize high sensitivity and stability at the same time. The fine position and orientation of each mirror is controlled with coil-magnet or electro-static actuators.

In observation runs, the outputs of an interferometer, which could contain the signal of GWs, are recorded as a time-series data with analog-to-digital converters at a sampling frequency of 10-20 kHz. Since the interferometer is a very sensitive instrument, and easily affected by external disturbances, signals to check the environment and detector condition are usually recorded together. The data have a precise time index, usually synchronized with a global positioning system (GPS) within an accuracy of 1 μsec. A timing signal is used in combined data-analysis with multiple detectors, or to determine the signal-arrival time when a gravitational-wave signal is detected.

1. LIGO

The largest interferometric detector currently under operation is LIGO (Laser Interferometer Gravitational-wave Observatory), placed at two sites (Hanford, Washington and Livingston, Louisiana) in the USA [4]. Each site has a power-recycled Michelson interferometer with 4-km Fabry-Perot arm cavities. The Hanford site also has a 2-km

TABLE 1. Interferometric gravitational-wave detectors under operation

LIGO [4]	(USA.)	Laser Interferometer Gravitational Wave Observatory Fabry-Perot Michelson with power recycling Baseline: 4 km (2 detectors) and 2 km Sensitivity $3 \times 10^{-23}/\sqrt{\mathrm{Hz}}$ (at 100-300 Hz)
VIRGO [5]	(ITA/FRA)	Fabry-Perot Michelson with power recycling Baseline: 3 km Sensitivity $5 \times 10^{-23}/\sqrt{\mathrm{Hz}}$ (at 200-300 Hz)
GEO [6]	(GER/UK.)	Michelson interferometer with dual recycling Baseline: 600 m Sensitivity $3 \times 10^{-22}/\sqrt{\mathrm{Hz}}$ (at 500 Hz-1 kHz)
TAMA [7]	(JPN)	Fabry-Perot Michelson with power recycling Baseline: 300 m Sensitivity $1.5 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ (at $\sim$ 900 Hz)

interferometer, sharing the building and the vacuum system with the 4-km detector. The long separation between two sites, about 3000 km, ensures that the local disturbances around the detectors are uncorrelated, which enables us to drastically reduce the number of fake events caused by the detector instability and so on. In addition, the separation corresponds with a substantial baseline to identify the sky position of the source by measuring the difference in the signal arrival time. The interferometers at the two sites are co-aligned to maximize the correlations of real signals.

Construction of the detector was started in the year 1995, and the detector sensitivity reached the design sensitivity, $3 \times 10^{-23}\sqrt{\mathrm{Hz}}$ for 4-km detectors, in 2005 [18]. Five observation runs, called science runs, have been carried out since the first run (S1) in 2002. The second science run (S2) was held for 59 days between February to April in 2003, and the third run (S3) was for 70 days from October 2003 to January 2004. The fourth run (S4) was held from February to March 2005 for 29 days. The collected data have been analyzed to search for gravitational-wave signals with various waveforms, and the results have been published. The latest observation, the fifth science run (S5), was started in November 2005 and ended in October 2007. In this run, LIGO collected 1 year of triple coincidence data, with a triple-coincidence duty cycle of 53% (and with about a 75% duty cycle for each detector) [19]. At the time of S5, the observable range was 15 Mpc for a binary inspiral of 1.4 $M_\odot$ neutron stars, with averaged sensitivity over all-sky-positions and polarizations of the sources. This range corresponds to cover about 200 Milky-way equivalent galaxies.

2. VIRGO

VIRGO is a 3-km interferometric detector placed close to Cascina (Pisa, Italy), constructed by the collaboration of French and Italian groups [5]. VIRGO has an optical configuration of a Fabry-Perot-Michelson interferometer with power recycling. The characteristic feature of VIRGO is that each mirror is suspended from a Superattenuator, which is designed to reduce the effect of seismic vibrations well below the sensitivity curve at a low-frequency band well below 10 Hz. The Superattenuator consists of a 6-m inverted pendulum and a chain of six seismic filters.

VIRGO finished its first phase of commissioning, and the first observation run, VSR1 (VIRGO Science Run 1), was carried out from May to October in 2007, joining the LIGO S5 run [9, 20]. The observation duty cycle was 81%, and the observable range for neutron-star inspirals was 4 Mpc. Currently, the floor level sensitivity is about $5 \times 10^{-23} \sqrt{\text{Hz}}$, which is very close to the designed sensitivity [9]. The observable range is more than 5 Mpc for binary inspiral of 1.4 $M_{\odot}$ neutron stars, with averaged sensitivity over all-sky-positions and polarizations of the sources.

3. GEO600

GEO600 is an interferometer with a 600-m arm length, built in Hannover, Germany, by a German-British collaboration [6]. In order to overcome the disadvantage of a shorter arm length than LIGO and VIRGO, GEO600 incorporates advanced techniques in its optical configuration and in the design of the mirror suspension. The optical configuration of GEO60 is different from those of LIGO, VIGO, and TAMA; its has a dual recycling (power and signal recycling) configuration instead of Fabry-Perot arm cavities. Signal recycling is used to tune the observation band and to adjust the response of the detector to incident GWs. Another distinguishing feature of GEO600 is that the suspension wire of each test-mass mirror is made of fused silica, which has a higher quality factor than metal ones, in order to reduce the effect of suspension thermal noise.

The observation runs of GEO600 have been carried out in coordination with these of LIGO. In S4, the GEO600 detector was operated with a high duty cycle of 95%, and for the longest continuous operation of more than 52 hours. GEO600 has a floor sensitivity of better than $3 \times 10^{-22} \sqrt{\text{Hz}}$. In the S5 run, GEO600 was operated along with the LIGO detectors, splitting the term into detector improvement periods and a full observation period. During the detector improvement periods, the detector was operated in the so-called night- and weekend-mode. At this time, observation data were taken during nights and weekends. The day time was dedicated to commissioning work, while mainly focusing on gaining a better understanding of the performance and improving the data quality. The duty cycle for science data was about 46-56% during these periods. In the period from May to October, 2006, GEO600 was operated in a full-time observation mode. The detector was operated with a duty cycle of about 95%, and 152 days of science data were collected in 168 days [21].

The GEO group has an upgrade plan of GEO-HF [22]. Since it has a constraint in the arm length, it is difficult to improve its sensitivity in the low-frequency region. Thus, the GEO upgrade will concentrate on improving its sensitivity at high frequencies, at which the sensitivity is limited by shot noise. In GEO-HF, the laser source will be upgraded to a higher power one, and the signal-recycling parameters will be redesigned for better shot noise. The mirrors will be replaced so as to have lower thermal noise. In addition, GEO-HF might include the use of advanced technique involving squeezed states of light.

4. TAMA300

TAMA is a Japanese project to construct and operate an interferometric detector with a 300-m baseline length at Mitaka, Tokyo [7]. In the interferometer, called TAMA300, the arms of the Michelson interferometer are replaced by 300 m Fabry-Perot arm cavities to enhance the sensitivity to GWs. In TAMA, nine observation runs have been carried out so far, since the first observation run in 1999, and 3000 hours of data have been collected. Among them, a large amount of data were collected in the sixth, eighth, and ninth data-taking runs (DT6, DT8, and DT9, respectively). DT8 was carried out in corporation with LIGO S2 from February to April in 2003, and data were jointly analyzed with LIGO [23, 24]. In DT9, which was carried out from November 2003 to January 2004, most of the day time was spent to adjust and to characterize the detector during the first half term. On the other hand, data of uniform quality with a high duty cycle was collected in the second half; the duty cycle was 96% in this quiet term of DT9. The data obtained in DT9 was analyzed to search inspiral events, burst events, signals from pulsars, and ringdown waves from blackhole quasi-normal modes [25, 26, 27, 28]. TAMA has a sensitivity of $1.5 \times 10^{-21}\ /\sqrt{\mathrm{Hz}}$ in strain. The observable range is 73 kpc for a binary inspiral of 1.4 $M_{\odot}$ neutron stars, which sufficiently covers the inspiral events in our galaxy.

Currently, TAMA is in an upgrade phase; the seismic isolation systems have been replaced by better ones, called SAS (Seismic Attenuation System). The replacement has been finished and the improvement by the SAS has been confirmed experimentally. The interferometer will be operational again by the summer of 2008 [29, 30].

III. RESULTS FROM OBSERVATION RUNS

The observation data collected by current detectors are analyzed to look for gravitational-wave signals. There are several kinds of target gravitational-wave sources in these interferometric detectors [16, 17], and data-analysis schemes are being developed and applied to the observation data. The target GWs are classified by the signal waveforms and gravitational-wave sources: chirp waves from binary inspirals, burst waves from binary mergers and gravitational core-collapse, continuous waves from pulsars and stable binaries, and stochastic background from the early universe and the superposition of unresolved sources.

Since gravitational-wave signals are considered to be faint, an efficient data-analysis scheme is required to extract the signals of GWs from noisy detector outputs. The searches are roughly processed in the following steps. (1) Data conditioning. Since gravitational-wave detectors are very sensitive instruments, they could be affected by environmental disturbances, and data quality and calibration factors could be changed during long-term observation runs. In addition, the detector output usually contains undesired signals, such as line noises from the AC power supply, mechanical resonances of the instruments, and so on. In the data-conditioning step, the data are usually reshaped to have uniform quality in time and/or frequency. (2) Data processing with statistics. Statistics are defined to be suitable for the target gravitational-wave waveforms, and data streams are processed with them. Since the detection efficiency and signal-to noise ratio (SNR) are directly related to the statistics used in the analysis, selecting the statistics is the key feature in the gravitational-wave data analysis. (3) Extraction of signal candidates. Signal candidates are extracted by setting thresholds on the statistics obtained in the previous step. It is necessary to avoid arbitrariness as long as possible while tuning the thresholds, because the detection or non-detection of a gravitational-wave signal is judged by these thresholds. One method is to tune the analysis parameters, including the threshold, with a small subset of the observation data, which is called playground data. The playground data are only used in the tuning, and are not used in the signal search. (4) Veto. The outputs of detectors are non-stationary and non-Gaussian in general, which could result in fake gravitational-wave signals. The fakes are rejected by investigating the signal behavior, and/or comparing the output (the arrival time or the amplitude of the signal) of multiple detectors. (5) Signal search and interpretation of the result. Significant events are searched from the resultant event candidates. If there is no significant signal, an upper limit is set on the astrophysical parameters, such as the signal event rate, gravitational-wave amplitude, or parameters on gravitational-wave sources. In setting an upper limit, results from signal injection tests are often used: simulated gravitational-wave signal are artificially added to the detector (hardware injection) or detector output data (software injection). The obtained data are processed by the same analysis pipeline as the raw data. From the results of the signal injection test, we obtain the statistical distribution when real signals are included in the observation data.

A little more detailed explanations of the analysis, and the obtained results are described in this Section: chirp waves, burst waves, continuous waves, stochastic background waves, and also GWs from gamma-ray bursts [31].

1. Chirp waves from binary inspirals

In an inspiral phase of a compact-star binary system, the orbit of the binary gradually shrinks in time, by loosing the orbital energy as gravitational-wave radiation. The radiated GW, a chirp wave, has a sinusoidal waveform with increasing frequency and amplitude in time. The phase and amplitude evolution is confidently predicted from the relativistic equation of motion with a post-Newtonian approximation. Several neutron-star binary systems have been discovered so far [32, 33] and the merger rate is estimated using the observation results and knowledge of the star-formation rate [34, 35]. Since binary inspirals are a sure gravitational-wave source with predicted waveform and event rate, they are often used as a benchmark of detector performance.

The highest frequency of the radiated GW depends on the inner-most stable circular orbit determined by the total mass of the binary. It is about 1.6 kHz for a binary system with a total mass of 2.8 $M_{\odot}$, and is inversely proportional to the mass. Ground-based detectors with 10 Hz - a few kHz observation bands target at neutron-star binaries or small blackhole (BH) binaries. Space detectors, DECIGO [13] and BBO [14, 15], target at intermediate-mass BH binaries at 0.1-1 Hz band. A larger space detector, LISA [12], targets at massive BH binaries at around the 1 mHz band.

Since time-frequency evolution of the signal is well-predicted, an effective and sophisticated method of matched filtering can be used in a chirp-wave search; correlations between the data and a template (the predicted waveform) are calculated to extract a gravitational-wave signal from noisy data [36, 37]. In a search over a wide parameter space, such as masses of the binary stars, a set of templates is prepared to cover the parameter range. By setting a threshold on the output of the matched filter, an event candidate list is generated. The candidate lists from the different detectors are then compared, and events are kept only if they pass signal-consistency vetoes and coincidence vetoes. The signal-consistency vetoes use evaluation statistics which are constructed to distinguish whether the candidate behaves like a real signal or not. In an inspiral searches, a well-investigated method of the χ^2-veto is usually used. This tests the hypothesis that the distribution of the signal energy in each frequency band is consistent with the template waveform. The same search procedure is applied to data streams whose time-stamps are artificially shifted, so as to produces off-source candidate lists and to estimate the background of fake events. By comparing the on-source distribution with the background, the statistical significance of the on-source events is evaluated.

As a result of the inspiral search with LIGO observation data taken in the third (S3) and fourth (S4) science runs, no gravitational-wave candidate has been detected [38]. In the absence of detection, the upper limits on the binary-coalescence rates are set to be 0.5 events/yr/L_{10} with a confidence level of 90% for neutron-star and BH binaries. L_{10} is 10^{10} times the blue solar luminosity, corresponding to approximately 0.59 MWEG (Milky Way Equivalent Galaxy). The data from the fifth science run (S5) of LIGO is presently being analyzed. Since the data is better both in quality and quantity, the S5 result is expected to set more stringent upper limits by several orders of magnitude [38]. The other upper limit was set using 2705 hours of observation data with the TAMA300 detector, to be 12 events/yr/L_{10} with a confidence level of 90% [28].

2. Burst waves from mergers and core-collapses

Burst of large and short GWs are radiated from violent and catastrophic phenomena in the universe such as the merger phase of a binary system and the gravitational collapse of a stellar core. Since these events are chaotic in general and hard to model or to predict the gravitational-wave waveform, a matched filtering method cannot be used in the search for burst waves. Besides, more robust methods of excess-power-type filers have been proposed, and used in search analyses. In these filters, we define evaluation statistics, and record the filter output as a gravitational-wave event candidates if it is above a given threshold. Since these filters look for unusual glitches or non-stationary waveforms in the data stream, they are also sensitive to non-stationary noises of the detector. Thus the evaluation and reduction of fake-event backgrounds are critical problems in burst-wave searches.

Fake events are rejected by coincidences by multiple detectors, by a signal-based veto with waveform behaviors, and by auxiliary signals to monitor the detector status and the environment around the detector. Among them, the most powerful and reliable way will be a coincidence analysis with multiple independent detectors. If we detect gravitational-wave candidates by multiple detectors within acceptable time differences, we can declare the detection of a real signal with high confidence. In a rough estimation, the fake rate is reduced by a power of the number of independent detectors. On the other hand, fake reduction with a single detector is also important, even in a coincidence analysis, so as to reduce accidental coincidences. In observation runs, many auxiliary signals are recorded together with the gravitational-wave signal-channel in order to monitor the detector status. Since some of them are sensitive to detector instabilities, it is possible to reject non-stationary noises with them. In addition, even without precise gravitational-wave waveforms, fake events are rejected by investigations of the signal behavior with our knowledge or assumptions concerning the waveforms. The resultant false alarm, or background, rate is estimated by analyzing time-shifted data in the same way as in chirp analyses.

As the result of searches in the fourth science run (S4) of the LIGO and GEO600 detectors, no surviving candidate event above the estimated background was found. Then, an upper limit on the rate of detectable events has been sets to be 0.15 event/day with a 90% confidence level [39]. The range of the detectable signals in the search pipelines is measured by injecting signals in the data, and then by measuring the detection efficiency. Unlike the case of chirp-wave searches, no precise and analytical burst waveform is available, except for some examples from numerical simulations [40, 41]. In the S4 burst analysis, analytically assumed waveforms have been used to estimate the detection efficiency: Sine-Gaussian signals with different central frequencies and Q-values, Gaussian signals with different time scales, and band-limited white noises. The signal-injection simulation shows that the detector has a 50% detection efficiency for $h_{\rm rss} = 1.4 \times 10^{-21}\,{\rm Hz}^{-1/2}$ or an equivalent emission energy of roughly $10^{-7}\,M_\odot$ at the Galactic center. Here, $h_{\rm rss}$ is the root-sum-square amplitude of the burst wave, defined by $h_{\rm rss} = \left[\int (h_+^2 + h_\times^2)dt\right]^{1/2}$.

The most stringent upper limit on the burst-wave rate has been set by the network observation of resonant-mass detectors. With the observation of five resonant-mass detectors (IGEC consortium), an upper limit of 4×10^{-3} event/day with a 95% confidence level has been set, for $h_{\rm rss} > 10^{-18}\,{\rm Hz}^{-1/2}$ signals [42]. In the recent results of four sensitive resonant detectors (IGEC-2), the sensitivity of the detector network was improved by a factor of ~ 3, and an upper limit was set to the lower amplitude [43].

3. Continuous waves from pulsars and binaries

A continuous wave, a sinusoidal wave with a stable frequency for over many years, is radiated from a quasi-stationary compact binary and a non-axissymmetric rotating neutron star. Though the amplitude of the expected signal is smaller than that from short duration signals, the SNR can be gained by long-time coherent integration of the observation data by a few orders of magnitude. The waveform of the signal is well-modeled: a simple sinusoidal wave with phase and amplitude modulation caused by the motion and rotation of Earth. Thus, the method of matched filtering can also be applied in the search for continuous waves. When the source parameters, such as the rotation frequency and the star position in the sky, are accurately determined by observations with electromagnetic waves, the matched filtering becomes equivalent with a simple Fourier transform with phase and amplitude corrections [44]. When some of the pulsar parameters are not known, a survey in a wide parameter space is carried out, which sometimes requires a challenge concerning the computational cost.

For ground-based detectors with a 10 to a few kHz observation band, fast rotating neutron stars are the targets of continuous wave searches. As a result of signal searches from 78 known radio pulsars using the third (S3) and fourth (S4) observation run of the LIGO and GEO600 detectors, no GW was detected, and thus, amplitude upper limits are set for them [45]. The tightest upper limits with a confidence level of 95% are 2.6×10^{-25} for PSR J1603-7202 on the gravitational-wave amplitude, and the equatorial ellipticity of less than 10^{-6} for PSR J2124-3358. Most of the amplitude upper limits do not reach to the indirect upper limits estimated from the observed frequencies and spin-down rates using electro-magnetic waves. However, in the case of the Crab pulsar, the upper limit is almost comparable with that which comes from the spin-down observation. Moreover, it is estimated that with several months of data at the sensitivity of the fifth science run (S5) of LIGO, the observations will beat the spin-down upper limit by a few factors.

There is a possibility of pulsars which are not found by electro-magnetic observations, because of a non-optimal alignment of the spin axis to Earth, or the absorption of radio waves by the surrounding gases. The search for such sources will bring a new discovery by GWs. The survey of unknown pulsars requires a search for periodic signals in multi-dimensional parameter space: sky-position, the period or frequency, the derivative of the frequency or spin-down rate of the source. Thus, a full-scale survey with coherent integrations of long-term observation data is not computationally realistic. Thus, semi-coherent methods of summing the signal power obtained by a series of short Fourier transforms (SFTs) of short data chunks are used. A simple method, called StackSlide, averages the normalized or weighted power from each SFT, correcting the effect of a Doppler shift in the signal frequency, depending on the sky-position of the target. Another method applies a general method for pattern recognition, a Hough transform, to the gravitational-wave search. The Hough transform converts a set of SFTs to a sky-map of the signal-significance. In an all-sky search with the LIGO detectors, data from the fourth LIGO science run (S4) was used for periodic GWs in the frequency range of 50-1000 Hz and with the frequency change rate in the range of -1×10^{-8} Hz/s to zero [46]. As a result, no evidence of detection was found, and the upper limit on the gravitational-wave amplitude for radiation from isolated rotating neutron stars was set to be 4.28×10^{-24} (near 140 Hz) with 95% confidence.

4. Stochastic gravitational wave background

A stochastic background of gravitational radiation is expected to come from the superposition of many unresolved gravitational-waves of cosmological origin (the amplification of quantum vacuum fluctuations during inflation, pre-big bang models, phase transitions, and cosmic strings), and astrophysical origin (rotating neutron stars, supernovae, and low-mass X-ray binaries). The stochastic background is described by $\Omega_{\rm GW}$, which is proportional to the energy density in GWs per logarithmic frequency interval. Since the background gravitational-wave signals cannot be distinguished from detector instrumental noise only with one detector, the searches are performed by appropriately combining the cross-correlations of two detectors. The optimal filter is realized by multiplying the Fourier transform of the data from two detectors by the overlap reduction function, which depends on the relative orientation and distance of the two detectors. The overlap reduction function has the maximum value of unity when the two detectors are co-aligned and placed much closer than the wavelength of the target signal. The cross-correlation result is compared with the background distribution obtained by a correlation with time-shifted data.

Recent results from searches for isotropic backgrounds come from an analysis of the fourth LIGO data (S4), setting a 90% Bayesian upper limit at $\Omega_{\rm GW} \times (H_0/72\,[\rm km/s/Mpc]) < 6.5 \times 10^{-5}$ for a frequency independent gravitational-wave spectrum in the frequency range 51-150 Hz, where H_0 is the Hubble parameter [47]. In this analysis, the known instrumental correlations at 1 Hz, which were likely caused by the sharp ramp of a one-pulse-per-second signal in the data-acquisition system to synchronize it with the Global Positioning System (GPS) time reference, was properly excluded. This limit is slightly above the one that may be inferred from measurements of light-element abundances, WMAP data and the big bang nucleosynthesis model. However, preliminary result from the LIGO S5 run sets a more stringent upper limit than this [48].

5. Signals from gamma-ray bursts

Besides the data analysis using only the output of the gravitational-wave detectors, signal searches triggered by electromagnetic observations, particular by X-ray and gamma-ray bursts (GRB), are being carried out. Currently, it is commonly accepted that progenitors of long-duration GRBs are core-collapse supernovae, and those of short GRBs are mergers of compact-star binary systems. Since gravitational-wave radiation is predicted in both cases, the search for gravitational-wave signal around the time of GRB observation would provide new information on the mechanisms of these phenomena.

In a triggered search during the second to fourth science runs (S2, S3 and S4) of LIGO, short-duration (1-100 ms) gravitational-wave signals were searched around the 39 gamma-ray bursts detected by satellite experiments [49]. In this search, cross-correlations between two detector data streams surrounding the GRB trigger time were calculated and the statistical significances were tested using the result of off-source analysis results. The on-source data segment was selected to be 180 s, with 120 s before the GRB trigger time, and 60 s after the trigger time. This search window is longer than the expected time delay, which is in the order of several seconds, so as to take into account the uncertainty in the burst model and in the trigger time of the GRB observation. As a result of the analysis, no evidence for association if gravitational radiation with GRBs was found, and the upper limit on the root-sum-square amplitude and on the energy radiated by the GRBs were set.

Other recent search results are for the GRB070201, an intense, hard GRB localized within an area that includes one of the spiral arms of the M31 Galaxy. This event occurred during the fifth science run (S5) of LIGO [50]. Since M31, which is at approximately 770 kpc from Earth, is within the observable range for compact-star inspirals in

S5, this GRB could have been associated with a detectable gravitational-wave signal. An inspiral search was carried out on that data for systems with component masses in the range 1-3 $M_\odot$ and 1-40 $M_\odot$, respectively. A search for an unmodeled burst was also carried out, by cross-correlating the data stream from the two detectors at the Hanford site. Regarding the results of these searches, no related signal was found. The inspiral search excluded the possibility that the GRB was due to a compact binary inspiral in M31, with a high confidence greater than 99%. In an unmodeled burst search, a 90%-confidence upper limit was set on the power emitted in GWs, to be 8×10^{50} erg, assuming an isotropic gravitational-wave emission of the progenitor. Since this upper limit is orders of magnitude larger that the estimated energy released in gamma rays at the M31 distance, a soft gamma ray repeater flare event in M31 is not ruled out by this observation.

IV. NEXT-GENERATION DETECTORS

In order to open a new window of gravitational-wave astronomy, it is necessary to observe many and various kinds of gravitational-wave signals. For this purpose, several future plans have been proposed, or have already started.

There are two ways to increase the detection possibility of gravitational-wave signals (Fig. 3). One is to improve the sensitivity of ground-based detectors to watch distant galaxies. If the sensitivity of a detector is improved by a factor of 10, the volume and event rate increase by a factor of 10^3. Another way is to expand the observation frequency band, particularly to lower frequencies, to observe larger-scale and more stationary phenomena. The frequency of the GWs depends on the time scale of the source. Since target sources are larger scale, or almost stationary phenomena, signals with large amplitude or reliable signals are expected at low frequencies. To observe a low frequency band, we need space detectors, because it is impossible to shield local gravity-gradient noise, and because the baseline length of an interferometer is limited to a few tens of kilometers, at the longest.

Future ground-based detectors (Advanced LIGO, Advanced VIRGO, LCGT, and ET) and space detectors (LISA and DECIGO) are reviewed in this Section.

1. Enhanced and Advanced LIGO

Advanced LIGO is an upgrading plan of existing LIGO detectors, being designed to improve the sensitivity by a factor of 10 in the gravitational-wave strain amplitude, from the current LIGO detectors, by replacing almost every part of the detectors, except for the facilities and the vacuum system [8, 51]. The seismic noise level, which is the dominant noise at low frequencies, will be reduced by supporting the platform of the detectors with a new active anti-seismic system, operating at lower frequencies. The thermal noise of the suspension system, which will be a problem at intermediate frequencies, will be reduced by using a multiple pendulum with a final stage fibers made of fused silica. In order to improve the shot-noise-limited sensitivity at high frequencies, new low-loss optics and a higher power laser source will be installed. In addition, the optical configuration will be upgraded to a resonant-sideband extraction (RSE) configuration,

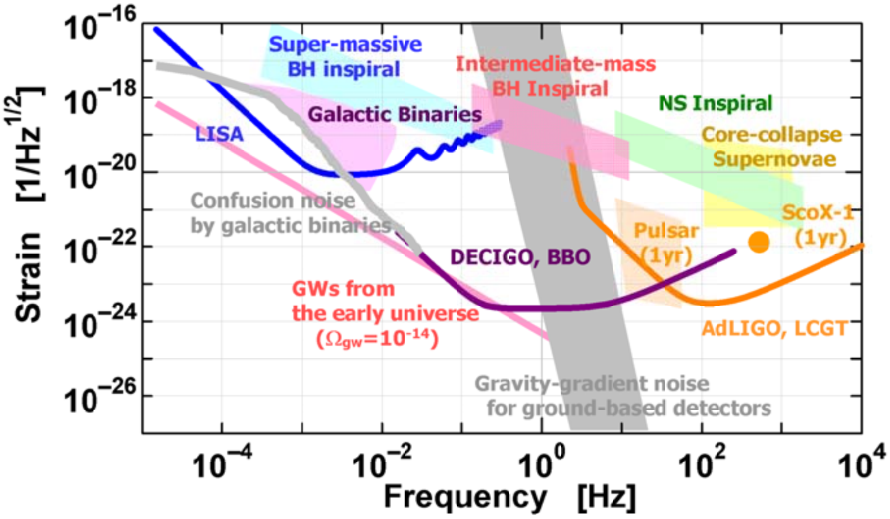

FIGURE 3. Sensitivity of gravitational wave detectors, and target sources.

which will provide the ability to tailor the sensitivity depending on the frequencies of the target sources. With an improved sensitivity, advanced LIGO detectors will have an observable range of 350 Mpc for neutron-star binaries. It is estimated that the expected detection event rate with advanced LIGO will be between several to an order of one hundred events per one year of observation time [34]. Advanced LIGO is scheduled to start observations in the year 2014.

Before upgrading to Advanced LIGO, a significant set of improvements, called Enhanced LIGO, is planed. In this plan, the current LIGO sensitivity will be improved by a factor of 2, which corresponds to a factor of 8 gain in the volume within the observable range. Enhanced LIGO will allow early tests of some of the Advanced LIGO hardware and techniques. The technical elements included in enhanced LIGO will be a higher power (35 W) laser source, an advanced readout scheme (DC readout) of the phase change at the photo-detection port, and an output modecleaner to eliminate junk light on the photodetectors. Enhanced LIGO is planed to start observations by 2010, and to stop for Advanced LIGO in 2011.

2. Advanced VIRGO

VIRGO has a similar upgrading plan to that of LIGO from the current detector: Advanced VIRGO, which will have a better sensitivity by 10 times than that of nominal initial VIRGO design goal, and VIRGO+, which is an intermediate step to Advanced VIRGO [9, 20]. Advanced VIRGO will include a major upgrade of nearly all subsystems of VIRGO. Larger mirrors with better coatings will be installed to reduce radiation-pressure noise and thermal noise of the mirror coating. The laser source will be replaced by a higher power one, and a thermal compensation system will be installed. The signal-recycling mirror will be installed to realize resonant-sideband extraction. The final stage

TABLE 2. Next-generation interferometric gravitational-wave detectors

Ground-based detectors		
Ad.-LIGO [8]	(USA.)	Update plan of LIGO Narrow-band Resonant-Sideband Extraction Baseline: 4 km (3 detectors), Operation in 2014 Target sensitivity $3 \times 10^{-24}/\sqrt{\mathrm{Hz}}$ (at $\sim$ 300 Hz)
Ad.-VIRGO [9]	(Euro)	Update plan of VIRGO Baseline: 3 km, Operation around 2014 Target sensitivity $3 \times 10^{-24}/\sqrt{\mathrm{Hz}}$ (at $\sim$ 300 Hz)
LCGT [10]	(JPN)	Large-scale Cryogenic Gravitational-wave Telescope Broad-band Resonant-Sideband Extraction Baseline: $\sim$ 3 km, Operation around 2014 Target sensitivity $4 \times 10^{-24}/\sqrt{\mathrm{Hz}}$ (at $\sim$ 100 Hz) Underground site of Kamioka mine, Cryogenic mirrors
ET [11]	(Europe)	Einstein Gravitational-wave Telescope Resonant-Sideband Extraction with QND Baseline: $\sim$ 30 km Target sensitivity $\sim 10^{-25}/\sqrt{\mathrm{Hz}}$ (at $\sim$ 100 Hz) Underground site, Cryogenic mirrors
Detectors in space		
LISA [12]	(ESA/NASA)	Lase Interferometer Space Antenna Baseline: 5×10^9 m, Launch after 2014 Target sensitivity $2 \times 10^{-20}/\sqrt{\mathrm{Hz}}$ (at $\sim$1 mHz) Optical transponder type
DECIGO [13]	(JPN)	DECi-hertz Interferometer Gravitational Wave Observatory Baseline 5×10^6 m, Launch $\sim$2025 Target sensitivity $2 \times 10^{-22}/\sqrt{\mathrm{Hz}}$ (at $\sim$0.1 Hz) Fabry-Perot type
BBO [14]	(NASA)	Big-Bang Observer Baseline 5×10^7 m, Launch $\sim$2025 Optical transponder type

of the mirror suspension fibers will be replaced by fused-silica ones to reduce the suspension thermal noises.

3. LCGT

LCGT (Large-scale Cryogenic Gravitational-wave Telescope) is a Japanese project to construct a large interferometer with a 3-km baseline length at an underground site of Kamioka, Gifu. The underground site will provide a stable environment both in seismic fluctuations and atmosphere temperature [10]. The most distinguishing feature of LCGT is that the main test-mass mirrors of the interferometer are cooled down to 20 K so as to reduce the thermal noise. The mirrors are made of sapphire, which has good properties concerning mechanical loss and thermal conductivity at cryogenic temperature. Each mirror will be suspended as a pendulums at cryogenic temperature, which will be suspended from a Seismic Attenuation System (SAS) placed at room temperature.

As a laser source, a Nd:YAG laser with an output power of 150 W will be used. LCGT will have a broad-band resonant-sideband extraction (RSE) configuration to optimize the optical readout noises (shot noise and radiation pressure noise) and the observation bandwidth. LCGT will have a comparable sensitivity as that of Advanced LIGO, expecting more than several detections of gravitational-wave signals from neutron-star inspiral events, in a one-year observation.

Though the funds necessary to construct LCGT have not yet been approved, its prototype interferometer, CLIO (Cryogenic Laser Interferometer Observatory), is under development at the Kamioka site [52]. CLIO is a cryogenic interferometer with a baseline length of 100 m. The purpose of CLIO is to demonstrate the key features of LCGT, and to reduce the technical risks in LCGT. Currently, CLIO has been operated at cryogenic temperature, and has shown a stable seismic environment at low frequencies.

4. ET

Einstein Gravitational-wave Telescope (ET) is an ambitious future detector being proposed by European groups [11]. The sensitivity goal of ET is set at another factor-of-10 improvement from those of Advanced LIGO, Advanced VIRGO, and LCGT. The conceptual design includes a large baseline length of $\sim 30\,\mathrm{km}$, an underground site to reduce seismic and gravity-gradient noises, ultra-low frequency suspensions for mirrors to expand the observation band to lower frequencies, and cryogenic mirrors to reduce thermal noises. In addition, quantum non-demolition techniques are likely to be employed.

5. LISA

LISA (Laser Interferometer Space Antenna) is a space mission to observe many fascinating sources at low frequencies between 10^{-4} to 0.1 Hz, which is inaccessible to ground-based interferometers because of the unshieldable background of local gravity-gradient noise and limited baseline length to a few kilometers [12]. The main target sources of LISA are galactic binaries and the massive blackholes (MBHs). Since some galactic binaries are well-studied, such as X-ray binary 4U1820-30 [53], they represent one of the most reliable sources of LISA. The detection of GWs from known binaries with theoretically predicted amplitude and polarization will be a fundamental test of gravitational physics. Another target of LISA is to learn about the formation, growth, and surroundings of MBHs expected to exist at the centers of most galaxies. Observations of signals from MBH mergers in distant galaxies would test General relativity and black-hole theory to unprecedented accuracy.

The LISA mission is comprised of three spacecraft located 5×10^6 km apart, forming an equilateral triangle. The center of the triangular formation is in the heliocentric orbit, following the Earth by 20 degrees. The change in the distance between the spacecraft is measured by laser transponders. Each spacecraft has a 1 W laser source with a wavelength of 1064 nm, and 30 cm telescopes to transmit the laser beam to the other two spacecraft. The laser light going out from the center spacecraft to the distant spacecrafts is phase-locked to the local laser source, which provides a return beam with full intensity. The center spacecraft superimposes the return light with the on-board laser light to obtain information about any phase change, or a change in the arm length. A proof mass made of Au-Pt alloy is located at the center of each spacecraft, which serves as a reference of the spacecraft position and the optical path length of the interferometer. The spacecraft act as a shield against the solar radiation pressure and so on., with drag-free control measuring the relative motion between the spacecraft and the reference mass inside it, and by feeding the signal back to thrusters on the spacecraft. Each of the three LISA spacecraft has a launch mass of about 400 kg, and all of them will be launched with a single launch vehicle. The nominal mission lifetime is two years.

The key technologies for LISA will be demonstrated in orbit by the LISA Pathfinder mission. Its objectives are to demonstrate drag-free and attitude control in spacecraft with two test masses, to test the feasibility of a laser interferometer at high accuracy, to test the endurance of the different instruments and hardware in the space environment, and to validate the new technologies and measurement strategies so as to ensure the success of LISA. The spacecraft has a launch mass of 1900 kg, and will be launched in 2010.

6. DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory) is a future Japanese space gravitational wave antenna [13]. It aims to observe GWs from various kinds of sources, with sufficient sensitivity to establish gravitational-wave astronomy at an observation frequency of around 0.1 Hz. This frequency band is the gap region between LISA and terrestrial detectors, such as Advanced LIGO and LCGT. In addition, this frequency band provides a possibility to observe GWs from cosmological distance, because this band is free from confusion noises, irresolvable gravitational-wave signals, from too many white-dwarf binaries in our Galaxy. DECIGO has roughly three scientific targets: (1) the characterization of dark energy by observing distant ($z \simeq 1$) binary inspirals of neutron stars, (2) obtaining information on the formation mechanism of supermassive black holes by observing binary inspirals of intermediate mass BHs, and (3) the verification and characterization of inflation by observing the stochastic background GWs from the early universe.

In the pre-conceptual design, DECIGO is formed by three drag-free spacecraft, 1000 km apart from one another. The relative displacements between proof masses housed in these spacecraft are measured by Fabry-Perot interferometers. The Fabry-Perot configuration is adopted because it provides a better best sensitivity than that of the optical transponder configuration adopted by LISA. The mirrors forming the cavities, which work as proof masses in the spacecraft, have a diameter of 1 m, with moderate reflectivity to realize a cavity finesse of 10. The laser source of DECIGO will have an effective power of 10 W with a wavelength of 532 nm. The orbit and constellation of DECIGO is to be determined; one candidate is the orbit around the sun trailing the earth.

A long and intense development phase will be required in order to realize DECIGO.

The launch of DECIGO is planed to be in 2024 after research and development with table-top experiments, prototypes, and two milestone missions of DECIGO pathfinder (DPF) and Pre-DECIGO. DPF will be one small satellite consisting of two proof mass mirrors, which form a short Fabry-Perot cavity [54]. The cavity length is measured by a stabilized laser source, and the mirrors are kept in the satellite with a drag-free control. The target of DPF will be a technical demonstration of drag-free control, laser stabilization in space, precise measurements with the Fabry-Perot cavity, and the mirror clump system used at launching the satellite. In addition, since DPF will have a modest sensitivity for gravitational-wave events, some scientific results are expected by continuous observation at the DECIGO frequency band. The objectives of Pre-DECIGO is to observe GWs with moderate technical difficulties.

V. SUMMARY AND CONCLUSION

The direct observation of gravitational waves is expected to reveal new aspects of the universe; observations with gravitational waves will provide complementary information to that with electromagnetic waves or, moreover, completely new information that cannot be obtained by other observations.

Currently, the construction of the first-generation interferometric detectors (LIGO, VIRGO, GEO600, and TAMA300) have been completed and observation data of more than one year have been obtained. The data are analyzed to look for gravitational-wave signals. Though no gravitational-wave signal has been found to date, results with scientific significance have been obtained: upper limits on the event rate, strain amplitude, and radiated energy. In the case of GRB070201, the inspiral search excludes the possibility that the GRB was due to the binary inspiral in M31.

As future plans of ground-based detectors, Advanced LIGO, Advanced VIRGO, and LCGT have been proposed, and detailed designs are being refined. These detector will have sufficient sensitivities to cover the 200-350 Mpc range for neutron-star inspiral events, with which we can expect a detection rate of more than several gravitational-wave signals per year. These detectors will be operational in around 2014. As for space detectors, Laser Interferometer Space Antenna (LISA) will be launched after 2014, targeting low-frequency signals. Since the LISA targets include galactic binaries as reliable gravitational-wave sources, the direct observation of gravitational waves is guaranteed if LISA achieve its designed sensitivity. Another space detector, DECIGO, will be launched in 2024, which is designed to have sensitivity at the intermediate frequency range between the terrestrial and LISA detector bands. DECIGO will be a powerful detector for gravitational-wave astronomy, as well as cosmology. An ambitious ground-based detector, called Einstein gravitational-wave telescope, ET, is planed as a third-generation detector. At that time, we will be able to observe throughout the universe by means of gravitational waves.

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