Space Gravitational Wave Antenna DECIGO and B-DECIGO

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Abstract
DECi-hertz Interferometer Gravitational-wave Observatory (DECIGO) is a future Japanese space gravitational wave antenna. The most important objective of DECIGO, among various sciences to be aimed at, is to detect gravitational waves coming from the inflation of the universe. DECIGO consists of four clusters of spacecraft, and each cluster consists of three spacecraft with three Fabry-Perot Michelson interferometers. As a pathfinder mission of DECIGO, B-DECIGO will be launched, hopefully in the 2020's, to demonstrate technologies necessary for DECIGO as well as to lead to fruitful multi-messenger astronomy. B-DECIGO is a smaller-scale or simpler version of DECIGO with the sensitivity slightly worse than that of DECIGO, yet good enough to provide frequent detection of gravitational waves.

1. Introduction

The detection of gravitational waves for the first time in the history of mankind by Advanced LIGO established completely new astronomy, which is gravitational wave astronomy [1]. Since then several detections have been made for gravitational waves from the black hole binary coalescence, and finally, after Advanced Virgo joined the observation run gravitational waves coming from the neutron star binary coalescence were detected [2]. The coalescence and its afterglow were also observed by electromagnetic waves of various wavelengths [3, 4]. This was the beginning of multi-messenger astronomy. It is expected that the addition of Large-scale Cryogenic Gravitational-wave Telescope (KAGRA) [5] and LIGO-India to the existing world network will improve the quality of astronomy. The Upgrade of such 2nd-generation detectors, as well as the establishment of the 3rd-generation detectors, are also planned [6, 7]. On the other hand in space, Laser Interferometer Space Antenna (LISA) is expected to open a new window of gravitational waves [8]. LISA Pathfinder was already launched, and it demonstrated that the measured acceleration noise satisfied the requirement for LISA [9]. Truly gravitational wave astronomy is regarded as one of the most exciting fields of science in the 21st century.

In such circumstances, one of the most attractive objectives for gravitational wave astronomy is the detection of gravitational waves produced in the inflation period of the universe. DECi-hertz Interferometer Gravitational-wave Observatory (DECIGO) [10] is a future Japanese space gravitational wave antenna with the detection of gravitational waves from the inflation as the most important objective. The idea of DECIGO was first brought into existence in 2001. At that time the main objective of DECIGO was to measure the acceleration of the expansion of the universe by observing the waveform of gravitational waves coming from the neutron star binary coalescences at a far distance from the earth [11]. The initial design of DECIGO was a simple Michelson interferometer. Years later the main objective of DECIGO was shifted to the detection of gravitational waves coming from the inflation, and as for the design of DECIGO, Fabry-Perot arm cavities were added to improve the target sensitivity of DECIGO [12]. The roadmap of DECIGO has also been changed. Originally we planned to launch DECIGO Pathfinder [13] first, then pre-DECIGO, and finally DECIGO. However, because DECIGO Pathfinder was not approved as a formal mission, and LISA Pathfinder successfully demonstrated the acceleration noise and drag-free system, we decided to proceed to Pre-DECIGO [14], skipping DECIGO pathfinder. We also changed the name of Pre-DECIGO to B-DECIGO to make the name worthy of its fruitful sciences expected to obtain. We hope to launch B-DECIGO in the 2020’s.

In this paper, we will summarize the objectives and design of DECIGO as well as B-DECIGO.

2. DECIGO

2-1. Objectives of DECIGO

There are many scientific objectives for DECIGO, which are summarized in the following:

(1) Detection of gravitational waves coming from the inflation

It was predicted that the inflation took place right after the birth of the universe. During the inflation period, the quantum fluctuations of space and time could produce gravitational waves. Therefore, the detection of such gravitational waves could strongly indicate the existence of the inflation. Moreover, because the spectrum and amplitude of the expected gravitational waves depend on the model of the inflation [15], the detection of gravitational waves from the inflation by DECIGO could reveal the true mechanism of the inflation.

There are also interesting investigations possible regarding various physical quantities of gravitational waves in the very early stage of the universe if we can detect gravitational waves from the inflation. One possibility is to study a parity violation between the two circular polarizations [16]. Another possibility is to separate the effects of tensor, scalar, and vector modes of gravitational waves [17]. Thermal history could be also revealed by detecting the spectrum of gravitational waves from the inflation, because the frequency dependence of gravitational waves from the inflation depends on when the inflation period ended, which is related to the thermal history of the universe [18, 28].

The direct observation of the inflation is possible only through gravitational waves because electromagnetic waves cannot propagate straight until 380,000 years after the birth of the universe. The detection of gravitational waves from the inflation is the most important objective of DECIGO.

(2) Direct measurement of the acceleration of the expansion of the universe

According to the observation of supernovas, it was demonstrated that the expansion of the universe is accelerated [19], and the entity that causes the acceleration is called dark energy. It is extremely important to measure the acceleration of the expansion of the universe directly and reliably. Luckily it is possible to do this by measuring gravitational waves coming from neutron star binaries at far distances (redshift: z~1) from the earth, because the phase of the waveform could shift if the sources are moving away with accelerations (See Fig. 1) [11, 26]. The optical distance and redshift of the source can be measured and the relationship between them could provide the information regarding the acceleration of the expansion of the universe [27]. It should be noted that this measurement does not require any assumptions, which are necessary for the supernova measurement. Therefore, this measurement is very important for characterizing the dark energy. This is one of the very important objectives for DECIGO.

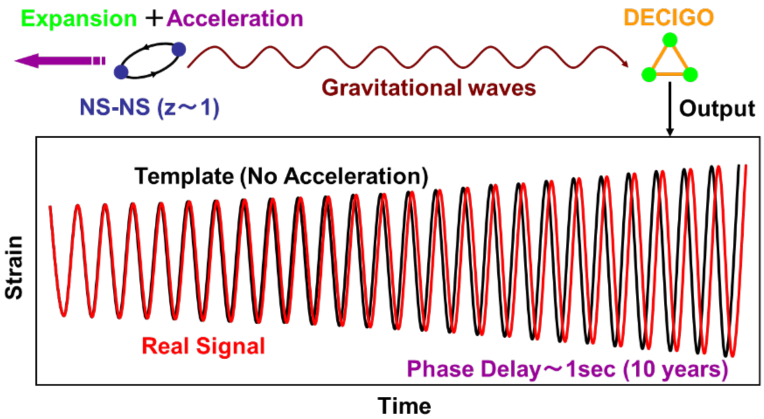

Fig. 1. Gravitational wave signals coming from a neutron star binary at a redshift of 1 with and without the acceleration of the expansion of the universe.

(3) Mechanism of formation of giant black holes

There are giant black holes at the center of galaxies, and the mechanism of formation of such giant black holes is not yet known. DECIGO aims at detecting gravitational waves coming from many intermediate-mass black hole binary coalescences. The statistics of the relationship between the frequency and mass of the sources could reveal the formation mechanism of intermediate-mass black holes. Because the mass of the black holes, which DECIGO observes, is lighter than that of LISA, the information, which DECIGO could provide, is the formation mechanism of giant black holes at earlier stages. Therefore, DECIGO could provide a complete evolution scenario of formation of giant black holes together with the information obtained by LISA.

(4) Prediction of neutron star binary coalescences

DECIGO is expected to measure gravitational waves from neutron star binaries even at a redshift of 5, five years before the coalescences. This indicates that 10,000 neutron star binary gravitational wave signals per year are expected to be detected, from the currently expected occurrence frequency of the neutron star binary coalescences. The angular resolution of the sources is expected to be a few arcseconds. DECIGO can predict when the neutron star binary coalescence occurs precisely even five years before the coalescence. Therefore, it is possible for many electromagnetic telescopes to aim at the target in advance to observe gamma-ray burst at the coalescence, and after the coalescence, optical, infrared-red, radio, and X-ray afterglow. This will lead us to a fruitful multi-messenger astronomy, and we expect that we will understand what happens in the neutron star binary coalescence.

(5) Test of general relativity in the region of the strong gravitational field

DECIGO expects to detect gravitational waves produced in the ringdown phase of the intermediate-mass black hole binary coalescences with a high signal-to-noise ratio. Although the waveform of gravitational waves coming from the inspiral phase of the black hole binary coalescence was already measured to agree with the waveform calculated by numerical relativity, there could be disagreement for the ringdown because the gravitational field in the ringdown phase is stronger than that in the inspiral phase.

There is also a variety of other objectives for DECIGO [20-24]. Therefore, it is extremely important to realize DECIGO to expand further gravitational wave astronomy, which has been established by LIGO and Virgo, and will be expanded by LISA.

2-2. Design of DECIGO

DECIGO consists of four clusters of spacecraft. Each cluster consists of three spacecraft separate from each other by 1,000 km, forming an equilateral triangle (See Fig. 2). A change in distance between any two spacecraft in one cluster, caused by gravitational waves passing by, is measured by an interferometer. Each spacecraft contains two mirrors (1 m in diameter, 100 kg in

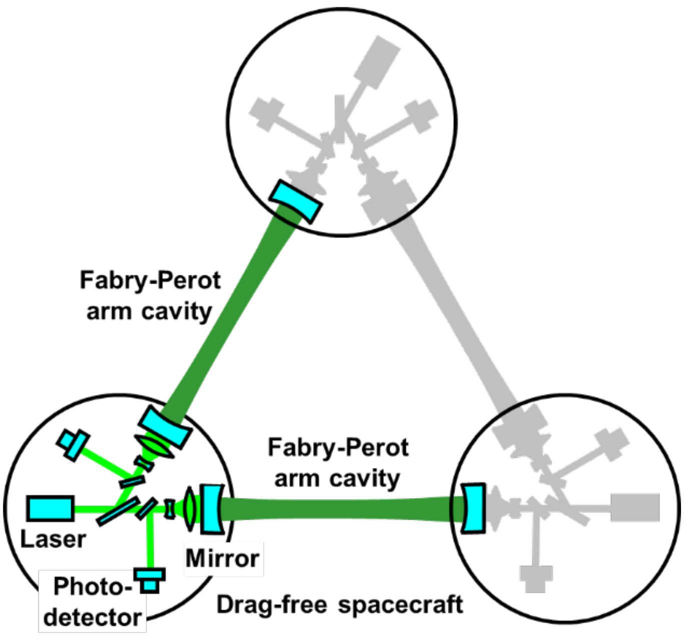

Fig. 2. Pre-conceptual design of one cluster of DECIGO.

mass), and one mirror in one spacecraft and another mirror in another spacecraft form a Fabry-Perot arm optical cavity. The interferometer employed to measure the distance is a Fabry-Perot Michelson interferometer with a finesse of 10, illuminated by a laser (515 nm in wavelength, 10 W in laser power). There are three sets of Fabry-Perot Michelson interferometers in one cluster, sharing the mirrors as the same arm cavities. Two outputs of the three interferometers are used to obtain full information of the detected gravitational waves, such as polarizations of gravitational waves. The third interferometer is implemented as redundancy for backup.

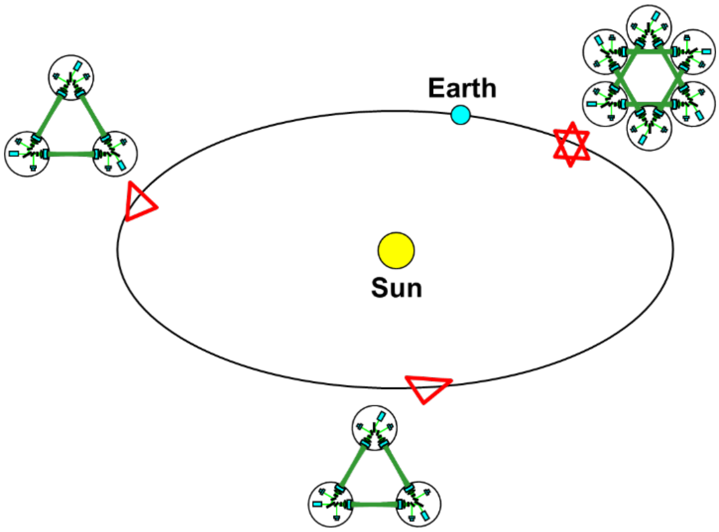

Fig. 3. Orbit of DECIGO.

The clusters are placed in a heliocentric earth-trail orbit as shown in Fig. 3. Two clusters are placed at the same place with a slight separation from each other. Three spacecraft, forming each cluster, are put in a record-disc orbit, in which the three spacecraft maintain an equilateral-triangle shape with slight perturbations from the planets rotating around the sun. The large separation between the clusters increases an angular resolution of the sources, while the two clusters at the same position are required to improve the sensitivity of DECIGO by taking a correlation of the outputs of the two clusters.

Each spacecraft has a drag-free function. The relative position of the floating mirrors with respect to the outer spacecraft is locally measured, and the position of the spacecraft is controlled by thrusters to maintain the relative position. This way the mirrors are not exposed to the drag or radiation pressure of the sunlight, ensuring the pure trajectory of gravity for the mirrors.

Here let us explain the most important design feature of DECIGO, which is a Fabry-Perot Michelson interferometer instead of simple Michelson interferometer with a light transponder function. First, let us consider a simple Michelson interferometer with a very long arm length. In such an interferometer only a small fraction of the laser light emitted from one spacecraft can reach the second spacecraft because of the refraction features of light. Therefore, regular reflection of the light by a mirror in the second spacecraft is not good enough; most of the light will be lost. Thus, the second spacecraft should be equipped with another laser source, and the laser light emitted from this second laser is phase-locked to the laser light coming from the first spacecraft. This technique, which is called the light transponder function, is used for LISA.

The quantum noise of the interferometer consists of the radiation pressure noise and shot noise corresponding to the laser power that reaches the mirror in the second spacecraft (See Fig. 4). The sensitivity of the light-transponder-type interferometer for gravitational wave signals is limited by the radiation pressure noise at low frequencies and shot noise at intermediate and higher frequencies if all the other noise sources are suppressed well enough. The radiation pressure noise has a frequency dependence of f^{-2} because the radiation pressure force noise is white, and the shot noise is white in principle but above a corner-frequency corresponding to the arm length, the shot noise shows an f-dependence because of the cancellation of the gravitational wave signals.

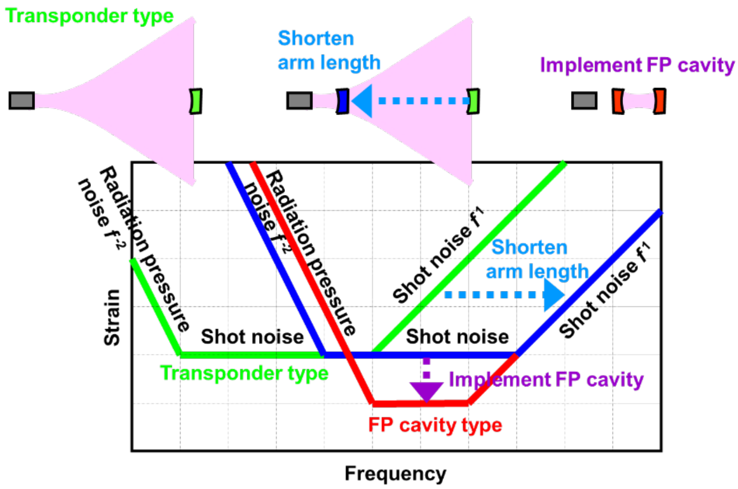

Fig. 4. Quantum noise of interferometers from the transponder type to Fabry-Perot cavity type.

Now let us reduce the arm length gradually to see how the quantum noise changes. The laser power that can reach the mirror is inversely proportional to the square of the arm length. The radiation pressure noise in terms of displacement of a mirror is proportional to the square root of the laser power. We should also recall that the displacement sensitivity divided by arm length is the strain sensitivity. As a result, the radiation pressure noise in terms of strain is inversely proportional to the square of the arm length. As for the shot noise, because the displacement shot noise is inversely proportional to the square root of the laser power, the strain shot noise does not depend on the arm length. The arm-length dependences of the radiation noise and the shot noise ensure that the cross-over frequency between the two quantum noises is inversely proportional to the arm length. As for the corner frequency of the shot noise, it is inversely proportional to the arm length. Therefore, altogether, the quantum noise shifts to higher frequencies by a factor determined by the ratio of the arm length with the shot noise level at intermediate frequencies unchanged.

Let us reduce the arm length more until almost all the laser light power emitted from the first spacecraft is received by the mirror in the second spacecraft, we stop reducing the arm length there and implement Fabry-Perot arm cavities. The radiation pressure noise is proportional to the finesse of the cavity, the shot noise is inversely proportional to the finesse, and the corner-frequency is inversely proportional to the finesse. As a result, the sensitivity is improved at a limited frequency range at the expense of some degradation of the radiation pressure noise at lower frequencies.

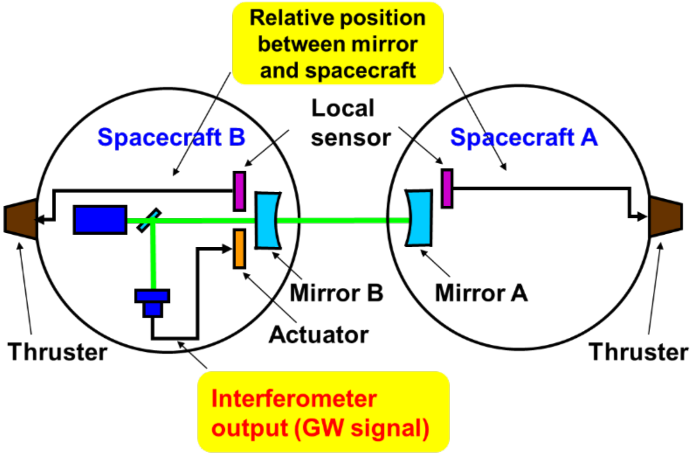

Fig. 5. Drag-free system and Fabry-Perot cavity control system.

Here if we optimize the design parameters in such a way that only the merit is in effect and the demerit is not in effect. This is actually possible if only the degradation of the radiation pressure noise is covered by the confusion limiting noise, which results from unresolvable gravitational wave signals coming from white dwarf binaries, etc. in our galaxy.

Of course, it should be noted that reducing the arm length and implementing Fabry-Perot cavities make the acceleration noise of the mirror coming from other practical noise sources larger. Thus the requirement of the acceleration noise is more stringent for an interferometer with a shorter arm length. Nevertheless, we believe that the practical noise can be reduced eventually so that the sensitivity is limited by only quantum noise.

It should be also important to explain the compatibility of the Fabry-Perot interferometric configuration and the drag-free function (See Fig. 5). As a drag-free function, the relative position of Mirror A inside Spacecraft A with respect to the outer spacecraft is locally measured, and Spacecraft A is controlled in such a way that the relative position is maintained. The distance between Mirror A inside Spacecraft A and Mirror B inside Spacecraft B is measured by a Fabry-Perot interferometer and let us assume that Mirror B is controlled in such a way that the distance is maintained. As a drag-free function, the relative position of Mirror B with respect to the outer spacecraft is locally measured, and Spacecraft B is controlled in such a way that the relative position is maintained. In this hierarchy of the control system, the noise of the motion of both spacecraft caused by the

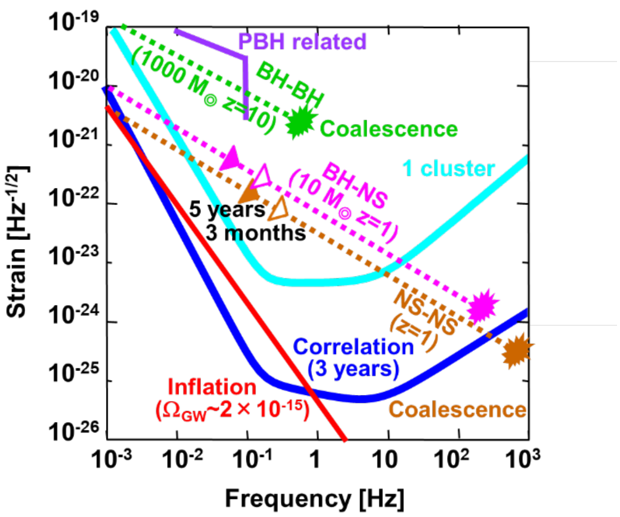

Fig. 6. Target sensitivity of DECIGO and expected gravitational wave signals.

drag or solar radiation pressure does not impair the interferometer output signal. Therefore, the Fabry-Perot interferometric configuration is compatible with the drag-free function of the spacecraft.

The target sensitivity is shown in Fig. 6. The expected strain sensitivity is ~4×10^{-24} $Hz^{-1/2}$ between 0.1 Hz and 10 Hz for one cluster of DECIGO. If we take correlation of the two clusters of DECIGO at the same position for three years, the expected sensitivity is ~1×10^{-25} $Hz^{-1/2}$ between 0.1 Hz and 10 Hz.

Some of the important optical and mechanical parameters are summarized in Table 1.

Table 1. Optical and mechanical parameters of DECIGO and B-DECIGO.

Item	DECIGO	B-DECIGO
Distance between satellites	1000 km	100 km
Effective laser power	10 W	1 W
Wavelength of light	515 nm	515 nm
Mass of mirror	100 kg	30 kg
Diameter of mirror	1 m	0.3 m
Finesse of cavity	10	100

3. B-DECIGO

3-1. Objectives of B-DECIGO

It is wise to verify the key technologies of DECIGO in a smaller-scale mission with still significant scientific objectives. Thus, we decided to try to launch B-DECIGO.

There are several technical objectives for B-DECIGO: the drag-free function of the spacecraft, formation flight technique, control of Fabry-Perot cavity, clamp release system of mirrors, orientation control system of mirrors and spacecraft, laser stabilization system, acceleration noise, etc. It is important to verify these necessary technologies as much as possible in terrestrial experiments before the launch of B-DECIGO. It is also important to rely on the technologies, which were already accomplished by LISA Pathfinder.

As for the scientific objectives of B-DECIGO, we can consider that B-DECIGO has the same objectives as DECIGO with a less occurrence frequency of detection of gravitational waves, except detection of gravitational waves from the inflation. Unfortunately, it is unlikely that B-DECIGO could detect gravitational waves from the inflation; we have to wait until DECIGO is launched. Nevertheless, there are a variety of significant sciences, which we can expect to be attained by B-DECIGO.

For example, when B-DECIGO is launched, we can expect that the sensitivity of the terrestrial gravitational wave detectors are improved significantly, and furthermore, they could be equipped with a function of variable-bandwidth observation. Because B-DECIGO can predict precisely when the next neutron star binary coalescence will occur a month before the coalescence, the terrestrial detectors can optimize the bandwidth of the sensitivity for the neutron star binary coalescence. This way the waveform of gravitational waves before and after the coalescence can be measured accurately so that we could determine the equation of state of neutron stars. This function of prediction will also lead to the detailed observation of the source by electromagnetic waves with various wavelengths even before and after the coalescence. This could establish a new kind of multi-messenger astronomy.

Another important role of B-DECIGO is the study of the foreground. There are two kinds of foreground: confusion limiting noise caused by unresolvable gravitational wave signals from white dwarf binaries, etc. in our galaxy below 0.1 Hz, and resolvable gravitational wave signals from neutron star binaries at far distances above 0.1 Hz. In DECIGO, we have to remove the latter signals one by one to reach the gravitational wave signals from the inflation, so with B-DECIGO we should study how we can do this.

It is also important to mention that B-DECIGO could determine the spin of black holes by analyzing the waveform of the chirp signals [25]. It should also be noted that the tidal parameters of a neutron star, with the data from B-DECIGO, can be determined much better than the case determined only by Advanced LIGO [25].

3-2. Design of B-DECIGO

The design of B-DECIGO is, in principle, a small-scale or simpler version of the design of DECIGO. The pre-conceptual design of B-DECIGO is the following. B-DECIGO has one cluster of spacecraft, which consists of three spacecraft with three sets of Fabry-Perot Michelson interferometers. The distance between the spacecraft is 100 km. The mirror has a diameter of 0.3 m and a mass of 30 kg. The laser has a power of 1 W and a wavelength of 515 nm. The finesse of the arm cavity is 100, which is a factor of 10 larger than that of DECIGO. This is necessary to make the corner frequency of the shot noise of B-DECIGO equal to that of DECIGO. The orbit of B-DECIGO is still under investigation. The light source is the intensity and frequency-stabilized laser with a wavelength of 515 nm, which is based on the frequency-doubled fiber DFB laser at 1030 nm. The frequency of the laser is stabilized in reference to the iodine-saturated absorption at 515 nm. For the light source, the output power of 1 W is required. The required frequency noise is 1 Hz $\mathrm{Hz}^{-1/2}$, and intensity noise is 1×10^{-8} $\mathrm{Hz}^{-1/2}$, respectively. Some of the important optical and mechanical parameters are summarized in Table 1.

The target sensitivity of B-DECIGO is 2×10^{-23} $\mathrm{Hz}^{-1/2}$ around 0.1 Hz, a factor of 5 worse than that of DECIGO. To realize this sensitivity, the displacement noise of 2×10^{-18} $\mathrm{Hz}^{-1/2}$ is required, which means that the force noise on the mirror should be less than 1×10^{-17} N $\mathrm{Hz}^{-1/2}$.

Some of the key technologies for B-DECIGO, such as thrusters and a fiber distributed feedback laser, are being studied by experiment. The best orbit for B-DECIGO has been also investigated from various standpoints.

4. Summary

Because gravitational wave astronomy has been established, it is important to proceed with DECIGO to reach one of the most exciting sciences in this field, which is the detection of gravitational waves coming from the inflation. This will lead us to the understanding of the mechanism of the birth of the universe. There are also various interesting sciences, which we can expect to obtain by DECIGO. It is also important to realize B-DECIGO to verify the key technologies required for DECIGO as well as to obtain a variety of exciting sciences.

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