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Current status of space gravitational wave antenna DECIGO and B-DECIGO

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 The Deci-hertz Interferometer Gravitational Wave Observatory (DECIGO) is a future Japanese space mission with a frequency band of 0.1 Hz to 10 Hz. DECIGO aims at the detection of primordial gravitational waves, which could have been produced during the inflationary period right after the birth of the Universe. There are many other scientific objectives of DECIGO, including the direct measurement of the acceleration of the expansion of the Universe, and reliable and accurate predictions of the timing and locations of neutron star/black hole binary coalescences. DECIGO consists of four clusters of observatories placed in heliocentric orbit. Each cluster consists of three spacecraft, which form three Fabry–Pérot Michelson interferometers with an arm length of 1000 km. Three DECIGO clusters will be placed far from each other, and the fourth will be placed in the same position as one of the other three to obtain correlation signals for the detection of primordial gravitational waves. We plan to launch B-DECIGO, which is a scientific pathfinder for DECIGO, before DECIGO in the 2030s to demonstrate the technologies required

for DECIGO, as well as to obtain fruitful scientific results to further expand multi-messenger astronomy.

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 Subject Index F30, F31

1. Introduction

Gravitational waves were detected for the first time by the Laser Interferometer Gravitational-wave Observatory (LIGO) in 2015 [1]. They found that the gravitational waves came from the merger of a black hole binary that occurred ~ 400 Mpc from Earth. This detection successfully established gravitational wave astronomy. After several subsequent detections of gravitational waves from black hole binary inspirals, in 2017, LIGO, together with Virgo, caught gravitational waves emitted from the merger of a neutron star binary [2]. This detection led to successful follow-up observations with electromagnetic waves [3,4]. This event not only revealed the mechanism of the r -process that occurred around the neutron star binary coalescence but also initiated multi-messenger astronomy. Since then, LIGO and Virgo have improved the sensitivity of the detectors significantly; during the latest observation run, detection became routine, once or twice a week. Soon the Large-scale Cryogenic Gravitational Wave Telescope (KAGRA) [5] will join LIGO and Virgo to improve the quality of gravitational wave detection. Furthermore, LIGO India will eventually join the world network.

There are also more challenging plans in the future: the Einstein Telescope (ET) [6] and Cosmic Explorer (CE) [7], with a longer arm length of 10 km in a triangular arrangement and 40 km as an “L,” respectively. They plan to accomplish significantly better sensitivity than the current ground-based detectors at frequencies down to a few hertz. In space, the European Space Agency (ESA) has a future mission called Laser Interferometer Space Antenna (LISA) [8] in collaboration with the National Aeronautics and Space Administration (NASA). LISA consists of three spacecraft with an arm length of 2.5 million kilometers. LISA aims at detecting gravitational waves coming from intermediate-mass to massive black hole binaries at frequencies between 1 mHz and 0.1 Hz. ESA and NASA launched the LISA Pathfinder [9] in 2015 and attained the acceleration noise requirement for LISA. Encouraged by these successful results, they plan to launch LISA in 2034.

In Japan, we have also been considering space missions: the Deci-hertz Interferometer Gravitational Wave Observatory (DECIGO) [10,11], and its scientific pathfinder B-DECIGO [12]. The Japanese Gravitational Wave Community (JGWC) already agreed in 2018 that we regard observations of gravitational waves by KAGRA as the highest priority, and after that, we develop gravitational wave astronomy by DECIGO and B-DECIGO. In this paper we will explain the design, objectives, and schedule of DECIGO and B-DECIGO in detail.

2. Design of DECIGO and B-DECIGO

2.1. General concept

DECIGO consists of four clusters of observatories. As shown in Fig. 1, we plan to put them into heliocentric orbit in such a way that two clusters are placed in the same position, and the other two clusters are distributed around the Sun. As shown in Fig. 2, each cluster consists of three spacecraft, which form an equilateral triangle with a side of 1000 km. Each spacecraft, which has a drag-free system, contains two mirrors floating inside the satellite as proof masses. DECIGO measures the

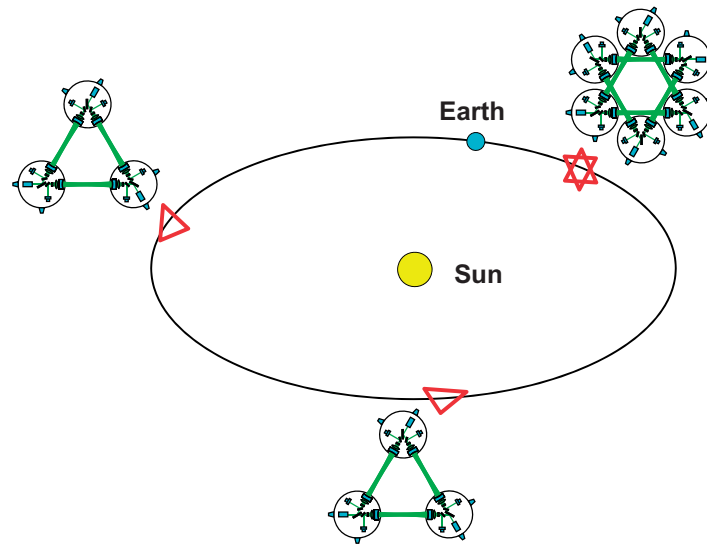


Fig. 1. Orbit of DECIGO. Four DECIGO clusters are put in heliocentric orbit: two at the same position and the other two at different positions.

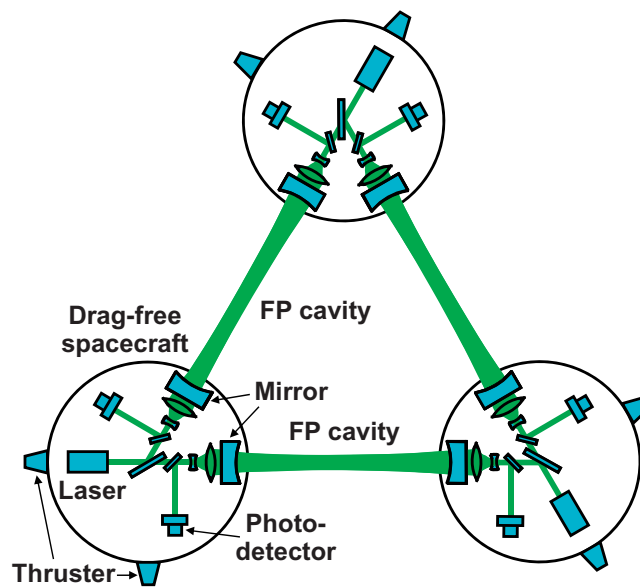


Fig. 2. Conceptual design of DECIGO. One DECIGO cluster consists of three drag-free spacecraft. FP cavities are used to measure changes in the arm length.

change in the distance caused by gravitational waves between the two mirrors, which are 1000 km apart. We employ a Fabry–Pérot (FP) cavity, consisting of the two mirrors, to measure arm length changes. The target frequency band of DECIGO is between 0.1 Hz and 10 Hz. The mission lifetime of DECIGO is at least three years.

The reasons for the above design choices for DECIGO are discussed below. First, let us explain the bandwidth of DECIGO. We chose the frequency band of DECIGO to be 0.1 Hz to 10 Hz because this frequency band is located in the gap between the frequency band of LISA and that of ground-based detectors. It means that DECIGO can be used as a follow-up detector after LISA detects gravitational waves coming from intermediate-mass black hole binaries. Also, DECIGO can be used

as a forecast detector before the ground-based detectors detect gravitational waves coming from 10–100 solar-mass black hole binaries or neutron star binaries.

Another justification for this frequency band comes from consideration of the importance of low-frequency gravitational waves and confusion limiting noise. Generally speaking, we can say that in a lower-frequency regime, the expected number of gravitational wave sources is larger, relative to the amount of available data. This is because, at lower frequencies, the evolution timescale becomes longer, and we also have a larger variety of gravitational wave sources. Up to ~ 0.1 Hz, the confusion limiting noise is dominated by a large number of gravitational wave signals coming from white dwarf binaries. These gravitational wave signals are so abundant that many more than two signals are likely to exist within one frequency resolution bin, which is determined by the observation time. As a result, separation of these signals becomes a significant challenge, and they form a sensitivity limit for signals in that frequency range. This confusion limiting noise due to white dwarf binaries exists only below ~ 0.1 Hz because they merge when their gravitational waves reach ~ 0.1 Hz. While we still need to deal with gravitational waves from binaries composed of black holes and neutron stars, it is expected that, above ~ 0.1 Hz, we can open a deep window without this confusion limit of gravitational waves.

It should be noted that, based on recent observational results for binary mergers in the relatively low-redshift universe by the LIGO–Virgo collaboration, the total merger rates on our past light-cone are estimated to be $\sim 10^6$ yr $^{-1}$ for neutron star binaries and $\sim 10^4$ yr $^{-1}$ for black hole binaries. Here, we used the redshift dependencies of the rates modeled in Ref. [13]. At present, with the significant astronomical uncertainties, the redshift dependencies are highly uncertain, but, as mentioned in Sect. 3.2, B-DECIGO will be highly useful in obtaining related information.

It is also essential to point out that the expected strain of the primordial gravitational waves is relatively reachable around 0.1 Hz, compared with a higher-frequency regime. Therefore, the frequency band between 0.1 Hz and 10 Hz is the most fruitful band for future gravitational wave astronomy and physics.

2.2. Design of DECIGO

Now we optimize the arm length for the frequency band. We chose the arm length of DECIGO to be 1000 km. This size is much longer than ground-based detectors, but it is much shorter than LISA. We can justify this choice as optimizing the quantum noise, which consists of shot noise and radiation pressure noise, for this frequency band. If the arm length is long, the laser light interacts with the gravitational waves for a longer time, resulting in larger arm length changes due to gravitational wave signals. On the other hand, only a fraction of the light can reach the other mirror because of the diffraction of light, resulting in larger relative fluctuations of the shot noise. These two effects on signals and shot noise cancel each other [11]. Therefore, the shot noise in terms of strain (simply called “shot noise” hereafter) does not depend on the arm length.

Incidentally, the shot noise is white at frequencies below a frequency determined by the propagation time of the light in the arms. This is because part of the gravitational wave signals cancel above the corner frequency. More precisely, the corner frequency of the shot noise is inversely proportional to the arm length of the detector.

As for the radiation pressure noise, a shorter arm length increases the radiation pressure noise in terms of strain (simply called “radiation pressure noise” hereafter) for two reasons: higher illuminating laser power and lower signals. As a result, the crossover frequency between the radiation pressure noise and shot noise is inversely proportional to the arm length of the detector.

Table 1. Optical and mechanical parameters of DECIGO and B-DECIGO [11].

Optical/mechanical parameter	DECIGO	B-DECIGO
Arm length (km)	1000	100
Laser power (W)	10	1
Laser wavelength (nm)	515	515
Finesse	10	100
Mirror diameter (m)	1	0.3
Mirror mass (kg)	100	30
# of clusters	4	1
# of interferometers per cluster	3	3

Altogether, the quantum noise in terms of strain (simply called “quantum noise” hereafter) shifts to higher frequencies with a shorter arm length, maintaining the noise curve shape in the logarithmic scale. Moreover, if the arm length is short enough, we can even implement FP cavities to enhance the gravitational wave signals, thus to improve the shot noise at the expense of the radiation pressure noise and the bandwidth. With the above considerations, we found that an interferometer with an arm length of 1000 km, a mirror diameter of 1 m, and a laser wavelength of 515 nm accommodates a FP cavity with a finesse of 10 (See Table 1).

Other parameters of DECIGO are as follows. We chose the mass of the mirror to be 100 kg, and a laser power of 10 W to optimize the quantum noise around 0.1 Hz (see Table 1). As a result, the radiation pressure noise is larger than the shot noise below 0.1 Hz, the shot noise is white between 0.1 Hz and 10 Hz, and above 10 Hz the shot noise increases linearly with the frequency.

Another crucial element of DECIGO technologies is a drag-free system. A spacecraft receives non-gravitational forces from various entities, such as solar radiation and cosmic dust. As a result, the motion of the spacecraft due to such “drag” would be much larger than the motion change caused by gravitational waves. Thus, we need to employ a drag-free system. The drag-free system requires a proof mass floating inside the spacecraft. A local sensor implemented inside the spacecraft measures the relative position of the proof mass with respect to the spacecraft. Then the relative position signal is fed back to the thrusters attached to the spacecraft. The drag-free system controls the position of the spacecraft relative to the proof mass. In the case of DECIGO, the mirrors play the role of proof masses. The drag-free system requires accurate control of the spacecraft relative to the mirrors because a change in the gravitational field by the motion of the spacecraft could shake the mirrors. The required accuracy for relative motion of the spacecraft with respect to the mirrors is below 10^{-9} m Hz^{-1/2} at 0.1 Hz. It should be noted that a study of the fuel and thruster requirements is also critical [14].

Now let us explain in more detail about the interferometer and cluster configuration of DECIGO. As shown in Fig. 2, one cluster of DECIGO, which consists of three spacecraft, has three equilateral-triangular FP Michelson interferometers. Each FP Michelson interferometer has two FP cavities. Each FP cavity is shared by two different FP Michelson interferometers. Implementing two independent interferometers in one cluster is crucial to obtaining gravitational wave signals with different polarizations. The third interferometer is redundant; it plays the role of backup in case one of Ω the other two interferometers fails. We could also look at the null signal by combining the three interferometer outputs to improve the confidence in detected gravitational wave signals.

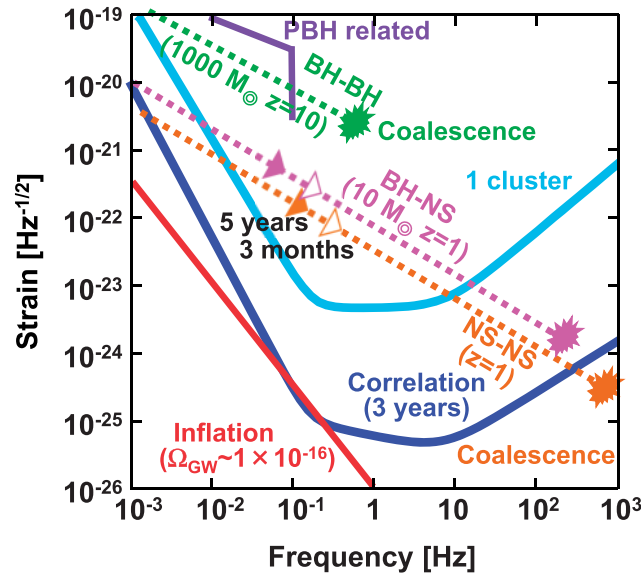


Fig. 3. Target strain sensitivity of one cluster of DECIGO (light blue line) and correlation of two clusters for 3 years (dark blue line), together with expected gravitational wave strain signals: primordial gravitational waves corresponding to $\Omega_{GW} \sim 1 \times 10^{-16}$ (red line), black hole (1000 solar mass) binary at $z = 10$ (BH–BH; green dotted line), black hole (10 solar mass)-neutron star binary at $z = 14$ (BH–NS; pink dotted line; filled and open triangles indicate 5 years and 3 months before coalescence, respectively), neutron star binary at $z = 1$ (NS–NS; brown dotted line; filled and open triangles indicate 5 years and 3 months before coalescence, respectively), and primordial dark-matter-related gravitational waves (PBH; purple line).

We plan to place four clusters of DECIGO in heliocentric orbit (See Fig. 1). We will place three clusters equally spaced around the Sun to ensure the best angular resolution for gravitational wave sources. We will place the fourth cluster together with one of the three clusters to obtain correlation signals for the detection of primordial gravitational waves. Since the noise of each DECIGO cluster is independent, while gravitational wave signals are common to two different clusters, correlating two cluster outputs improves the effective sensitivity of DECIGO. We plan to take the correlation signal for at least three years.

We plan to accomplish the quantum-noise-limited sensitivity for DECIGO by reducing all the other noise, such as the thermal noise of the mirrors and gravitational field fluctuations. As shown in Fig. 3, the target strain sensitivity of one cluster of DECIGO is about $4 \times 10^{-24} \text{ Hz}^{-1/2}$ around 1 Hz, and the target three-year-correlation strain sensitivity is about $7 \times 10^{-26} \text{ Hz}^{-1/2}$ around 1 Hz.

2.3. Design of B-DECIGO

We plan to launch B-DECIGO before DECIGO to expand gravitational wave astronomy and physics, as well as to demonstrate the technologies required to realize DECIGO. As shown in Fig. 1, B-DECIGO has one cluster, which consists of three drag-free spacecraft. The cluster has three FP Michelson interferometers in the same manner as DECIGO. The arm length of B-DECIGO is 100 km. The finesse of the FP cavities is 100, with a mirror diameter of 0.3 m and laser wavelength of 515 nm. We chose interferometer parameters with a laser power of 1 W and a mirror mass of 30 kg. Overall, the technologies required for B-DECIGO are slightly less challenging than DECIGO. The orbit of B-DECIGO is still to be determined. The target strain sensitivity of B-DECIGO is $6 \times 10^{-23} \text{ Hz}^{-1/2}$ around 1 Hz.

3. Objectives of DECIGO and B-DECIGO

3.1. Objectives of DECIGO

There are many science targets that DECIGO aims at, as shown in Fig. 3 (see also Ref. [15] for discussions on the proposal DO for ESA horizon 2050). The most important scientific objective of DECIGO is to detect primordial gravitational waves, which could have been produced during the inflation period [16–18] right after the birth of the Universe. In the standard inflation theory, stochastic gravitational waves are generated as quantum fluctuations of space-time. In the comoving frame, the wavelength of a gravitational wave mode does not change with time, but the Hubble horizon shrinks during the inflation phase. The quantum nature of a gravitational wave mode is lost when the horizon size decreases to a size comparable to its wavelength. After the horizon crossing, the mode is frozen (not in the sense of cryogenic freezing). At the end of inflation, the Hubble horizon began to expand in the comoving frame. When the horizon size again became larger than the wavelength, the gravitational wave mode was defrosted and started oscillating and propagating as a standard gravitational wave. Finally, these primordial gravitational waves reach us now.

Primordial gravitational waves with a larger wavelength extended beyond the horizon size at an earlier stage of the inflation period, and the wavelength relatively diminished below the horizon size at a more recent time. On the other hand, primordial gravitational waves with shorter wavelength extended beyond the horizon size at a later stage of the inflation period, and the wavelength relatively diminished below the horizon size at an earlier time. The frequency of the primordial gravitational waves which we aim at detecting with DECIGO is around 0.1 Hz. Thus, we could directly observe the inflation at a particular time, corresponding to the frequency of 0.1 Hz. Figure 3 indicates that DECIGO could barely detect the expected primordial gravitational waves from this inflationary scenario with the three-year correlation method. We plan to optimize the optical and mechanical parameters of DECIGO to improve the sensitivity further to ensure solid detection of the primordial gravitational waves or a significant upper limit.

There are many variants of the inflation models, and there is even a possibility that inflation did not take place. DECIGO could capture strong evidence supporting inflation and also provide us with crucial observational measures for discriminating between the inflation models. For example, DECIGO could determine the energy scale of the inflation as well as the reheating temperature of the inflation, depending on the model parameters. Here we should emphasize that electromagnetic waves started propagating straight some 380,000 years after the birth of the Universe. Thus, it is impossible to observe the Universe beyond that time directly with light; the primordial gravitational waves are highly penetrating and can be regarded as a precious fossil with which we can uniquely and directly access the beginning of the Universe.

Another important objective of DECIGO is to measure the acceleration of the expansion of the Universe without relying on astronomical empirical rules. The principle of the measurement is straightforward [10]. We just measure the phase and amplitude of the waveform of the gravitational waves coming from neutron star binaries far from the Earth (see Fig. 3). We can determine the distance to the binary by comparing the observed amplitude and the phase. For the dark energy parameters, the measurement accuracies were estimated in Ref. [13], considering a similar observational situation. Taking into account the updated binary merger rates and the difference in the assumed instrumental noise, DECIGO will be able to realize accuracies comparable to those presented in Ref. [13] (e.g. a 1%-level error for the parameter w_0). In addition, the waveform would show a phase change caused

by the acceleration of the expansion of the Universe. These measurements will be especially valuable for the investigation of dark energy because they are based only on fundamental laws of physics.

As for the detection of gravitational waves coming from neutron star binaries, DECIGO will provide a reliable and accurate prediction for their coalescences. DECIGO would catch $\sim 100,000$ gravitational wave events per year coming from neutron star binaries within a redshift of 5. The observable signals are up to several years in advance of the coalescences. The angular accuracy of the determination of the direction of the cosmological gravitational wave sources could be as small as ~ 1 arcsec (based on Ref. [13]). The accuracy of the predicted coalescence time could be typically ~ 0.1 s. This accurate prediction enables simultaneous gamma-ray observations and electromagnetic follow-ups to be more reliable and frequent. We can expect that multi-messenger astronomy will be developed significantly because of DECIGO.

The objectives of DECIGO also include the following (see Fig. 3). DECIGO could reveal the mechanism of the formation of massive black holes in the centers of galaxies, by detecting abundant gravitational waves coming from intermediate-mass black hole binaries. DECIGO is useful in examining the accuracy of general relativity [19]. For example, by detecting gravitational waves coming from neutron star and 10-solar-mass black hole binaries at a redshift of 1, the constraint on the Brans–Dicke parameter would be improved by four orders of magnitude compared with the current limit obtained by Cassini measurements. DECIGO could separate the scalar and vector modes, which could have been produced at the beginning of the Universe, from the tensor mode of gravitational waves [20]. DECIGO could examine the parity symmetry between the clockwise and counter-clockwise gravitational wave polarizations by placing two clusters of DECIGO at a slight distance [21]. DECIGO could determine whether primordial black holes are a contributor to dark matter by detecting gravitational waves emitted from the fluctuations of the mass density at the beginning of the Universe [22]. DECIGO could detect gravitational waves from a black hole binary merging in the ground-based detectors' frequency band with precise parameter estimations, especially of the coalescing time and sky location [23]. DECIGO could provide a meaningful upper limit for the number and mass of the scalar field by detecting gravitational waves emitted from the electroweak phase transition [24]. DECIGO could detect gravitational waves from cosmic strings that were produced in the GUT phase transition in the early Universe, by which we can confirm the seesaw mechanism for the generation of neutrino mass [25].

3.2. Objectives of B-DECIGO

The objectives of B-DECIGO are mainly astrophysical ones. B-DECIGO will predict the time and direction of neutron star binary coalescences ~ 100 times a year. The angular accuracy of the direction of the sources is about ~ 0.01 deg² (scaling results in Ref. [26] using Ref. [27]). The timing accuracy of the coalescences is about ~ 0.1 s for sources at a redshift of 0.1. This accurate prediction provides useful information to contribute significantly to multi-messenger astronomy. Moreover, B-DECIGO could reveal the formation mechanism of 30-solar-mass black holes, which were detected by LIGO and Virgo, by detecting abundant gravitational waves coming from 10- to 30-solar-mass black hole binaries.

Another vital role of B-DECIGO is to verify the various technologies required for DECIGO, including foreground clean-up [28]. DECIGO will detect many gravitational wave signals coming from neutron star and black hole binaries. We have to identify these signals and remove them from the observation data one by one in order to finally reach the primordial gravitational wave signals.

This foreground clean-up technology is, in principle, possible, but it requires a demonstration using real observation data. B-DECIGO will provide a framework for this demonstration.

4. Schedule of DECIGO and B-DECIGO

We plan to launch B-DECIGO as a precursor to DECIGO in the 2030s to demonstrate the technologies required for DECIGO, as well as to obtain fruitful scientific results to expand multi-messenger astronomy further. Then we hope to launch DECIGO at a later time, incorporating lessons learned from B-DECIGO.

We are also considering the possibility of having two missions in advance to demonstrate the technologies required for B-DECIGO. The first mission is to demonstrate the FP cavity operation with two super-small spacecraft in space. The two spacecraft have two mirrors, each of which is attached to each spacecraft. The two mirrors form an FP cavity, which is illuminated by laser light. We will control the FP cavity on resonance by feeding the cavity error signals back to the thrusters of the spacecraft. We are thinking of doing this mission in collaboration with the spacecraft engineering group, formation-flight group, infrared astronomy group, and X-ray astronomy group. We hope to launch this mission around 2024.

The second one is to demonstrate the combination of drag-free operation and FP cavity operation with two or three small spacecraft in space. B-DECIGO requires both these technologies, which are, in principle, compatible, but it is crucial to demonstrate this compatibility in a real mission. The formation-flight group is now considering leading this mission together with the DECIGO group and other groups. We hope to launch this mission in the late 2020s.

5. Conclusions

DECIGO aims at delivering a wide range of science. This includes the detection of primordial gravitational waves to verify and characterize the inflation of the Universe, measurement of the acceleration of the expansion of the Universe to provide reliable information for dark energy, prediction of accurate time and direction for electromagnetic follow-up observations, and other astrophysical and cosmological effects. B-DECIGO is a scientific pathfinder mission for DECIGO. It aims at performing astrophysical science as well as demonstrating the technologies required for DECIGO. We hope to launch B-DECIGO in the 2030s. We are considering the possibility of having two smaller missions in the 2020s to demonstrate the technologies necessary for B-DECIGO. We believe that in the future B-DECIGO and then DECIGO will expand gravitational wave astronomy and physics to full bloom.

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