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DECIGO : The Japanese space gravitational wave antenna

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Abstract. DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) is the planned Japanese space gravitational wave antenna, aiming to detect gravitational waves from astrophysically and cosmologically significant sources mainly between 0.1 Hz and 10 Hz and thus to open a new window for gravitational wave astronomy and for the universe. DECIGO will consist of three drag-free spacecraft, 1000 km apart from each other, whose relative displacements are measured by a differential Fabry-Perot interferometer. We plan to launch DECIGO in middle of 2020s, after sequence of two precursor satellite missions, DECIGO pathfinder and Pre-DECIGO, for technology demonstration required to realize DECIGO and hopefully for detection of gravitational waves from our galaxy or nearby galaxies.

1. Introduction

DECIGO (DECi-hertz Interferometer Gravitational wave Observatory) is the planned Japanese space gravitational wave antenna mission [1][2, 3, 4]. DECIGO is targeting to observe gravitational waves from astrophysically and cosmologically significant sources mainly between 0.1 Hz and 10 Hz, thus, to open a new window of observation for gravitational wave astronomy, and also for the universe.

The scope of DECIGO is to bridge (Fig. 1) the frequency gap between LISA [5] band and terrestrial detectors band such as advanced LIGO and LCGT [6]. The major advantage of DECIGO specializing in this frequency band is that the expected confusion limiting noise level caused by irresolvable gravitational wave signals from many compact binaries, such as white dwarf binaries in our Galaxy, is quite low above 0.1 Hz [7], therefore there is a potentially extremely deep window in this band.

Thus, as DECIGO will have sensitivity in the frequency range between LISA and terrestrial detectors band, DECIGO can serve as a follow-up for LISA by observing inspiraling sources that have moved above the LISA band, or as a predictor for terrestrial detectors by observing inspiraling sources that have not yet moved into the terrestrial detectors band.

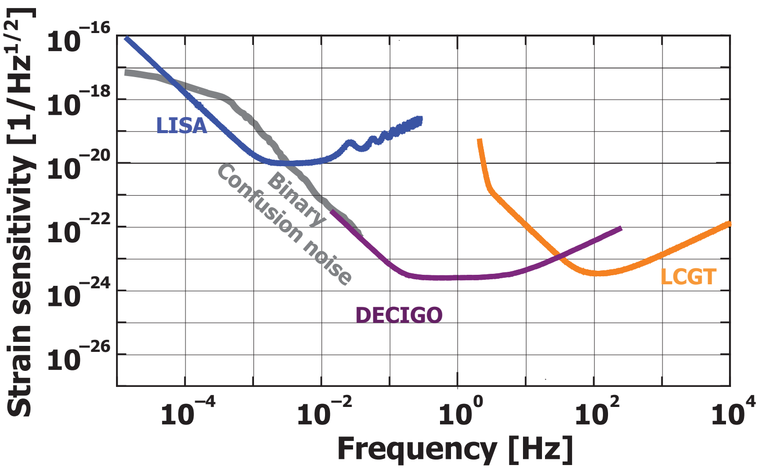

Figure 1. DECIGO design sensitivity with LISA and LCGT (on behalf of terrestrial detectors).

2. Pre-conceptual design

The pre-conceptual design of DECIGO consists of three drag-free spacecraft which keep triangular configuration with formation flying technique. The separation of each spacecraft (proof mass) is designed to be 1,000 km, whose relative displacements are measured by a differential Fabry-Perot (FP) interferometer (Fig. 2). The laser source is supposed to be frequency-doubled Nd:YAG laser with $\lambda = 532$ nm yielding output power of 10 W. The mass of the mirror is 100 kg with 1 m diameter, with low-loss High-reflectivity coatings, which enables the finesse of FP cavity to reach 10 with green light. Three sets of such interferometers sharing the mirrors as arm cavities comprise one cluster of DECIGO. As shown in Fig. 3, four clusters of DECIGO, located separately in the heliocentric orbit with two of them nearly at the same position, form the constellation DECIGO.

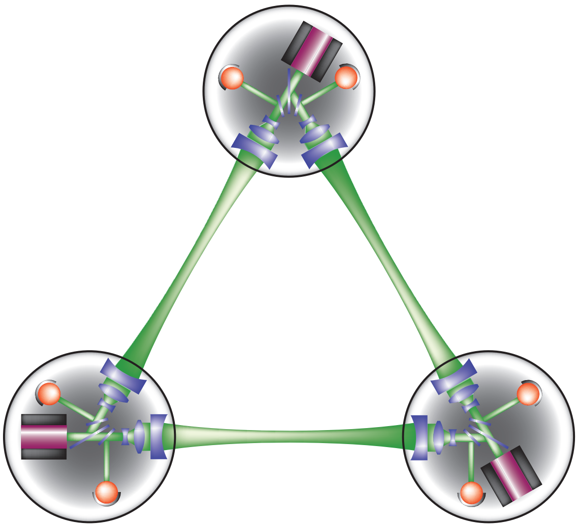

Figure 2. The pre-conceptual design of DECIGO. Three drag-free spacecraft keep 1000 km triangular configuration with formation flying technique. Each spacecraft will have light source and two proof masses.

The advantage of FP configuration is clearly that it can utilize much power of light for a better shot-noise-limited sensitivity than the transponder-type configuration (e.g. LISA). On the other hand, the FP configuration requires very accurate formation flying: the FP configuration requires the distance between two mirrors, thus, the distance between two spacecraft to be constant during continuous operations. This is a major difference between DECIGO and a transponder-type configuration, where the spacecraft are freely falling according to their local gravitational field.

3. Sensitivity goal and science

The target sensitivity of DECIGO, as shown in Fig. 4, is supposed to be limited by quantum noise in all frequency band: by the radiation pressure noise below 0.15 Hz, and by the shot noise above 0.15 Hz. In order to reach this sensitivity, all the practical noise should be suppressed well below this level. This imposes more stringent requirements than LISA for some subsystems of DECIGO, especially in the acceleration noise and frequency noise, therefore rigorous investigations are supposed to be indispensable for attainment of design sensitivity. Nonetheless, full success of DECIGO is expected to extract fruitful sciences.

- **Characterization of dark energy:** DECIGO will have enough sensitivity to detect gravitational waves coming from neutron star binaries at z=1 for five years prior to coalescences. Within this observable volume, about 50,000 neutron star binaries are expected to coalesce every year [8]. In addition to the physics of the neutron star, with precise analysis resolving gravitational wave signals coming from a number of binaries, it is possible to determine the acceleration of the expansion of the universe [1]. The constellation DECIGO is expected to have an angular resolution of about 1 arcsec, therefore, there is a chance to identify the host galaxies of each binary system. Thus, the acceleration of the expansion of the universe can also be measured by determining their red shifts optically [9], which will lead to better characterization of dark energy.

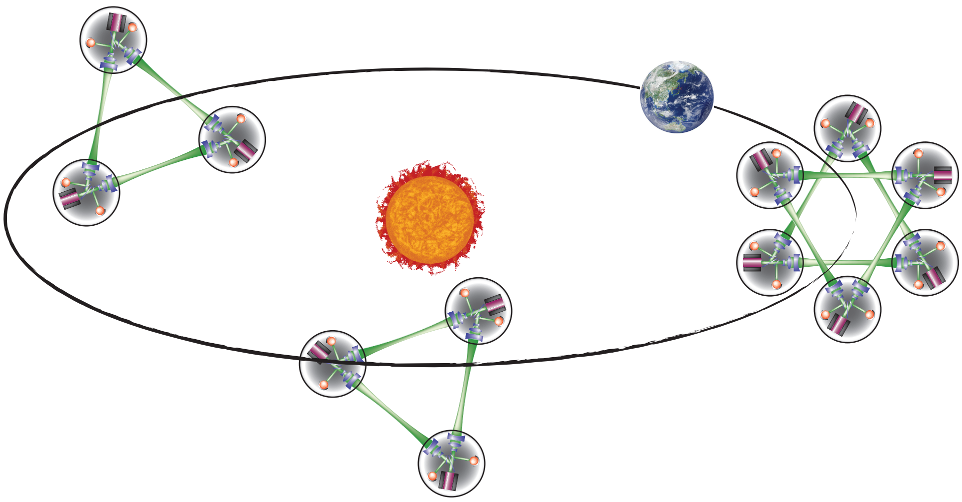

Figure 3. Constellation DECIGO in its orbit, which will have four clusters of DECIGO in total.

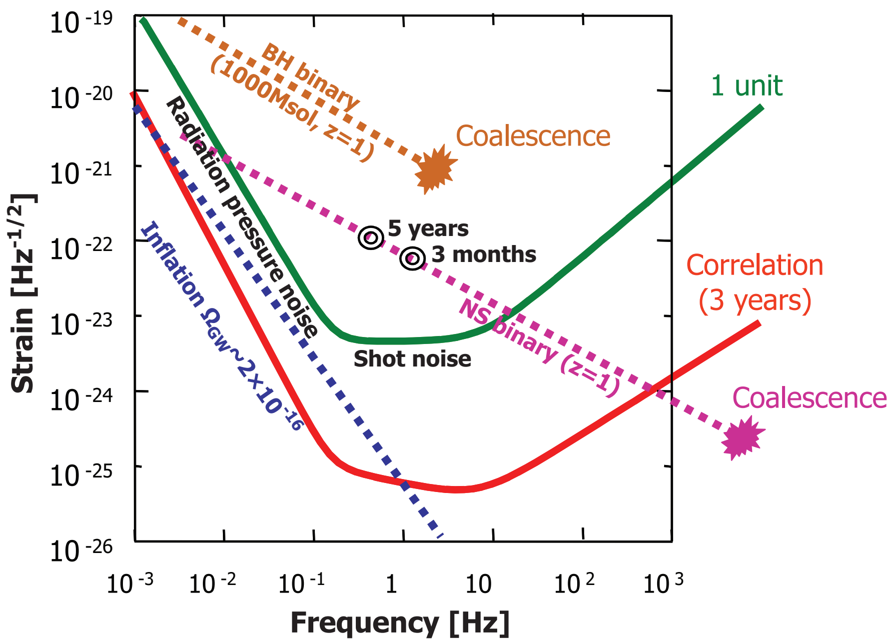

Figure 4. DECIGO design sensitivity (for 1unit and for 3 years correlation) and expected gravitational wave souces.

- **Formation mechanism of supermassive black holes:** DECIGO can detect gravitational waves coming from coalescences of intermediate-mass black hole binaries with an extremely high fidelity. For example the coalescences of black hole binaries of 1,000 solar masses at $z = 1$ give a signal to noise ratio of 6,000. This will make it possible to collect numerous data about the relationship between the mass of the black holes and the frequency of the coalescences, which will reveal the formation mechanism of supermassive black holes

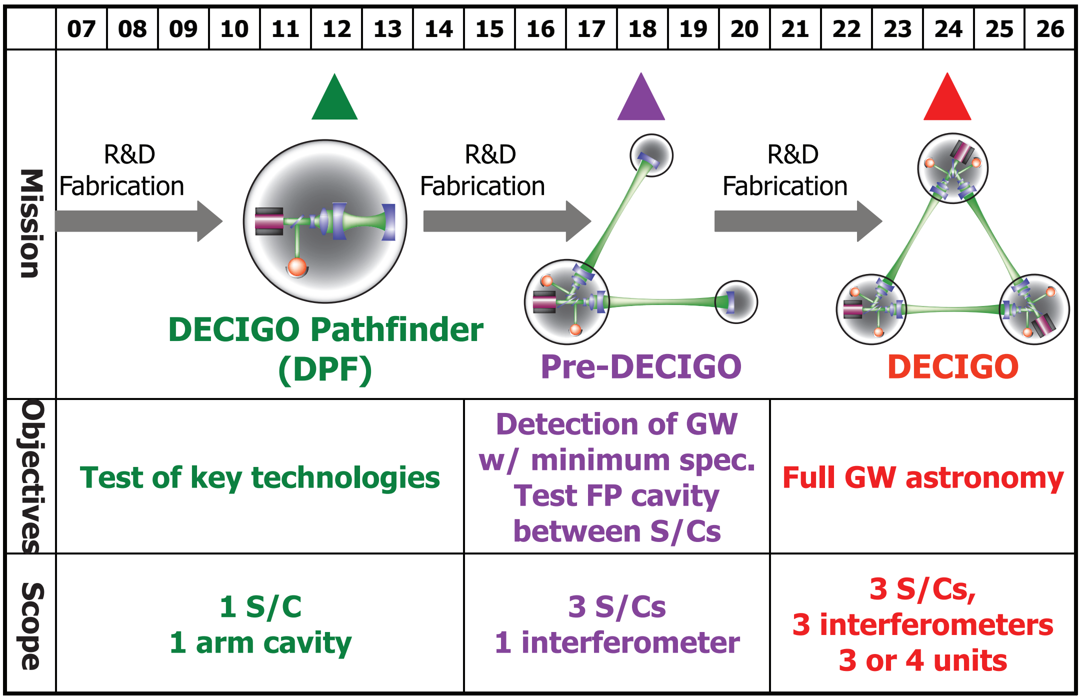

Figure 5. Roadmap of DECIGO. Pre-conceptual design of Pre-DECIGO is shown in addition to DPF and DECIGO.

in the center of galaxies.

- **Verification and characterization of inflation:** With correlation analysis of the data from the two clusters of DECIGO at nearly same location for three years, DECIGO will capable to detect stochastic background gravitational waves corresponding to $\Omega_{\rm GW} = 2 \times 10^{-16}$. According to the standard inflation model, it is expected that we could detect gravitational waves produced at the inflation period of the universe with DECIGO. This could be an extremely significant science driver for DECIGO because gravitational waves are the only means which make it possible to directly observe the inflation of the universe.

4. Roadmap

DECIGO is expected to be launched in the middle of 2020s (Fig. 5), before that, we plan to launch two precursor satellites: DECIGO pathfinder (DPF) [?] and pre-DECIGO(See Fig. 5). Major objective of these missions is a demonstration of key technologies for DECIGO just as LISA pathfinder [12] does for LISA, in addition, we also hope we can extract some scientific achievements with limited equipments allowed for these satellites in phases.

DPF tests the key technologies for DECIGO such as drag-free control of the spacecraft, stabilized laser system in space, precision laser metrology in space and test mass lock mechanism. At the same time, as DPF will have gentle sensitivity to the gravitational waves, it is expected that DPF will put some upper limit to the gravitational waves from the sources around center of our galaxy.

The technical objectives of Pre-DECIGO are demonstration of accurate formation flying, precision laser metrology with long baseline FP cavity and drag-free control for multiple spacecraft. Pre-DECIGO will have 100 km-scale FP cavity, therefore, it is supposed to have reasonable sensitivity to detect gravitational waves with minimum specifications. We hope that it will be launched around 2018.

Finally DECIGO is supposed to be launched around 2024 to open a new window of observation for gravitational wave astronomy.

5. DECIGO Pathfinder

DPF [10, 11] will employ a small-sized drag-free spacecraft that contains two freely falling proof masses, whose relative displacement is measured with a Fabry-Perot interferometer. A short Fabry-Perot cavity with finesse of 100 is illuminated by the frequency-stabilized Nd:YAG laser light yielding output powe rof 100 mW. The proof masses are clamped tightly for the launch and released gently in orbit. DPF is supposed to be delivered in the geocentric sun-synchronous orbit with an altitude of 500km. DPF will have strain sensitivity of $\sim 10^{-15}$ around the frequency band of 0.1-1 Hz.

The primary objective of DPF is to demonstrate key technologies for DECIGO such as drag-free control system, FP cavity precision metrology system in orbit, frequency-stabilized laser in orbit, and the clamp release mechanism. In addition, the scientific objective of DPF is to detect rather unlikely events of intermediate-mass black hole ($10^3 - 10^4 M_{\rm sol}$) inspirals in our galaxy; it is possible to detect such events with the aimed sensitivity of DPF.

Recently, DPF was identified as one of the candidate missions for the small satellite mission series which had been initiated by the Japanese space agency, JAXA/ISAS. This program is to launch at least 3 small satellites in upcoming 5 years using standard bus systems, whose scope is to reduce the cost of missions significantly compared with the conventional missions, and thus to increase a chance to go to space for a variety of fields. DPF is now selected as one of the potential mission candidates for the second or third missions, so DPF will be launched in 2012 (second mission) in the best and earliest case.

6. Conclusions

The future Japanese space gravitational wave antenna, DECIGO, is expected to detect gravitational waves from various kinds of sources and thus to open a new window of observation for gravitational wave astronomy. We have started serious R&D for DPF as one of the candidate missions for the small-spacecraft mission series to demonstrate the technologies required to realize DECIGO.

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