

The optimal approach of detecting stochastic gravitational wave from string cosmology using multiple detectors

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Abstract

String cosmology models predict a relic background of gravitational wave produced during the dilaton-driven inflation. Its spectrum is most likely to be detected by ground gravitational wave laser interferometers (IFOs), like LIGO, Virgo, GEO, as the energy density grows rapidly with frequency. We show the certain ranges of the parameters that underlying string cosmology model using two approaches, associated with 5% false alarm and 95% detection rate. The result presents that the approach of combining multiple pairs of IFOs is better than the approach of directly combining the outputs of multiple IFOs for LIGO, LIGOL, Virgo and GEO.

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1. Introduction

Stochastic gravitational wave background, which has two origins, is one target of gravitational wave interferometers (IFOs). It might result from an extremely large number of weak astrophysical gravitational wave sources, like compact stars in binary system (see, e.g., [1] for more details). It also might result from some processes of very early universe, like phase transitions or amplification of vacuum fluctuations in inflationary (see, e.g., [2–4] for reviews). In the latter case of origin, the gravitational waves carry the earlier information of the universe than that shown by electromagnetic waves. One of the most interesting processes in the early universe is from the string cosmology [5,6], which predicts a quite different gravitational wave background spectrum from that predicted by other cosmological models for early universe. That the energy density grows rapidly with frequency [7] means that the ground IFOs may be the best detectors. Several large scale ground IFOs are in operation: Laser Interferometric Gravitational

tional Wave Observatory (LIGO) [8] in Livingston (LIGOL) and in Hanford (LIGO), Virgo [9] near Pisa and GEO [10] in Hanover.

Two approaches of combining $2N$ detectors to improve the detection ability to the stochastic gravitational wave background are proposed in [11]: (i) correlating the outputs of a pair of detectors, then combining the multiple pairs, and (ii) directly combining the outputs of $2N$ detectors. As shown in [12], for $2N$ detectors with equal noise level, the data observation time and the overlap reduction functions, the optimal approach is to combine multiple pairs of two detectors comparing to directly combining $2M$ ($M \leq N$) detectors. But the real detectors should not be of identical noise levels and overlap reduction functions. We plot the proposed noise curves of detectors in Fig. 1 and the overlap reduction functions in Fig. 2. A number of authors [13–16] have used the approach of combining LIGO and LIGOL to detect the string cosmology gravitational wave background. A recent work [17] has shown that the approach of combining multiple pairs of IFOs using Virgo and LIGO and GEO can improve the detection ability to the stochastic gravitational wave background illustrated by a simulated isotropic gravitational wave background generated with an astrophysically-motivated spectral shape.

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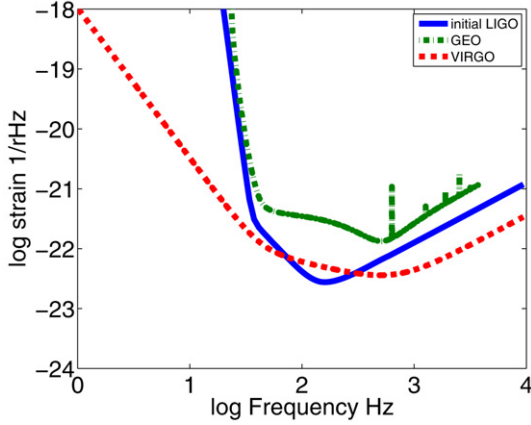


Fig. 1. The designed noise power spectrum of initial LIGO, Virgo and GEO. Data are taken from [22–24].

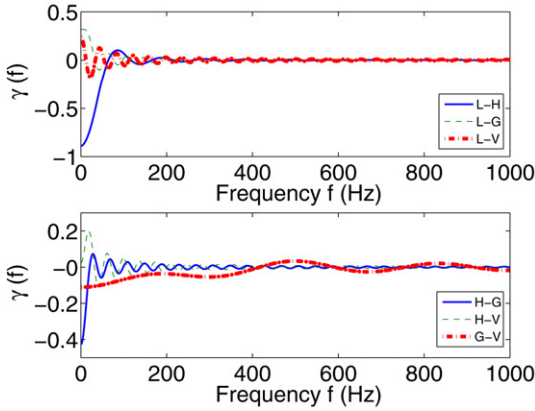


Fig. 2. The overlap reduction function. Data are taken from [22–25].

In this Letter we compare the two approaches by constraining the parameter space of gravitational wave background predicted from string cosmology using LIGO, LIGO, Virgo, and GEO. Our result shows that the approach of combining multiple pairs of IFOs is better than the approach of directly combining the outputs of multiple IFOs for those real IFOs at their designed noise levels. Our Letter is organized as follows. In Section 2 we review the two approaches of detecting a stochastic background using multiple detectors. In Section 3 after a brief review of the gravitational wave background produced by string cosmology, we implement the two approaches using four IFOs: LIGO, LIGO, Virgo and GEO at their designed noise levels. Our conclusion will be provided in Section 4.

2. Two approaches of detecting a stochastic background using multiple detectors

It has been shown [11] that after correlating signals of two detectors for time T (we take $T = 10^7$ sec = 3 months) the squared ratio of “Signal” (S) to “Noise” (N) is given by an integral over frequency f :

$$\left(\frac{S}{N}\right)^2 = \frac{9H_0^4}{50\pi^4} T \int_0^\infty df \frac{\gamma^2(f) \Omega_{\text{gw}}^2(f)}{f^6 P_1(f) P_2(f)}, \quad (1)$$

where $P_i(f)$ is the one-side noise power spectral density which describes the instrument noise $n_i(f)$ in frequency domain:

$$\langle \tilde{n}_i^*(f) \tilde{n}_i(f') \rangle = \frac{1}{2} \delta(f - f') P_i(|f|). \quad (2)$$

Eq. (1) is under the assumption that the noise of the detectors are (i) stationary, (ii) Gaussian, (iii) statistically independent of one another and of the stochastic gravitational wave background, and (iv) much larger in magnitude than the stochastic gravitational wave background.

$\gamma(f)$ is the so-called *overlap reduction function* first calculated by Flanagan [18], which shows the co-response of two detectors. This is a dimensionless function of frequency f , which is determined by the relative positions and orientations of two detectors. Explicitly,

$$\gamma(f) := \frac{5}{8\pi} \sum_A \int_{S^2} d\hat{\Omega} e^{i2\pi f \hat{\Omega} \cdot \Delta \vec{x}/c} F_1^A(\hat{\Omega}) F_2^A(\hat{\Omega}), \quad (3)$$

where $\hat{\Omega}$ is a unit vector specifying a direction on the two-sphere, $\Delta \vec{x} := \vec{x}_1 - \vec{x}_2$ is the separation vector between the central stations of the two detector sites, and

$$F_i^A(\hat{\Omega}) := e_{ab}^A(\hat{\Omega}) \frac{1}{2} (\hat{X}_i^a \hat{X}_i^b - \hat{Y}_i^a \hat{Y}_i^b) \quad (4)$$

is the i th detector’s response to a zero frequency, unit amplitude, $A = +, \times$ polarized gravitational wave, where $\hat{X}_i^a$ and $\hat{Y}_i^a$ are unit vectors pointing in the direction of the detector arms. The overlap reduction function $\gamma(f)$ in Eq. (3) is normalized for coincident and coaligned detectors: $\gamma(0) = 1$. We refer the reader to [2,11] for more details about the overlap reduction function $\gamma(f)$. Two approaches were shown in [11] for multiple IFOs, the optimal approach of combining multiple detector pairs:

$$\left(\frac{S}{N}\right)_{\text{opt I}}^2 = \sum_{\text{pair}} \left(\frac{S}{N}\right)_{\text{pair}}^2, \quad (5)$$

and the optimal approach of directly combining $2N$ detectors:

$$\left(\frac{S}{N}\right)_{\text{opt II}}^2 \approx \binom{12}{2} \left(\frac{S}{N}\right)^{2(34)} \left(\frac{S}{N}\right)^2 \cdots \binom{2N-1}{2, 2N} \left(\frac{S}{N}\right)^2 + \text{all possible permutations.} \quad (6)$$

In order to detect a stochastic background with 5% false alarm and 95% detection rate, the total optimal signal to noise ratio SNR_{opt} threshold should be 3.29.

3. Detecting a string cosmology background using two approaches by four IFOs

String cosmology, also denoted in the literature as the “pre-Big-Bang (PBB) models” depicts a different view of PBB era from the “slow-roll” (standard) inflation. The dilaton-driven inflation phase is well understood, followed by a sting phase which is currently not known. The “minimal” PBB model [19] describes the sting phase following the dilaton-driven inflation phase is a constant curvature phase. At the end of the string

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