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Measurement of parity violation in the early universe using gravitational-wave detectors

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ABSTRACT

A stochastic gravitational-wave background (SGWB) is expected to arise from the superposition of many independent and unresolved gravitational-wave signals, of either cosmological or astrophysical origin. Some cosmological models (characterized, for instance, by a pseudo-scalar inflaton, or by some modification of gravity) break parity, leading to a polarized isotropic SGWB. We present the first upper limit on this parity violation from direct gravitational-wave measurements by measuring polarization of the SGWB in recent LIGO data and by assuming a generic power-law SGWB spectrum across the LIGO-sensitive frequency region. We also estimate sensitivity to parity violation for future generations of gravitational-wave detectors, both for a power-law spectrum and for a specific model of axion inflation. Since astrophysical sources are not expected to produce a polarized SGWB, measurements of polarization in the SGWB would provide a new way of differentiating between the cosmological and astrophysical SGWB sources.

1. Introduction

A stochastic gravitational-wave background (SGWB) is expected to arise from the superposition of gravitational waves (GWs) from many uncorrelated and unresolved sources. Numerous cosmological SGWB models have been proposed, including inflationary models [1–4], models based on cosmic (super)strings [5,6], and models of alternative cosmologies [7]. Furthermore, various astrophysical models have been proposed based on integrating contributions from astrophysical objects across the universe, such as compact binary coalescences of binary neutron stars and/or black holes [8,9], magnetars [10,11], and rotating neutron stars [12]. Several searches for the *unpolarized* isotropic [13–15] and anisotropic SGWB [16,17] have been conducted using data acquired by interferometric GW detectors LIGO [18,19] and Virgo [20]. These searches have established upper limits on the energy density in the SGWB, and have started to constrain some of the proposed models [6,9,21]. By contrast, in this Letter we establish the first upper limits from direct GW measurements on the circularly polarized isotropic SGWB.[1] We note that since astrophysical sources are unlikely to induce a detectable polarization in the isotropic SGWB (as far as new physics operators are suppressed by a natural scale such as the Planck scale), detecting a circularly polarized SGWB is a potentially excellent way of distinguishing between the cosmological and astrophysical SGWB contributions.

Polarization asymmetry in the SGWB could be generated in the early universe if parity is violated either explicitly or spontaneously. Explicit breaking mechanisms are typically due to quantum gravity effects, such as the imaginary part of the Immirzi parameter [23] and higher curvature terms in some power-counting renormalizable theories of gravity [24], and break CPT as well. Those effects may become important only at extremely high energies (far above the Planck scale [25]) and thus should be greatly suppressed at the late stage of inflation, where gravitational waves of scales relevant for GW detectors are generated.[2] On the other hand, spontaneous breaking mechanisms are typically due to axial couplings of an axion (or an axion-like, pseudo-scalar field) to gravity [26,27] and/or a gauge field [28]. While such couplings are fundamentally higher dimensional operators, they manifest as terms linear in momenta in the dispersion relation of the graviton

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[1] An indirect measurement of the circularly polarized SGWB using the CMB data was first done in [22]. The analysis of [22], in which the polarization was taken as a free parameter, produced the upper bound $r < 0.59$ at 95% CL on the tensor-to-scalar ratio.

[2] Note that CPT violations in the gravity sector, if they exist, inevitably percolate to the photon and fermion sectors by loop corrections, and thus are subject to observational constraints.

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and/or gauge field once the derivative of the axion(-like) field obtains a large vacuum expectation value. For this reason their effects may become significant at relatively low energy, leading to a potentially observable parity-violating SGWB. An axial coupling to a gauge field is often considered in models of axion inflation and is more attractive for our purpose since the suppression scale is typically lower. Another attractive feature of axion inflation is that the spontaneous CPT breaking generated by the inflaton motion is turned off at the end of inflation. This model is therefore not subject to the strong constraints from CPT violations that are present for the explicit breaking models.

In all of these models, parity violation breaks the symmetry between the two circular polarization modes. The polarization asymmetry can be measured for a particular model by tracking the amplitude of different polarization modes as a function of time at a given GW detector and by comparing it to the same measurement made by other detectors at different locations. We follow the formalism developed in [29], modified to address a polarized SGWB as discussed in [30,31]. Using the latest SGWB measurement with LIGO detectors [15], we apply this formalism to produce the first constraints on parity violation for a generic power-law SGWB spectrum at interferometer scales. We also estimate the sensitivity of future GW detectors to SGWB polarization, assuming a power-law SGWB spectrum, and we illustrate how this technique could be used to constrain a specific model, namely the axion-inflation model [28]. In particular, we consider the upcoming second-generation GW detectors; Advanced LIGO (aLIGO) [32] detectors at Hanford, WA (H1) and Livingston, LA (L1), Advanced Virgo [33] in Italy (V1), GEO-HF [34] in Germany, and KAGRA [35,36] in Japan (K1) are expected to have $\sim 10\times$ better strain sensitivities than the first-generation detectors and to produce first science-quality data in 2015. We also consider an example configuration of a pair of third-generation GW detectors, with strain sensitivity similar to the proposed Einstein Telescope [37].

2. Search formalism

Following [30], we start from the plane-wave expansion of the metric at time t and position $\vec{x}$:

$$h_{ab}(t,\vec{x}) = \sum_A \int_{-\infty}^{\infty} df \int_{S^2} d\hat{\Omega}\, h_A(f,\hat{\Omega}) e^{-2\pi i f(t-\vec{x}\cdot\hat{\Omega})} e^{A}_{ab}(\hat{\Omega}), \quad (1)$$

where $e^A_{ab}(\hat{\Omega})$ is the polarization tensor associated with a wave traveling in the direction $\hat{\Omega}$, and f is frequency (we use natural units $c = \hbar = 1$). We consider the left- and right-handed correlators [30]:

$$\begin{aligned}&\langle h_{R/L}(f,\hat{\Omega}) h^*_{R/L}(f',\hat{\Omega}')\rangle \\ &\quad = \frac{\delta(f-f')\delta^2(\hat{\Omega}-\hat{\Omega}')}{4\pi}\big[I(f) \pm V(f)\big]\end{aligned} \quad (2)$$

where $h_L = (h_+ + ih_\times)/\sqrt{2}$, $h_R = (h_+ - ih_\times)/\sqrt{2}$, and $+$ and $\times$ are the standard plus and cross polarizations.

Note this is the point of departure from the past searches for unpolarized isotropic SGWB, which assume $V = 0$. Further note that $\langle h_R h_L^* \rangle$ vanishes due to statistical isotropy. The normalized energy density is then given by [30,29]:

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df} = \frac{\pi f^3}{G_N \rho_c} I(f). \quad (3)$$

where $d\rho_{\mathrm{GW}}$ is the energy density in the range $[f, f+df]$, G_N is Newton's constant, and ρ_c the critical energy density of the universe.[3] We also compute the standard cross-correlation estimator [29]:

$$\begin{aligned}\langle\hat{Y}\rangle &= \int_{-\infty}^{+\infty} df \int_{-\infty}^{+\infty} df'\, \delta_T(f-f')\big\langle\big(s_1^*(f) s_2(f')\big\rangle \tilde{Q}(f') \\ &= \frac{3H_0^2 T}{10\pi^2}\int_0^\infty df\, \frac{\Omega'_{\mathrm{GW}}(f)\gamma_I(f)\tilde{Q}(f)}{f^3},\end{aligned} \quad (4)$$

where

$$\begin{aligned}&\Omega'_{\mathrm{GW}}(f)\gamma_I(f) = \Omega_{\mathrm{GW}}(f)\big[\gamma_I(f) + \Pi(f)\gamma_V(f)\big], \\ &\gamma_I(f) = \frac{5}{8\pi}\int d\hat{\Omega}\,\big(F_1^+ F_2^{+*} + F_1^\times F_2^{\times *}\big) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}}, \\ &\gamma_V(f) = -\frac{5}{8\pi}\int d\hat{\Omega}\, i\big(F_1^+ F_2^{\times *} - F_1^\times F_2^{+*}\big) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}}.\end{aligned} \quad (5)$$

Here, T is the measurement time, $\delta_T(f) \equiv \sin(\pi f T)/(\pi f)$, $\tilde{s}_1(f)$ and $\tilde{s}_2(f)$ are Fourier transforms of the strain time-series of two GW detectors, $\tilde{Q}(f)$ is a filter, and $F^A_n = e^A_{ab} d^{ab}_n$ is the contraction of the tensor mode of polarization A, e^A_{ab}, with the response of the detector n, d^{ab}_n.[4] The factor $\gamma_I(f)$ is the standard overlap reduction function arising from different locations and orientations of the two detectors, and $\gamma_V(f)$ is a new function, associated with the parity-violating term and first computed in [38]. Fig. 1 shows these functions for two real detector pairs. Finally, $\Pi(f) = V(f)/I(f)$ encodes the parity violation, with maximal values $\Pi = \pm 1$ corresponding to fully right- or left-handed polarizations. Setting $\Pi = 0$ reproduces the standard unpolarized SGWB search [29].

Assuming stationary Gaussian detector noise (uncorrelated between two detectors), the estimator for the variance associated with $\hat{Y}$ is [29]:

$$\sigma^2 = \frac{T}{4}\int_0^\infty df\, P_1(f) P_2(f)\big|\tilde{Q}(f)\big|^2, \quad (6)$$

where $P_n(f)$ are the one-sided noise power spectral densities of the two GW detectors. In practice, we divide the sensitive frequency band of the GW detectors into bins $\Delta f = 0.25$ Hz wide [15]. We then compute the estimator $\hat{Y}_i$ and the variance σ_i^2 for each frequency bin i assuming a frequency-independent spectrum template $\Omega_{\mathrm{GW}}(f_i) = \Omega_0$ for each bin. Optimization of the signal-to-noise ratio then leads to the following optimal filter for a frequency-independent GW spectrum in the frequency bin f [29]:

$$\tilde{Q}(f_i) = \mathcal{N}\frac{\gamma_I(f)}{f_i^3 P_1(f_i) P_2(f_i)}, \quad (7)$$

with normalization constant $\mathcal{N}$ chosen so that $\langle\hat{Y}_i\rangle = \Omega_0$.

To perform parameter estimation in the parity-violating models, we adopt the Bayesian approach introduced in [21]. We define the following likelihood function:

$$L(\hat{Y}_i, \sigma_i|\vec{\theta}) \propto \exp\bigg[-\frac{1}{2}\sum_i \frac{(\hat{Y}_i - \Omega'_{\mathrm{M}}(f_i;\vec{\theta}))^2}{\sigma_i^2}\bigg]. \quad (8)$$

[3] Note that the similar Eq. (3) of [30] contains an additional factor of 4, which we believe is incorrect.

[4] Note that the minus sign in the equation for $\gamma_V(f)$ is missing in the intermediate expression in [30]; however, their final expression is correct and coincides with our computation.