Snowmass2021 - Letter of Interest

Correlating Stochastic Gravitational Wave Background with Electromagnetic Observations

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract: A stochastic gravitational-wave background (SGWB) arises as an incoherent superposition of uncorrelated gravitational wave sources. The directional structure of the SGWB may be correlated with sky-maps in the electromagnetic spectrum, such as cosmic microwave (or infrared) background, galaxy count surveys, or gravitational weak lensing surveys. Correlating the SGWB anisotropy at different gravitational wave frequencies with those in different bands of the EM spectrum may offer unique insights into the physics of very high energies, not reproducible in laboratories. This includes the physics of phase transitions in the early universe, cosmic strings network dynamics, origin (stellar vs primordial) of black holes, and others.

A stochastic Gravitational-Wave Background (SGWB) arises as an incoherent superposition of many gravitational wave (GW) sources, summed over all sky directions and both polarizations. Numerous SGWB models have been proposed, both cosmological and astrophysical, many of which are accessible to terrestrial and space-borne GW detectors—for reviews see [1,2]. Measurements of the SGWB therefore have the potential to provide information about the earliest phases of the evolution of the universe (including inflation), about fundamental particle interactions at very high energies not achievable in laboratories, and about the origin (primordial vs stellar) of binary black hole systems observed by Advanced LIGO and Advanced Virgo detectors.

The SGWB is typically described in terms of its energy density [3,4]:

$$\Omega_{\rm GW}(\hat{e},f) \equiv \frac{f}{\rho_c}\frac{{\rm d}^3\rho_{\rm GW}\left({\rm f},\hat{\rm e}\right)}{{\rm d}f{\rm d}^2\hat{\rm e}} = \frac{\bar{\Omega}_{\rm GW}}{4\pi} + \delta\Omega_{\rm GW}(\hat{e},f), \tag{1}$$

where $d\rho_{\rm GW}$ is the energy density of gravitational radiation stored in the frequency band $[f, f+df]$, $\hat{e}$ is the direction on the sky, and ρ_c is the critical energy density needed for a spatially flat Universe. In the second step, we have separated the isotropic and anisotropic components of the SGWB energy density. The anisotropic part can further be decomposed in spherical harmonics:

$$\delta\Omega_{\rm GW}(\hat{e},f) = \sum_{lm} a_{lm}(f) Y_{lm}(\hat{e}), \qquad C_l(f) = \frac{1}{2l+1}\sum_m \langle a_{lm}(f) a^*_{lm}(f)\rangle, \tag{2}$$

where we have assumed statistical isotropy and defined the angular power spectrum $C_l(f)$. While the isotropic SGWB component is expected to be larger than the possible anisotropy across the sky, there have been significant recent developments in the literature computing the levels of anisotropy for various astrophysical and cosmological SGWB models [5–24]. Some of them have also investigated the possibility of correlating the SGWB anisotropy with the anisotropy observed in electromagnetic (EM) tracers of the large scale structure, such as galaxy counts and weak lensing [12–14,16,18–20,25], or the Cosmic Microwave Background (CMB) [21]. In such cases, one defines the angular cross-correlation spectrum:

$$D(\theta) = \langle \delta\Omega_{\rm GW}(\hat{e}_1,f), \delta X(\hat{e}_2)\rangle = \sum_{lm} \frac{2l+1}{4\pi} D_l(f) P_l(\cos\theta) \tag{3}$$

where $X(\hat{e})$ describes an EM observation such as galaxy count distribution, and θ is the angle between the two sky directions $\hat{e}_1$ and $\hat{e}_2$. These SGWB-EM anisotropy correlations carry unique potential to probe different aspects of high-energy physics, as we outline in the following examples.

Phase Transitions: While most cosmological SGWB models predict isotropic backgrounds [26–33], recent studies have started to investigate anisotropy in these models. An example is the model of phase transitions (PT) in the early universe, which occurred as the universe cooled and went through symmetry-breaking transitions [34–42]. As bubbles of a new vacuum form and expand, collisions of bubble walls, combined with corresponding motion of the plasma and magnetohydrodynamic turbulences lead to formation of the SGWB [42]. A PT is expected to occur at the time of the electroweak symmetry breaking, at ~ 1 TeV scale, resulting in a potentially strong SGWB in both LISA and third-generation (3G) terrestrial detector bands [41,43]. Possible PTs at higher temperatures ($\sim 10^3 - 10^6$ TeV) would also be accessible to 3G detectors [43]. The PT would have occurred at slightly different redshifts in different causally disconnected regions of the universe, giving rise to anisotropy in the SGWB. The SGWB angular structure would not be affected by interactions with the plasma (i.e. effects such as Silk damping and baryon acoustic oscillations are not relevant for GWs), resulting in a simple angular spectrum: $C_l^{\rm GW} \sim [l(l+1)]^{-1}$ [21]. Assuming the PT happened after inflation, the primordial density fluctuations that led to the CMB angular spectrum would also have been present during the PT, imprinting a SGWB anisotropy at least as large as the CMB anisotropy [21].

The degree and nature of correlations between the two backgrounds would provide valuable insight into inflation and the ”dark ages“ of cosmic history.

Cosmic strings: Cosmic strings, either as fundamental strings or as topological defects formed during PTs in the early universe, are expected to support cusps[44–47] and kinks[48], which if boosted toward the Earth could result in detectable GW bursts. Integrating contributions of kinks and cusps across the entire string network results in a SGWB. Discovery of the cosmic superstring SGWB would open a unique and rare window into string theory[49]. The amplitude, the frequency spectrum, and the angular spectrum depend on fundamental parameters of cosmic strings (string tension, reconnection probability), and on the network dynamics model[50–52]. While the isotropic (monopole) component of this SGWB may be within reach of the advanced or 3G detectors[53], the anisotropy amplitudes are found to be $10^4 - 10^6$ times smaller than the isotropic component, depending on the string tension and network dynamics[6,54]. This level of anisotropy may be within reach of the 3G detectors. Correlating the anisotropy of this SGWB with anisotropy in the CMB or large scale structure may reveal details about the formation and dynamics of the cosmic string network.

Primordial Black Holes (PBHs): PBHs are of high interest as dark matter candidates and have been searched for using different observational approaches, including gravitational lensing, dynamical effects, and accretion effects. While constraints have been placed that disfavour PBHs as a significant fraction of the dark matter, they are far from conclusive due to the variety of assumptions involved, and consequently a window around $10M_{\odot}$ is still allowed. Cross correlating the map of the SGWB due to binary black hole (BBH) signals with the maps of galaxy distribution or dark matter distribution could provide additional insights on the origin of black holes[55–58]. In particular, in more massive halos the typical velocities are relatively high, making it harder for two PBHs to form a binary through GW emission, since the cross section of such a process is inversely proportional to some power of the relative velocity of the progenitors. The PBH binaries are therefore more likely to form binaries in low-mass halos. On the other hand, the merger probability for stellar black holes is higher in more luminous galaxies (or more massive halos). Therefore, if the BBH SGWB anisotropy is found to be correlated with the distribution of luminous galaxies, the BBHs would be of stellar origin, otherwise they would be primordial. While mergers of PBHs would tend to trace the filaments of the large-scale structure, stellar BBH mergers would tend to trace the distribution of galaxies of high stellar mass. The clustering of well-resolved individual GW sources may provide additional constraints[66–68], and efforts to combine well-resolved sources with the SGWB hold promise as well[65].

Outlook for GW-EM observations: Advanced LIGO and Advanced Virgo have produced upper limit measurements of the SGWB anisotropy in the 20-500 Hz band for different frequency spectra, and for both point sources and extended source distributions on the sky[59,60]. Similar techniques for measuring SGWB anisotropy in the 1 mHz band using LISA are being developed[61]. The first attempts to correlate SGWB measurements with EM observations are also being developed (for example with the SDSS galaxy survey, resulting in upper limits on the cross-correlation[62]). Much more remains to be done in order to fully explore the science potential of the SGWB-EM correlation approach. Systematic studies are needed to understand the angular resolution of GW detector networks and to perform optimal SGWB-EM correlation measurements so as to start constraining model parameters—e.g. Bayesian techniques applied to the BBH SGWB are particularly promising[63,64]. Further development of theoretical models of SGWB-EM anisotropy correlation is critical to enable formulation of suitable statistical formalisms to compare these models to the data. Finally, the study of the astrophysical and cosmological components of the SGWB and their correlations with different EM observations will be further deepened by the upcoming, more sensitive data coming from gravitational wave detectors (LIGO, Virgo, Kagra, Einstein Telescope, Cosmic Explorer, LISA), galaxy and weak lensing surveys (EUCLID, SPHEREx, DESI, SKA, and others), and CMB measurements.

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