

Snowmass2021 - Letter of Interest

The Stochastic Gravitational Wave Background as a Probe of New Physics from the Early Universe

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
- ☒ (TF9) Theory Frontier: Astro-Particle Physics and Cosmology
- ☒ (EF9) Energy Frontier: BSM: more general explorations

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Abstract: (maximum 200 words)

Direct detection of a stochastic gravitational wave background (SGWB) of primordial origin would be a profound discovery, providing deep insight into new physics. A variety of early Universe scenarios – including inflation, phase transitions, and topological defects – predict the production of a SGWB. Many of these scenarios are within reach of current and/or planned GW detectors. Measurement of the spectrum, polarization, and anisotropies can help identify the energy scale, cosmic era, and underlying physics responsible for its generation. The development of new detectors and technologies for GW observations will open new opportunities for fundamental physics, and in particular a new cosmic frontier for high energy physics. This white paper will highlight early Universe GW sources, connections to beyond the Standard Model particle physics, and discovery prospects.

Motivation: As the only known degrees of freedom that can propagate freely throughout the entire history of the Universe, gravitational waves (GWs) provide a unique window into our early cosmic history. Physical processes in the early Universe may have produced a stochastic GW background (SGWB) observable by present-day and/or future GW experiments. An important goal of the high energy physics and cosmology communities is to better understand and characterize possible early Universe sources of GWs for the potential insight they can provide into key aspects of high energy physics.

Sources: There exist several well-motivated early Universe sources of GWs, each relying on distinct physical mechanisms to produce gravitational radiation. As a result, predictions for the spectral shape of the resulting SGWB, and the corresponding detection prospects, vary markedly across these sources, several of which we describe briefly below. (For more in-depth reviews, see e.g. [1, 2]).

- **First-order Phase Transitions** – A first-order cosmological phase transition proceeds through bubble nucleation. The collisions of these bubbles, and the resulting motion of the cosmic fluid, can efficiently source GWs (see Refs. [3, 4] for a more in-depth discussion). The Higgs sector of the Standard Model of particle physics was initially thought to give rise to such a first-order transition during electroweak symmetry breaking, but the observed value of the Higgs mass precludes this possibility absent new interactions beyond the SM (BSM). Nevertheless, there are various well-motivated extensions of the SM that generically predict strong first-order PTs in the early Universe, and hence a sizable GW signal. The typical spectrum arising from a first-order PT is a broken power-law, with a peak frequency set by the typical separation between bubble centers when they collide, which in turn is set roughly by the Hubble parameter at the time of the transition. Electroweak-scale PTs can be tied to the mechanism of electroweak baryogenesis for explaining the baryon asymmetry of the Universe, and generally predict a peak frequency in the mHz regime. This implies an important connection between GW observations in this frequency band (covered by space-based interferometers such as LISA [5]) and the Higgs physics programs at the LHC and possible future colliders. Alternatively, transitions not tied to electroweak symmetry breaking, such as those arising from a dark sector dynamics, can be peaked across a much larger frequency range (see e.g. [6, 7, 8]). Predicting the GW spectrum from first-order PTs is a complicated theoretical problem that has seen much recent progress, but several important open questions remain.
- **Topological Defects** – Topological defects are produced in the early Universe following a symmetry-breaking phase transition that leads to a topologically-nontrivial vacuum structure. It has been shown that the field dynamics of a defect network generically leads to an approximately scale-invariant SGWB, which nevertheless may not be strong enough for near-future detection [9]. However, the SGWB signal can be much stronger in certain well-motivated scenarios, with cosmic strings being the most well-studied case [1, 10, 11, 12, 13, 14, 15]. Cosmic strings are effectively one-dimensional objects typically produced following a $U(1)$ -breaking phase transition in the early Universe [16, 17], and are also generally predicted in superstring theory [18, 19, 20]. The decay of oscillating cosmic string loops, provides the leading source of GW production by the string network. The continuous emission of GWs throughout the network's history accumulates and forms a SGWB. The SGWB from local or Nambu-Goto cosmic strings can be detectable, depending on the string tension, with the spectrum spanning a wide range of frequencies and thus relevant for CMB observations, pulsar-timing arrays (PTAs), LISA, LIGO, etc [21, 22]. For global cosmic strings, GW radiation is subdominant relative to Goldstone emission, yet may still be detectable [23]. Recent literature also demonstrates the potential of using the SGWB spectrum from strings to probe non-standard pre-BBN cosmic histories, including alternative equations of state (e.g. early matter domination, kination) and new degrees of freedom [24, 25, 26, 27, 28]. In addition, due to its close connection to broken $U(1)$ symmetries (or more generically when the 1st homotopy group of the vacuum manifold is nontrivial), the observation of a SGWB from strings may shed light on important aspects of BSM theory such as axion physics [23], the neutrino seesaw mechanism, leptogenesis and grand unification [29, 30].

- **Inflation** – A nearly scale-invariant SGWB is a generic prediction of slow-roll inflation [31]. The amplitude of the spectrum is set by the energy scale of inflation; current bounds place the resulting SGWB out of reach of most GW direct detection experiments. (But see the Big Bang Observer [32].) However, recent interest in axion-gauge field inflationary models suggests a more optimistic situation [33, 34, 35, 36], in which the spectrum is blue-tilted up to a potentially detectable amplitude at the frequencies spanned by current and proposed detectors [37]. In these scenarios, which can also be associated to mechanisms of baryogenesis [38], the SGWB spectrum has a net chirality. While the primary tensor spectrum is model-dependent, a SGWB is also sourced by inflationary scalar perturbations at second order [39, 40, 41], and can be correlated with the production of primordial black holes.
- **Cosmological Particle Production** – A SGWB can also arise from rapid particle production in the early Universe. Such a phenomenon can occur during preheating after the end of inflation [42, 43, 44, 45, 46, 47], where parametric resonance leads to large occupation numbers of the decay products of the oscillating inflaton. The resulting SGWB in this case is typically peaked at high frequencies ($\gtrsim 10^7$ Hz [48]). Particle production can also occur during inflation [49], or well afterwards [50], with a misaligned axion-like particle (ALP) coupling to additional hidden sector degrees of freedom [51, 52], for example.

Discovery prospects: The sources highlighted above predict contributions to the SGWB across a wide range of frequencies; exploring the physics of the early Universe through GWs therefore requires a diverse, multi-frequency strategy [53]. The CMB provides a probe of low-frequency gravitational waves arising from inflation. Pulsar timing arrays are sensitive to the nHz– μ Hz regime [54]. Current and proposed direct detection experiments that collectively span the μ Hz–kHz frequency range include: μ Ares [55] (μ Hz); LISA [5], Taiji [56], and successors [57] (\sim mHz); DECIGO [58], TianQin [59] and TianGO [60] (\sim dHz); Cosmic Explorer [61], Einstein Telescope [62], LIGO/Virgo [63] and its successors (Hz–kHz). Atom interferometer detectors have also been proposed for GWs across a range of frequencies [64, 65, 66, 67]. Higher frequency experiments face a lack of well-motivated astrophysical sources (though could still be interesting cosmologically), and generically have poorer sensitivity to a SGWB. This white paper will map out the SGWB frequency landscape for discovery potential. A rough correspondence between temperature of the cosmic fluid and SGWB frequency suggests mHz GWs might be sensitive to TeV-scale physics, offering complementarity to collider searches [68]. We will also consider the impact of astrophysical foregrounds, such as those due to local galactic binaries or unresolved black hole mergers at cosmological distances. Each of these detection methods faces new issues, ranging from technology development to computing challenges to the different sources of noise that need to be well-understood in order to isolate a genuine SGWB of cosmological origin.

The detection of a SGWB using any of the aforementioned methods would open up several exciting avenues for further investigation. Reconstruction of the spectral properties and net polarization can allow for discrimination between the possible sources outlined above and, in principle, extraction of the relevant underlying physical parameters. Anisotropies of the background would contain additional information about new physics [69], though are challenging to detect. A primordial SGWB would also contain information about the expansion history of the Universe following GW generation, and could be used to infer otherwise inaccessible details about our cosmic history, in particular the pre-BBN primordial dark age [24, 70].

Objectives and Conclusions: There are several goals we hope to achieve with the proposed white paper. One is to highlight recent theoretical advances and remaining open questions relevant for SGWB detection, ranging from predictions of spectra from the sources above to the modeling and analysis of foreground. Another is to investigate the complementarity between various existing and proposed experiments in exploring early Universe physics through the SGWB, and to address possible gaps in coverage that may exist. The ultimate aim, however, is to maximize the impact of GW experiments in advancing the Cosmic Frontier.

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