Snowmass2021 - Letter of Interest

Probing Fundamental Physics using the Stochastic Gravitational Wave Background 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
☐ (Other) *[Please specify frontier/topical group]*

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Abstract: (maximum 200 words)
Following the first gravitational wave (GW) observation by the LIGO/Virgo collaboration, gravitational wave astronomy represents nowadays a new way to probe astrophysics and cosmology. The detection of a stochastic gravitational wave background (SGWB) of cosmological origin would provide unique insights on the early stages of the Universe. This could probe open questions in fundamental physics, and contribute to the high energy physics effort in the search for new particles beyond the Standard Model (SM) and a new era in cosmology. In this letter we highlight physics cases that connect a SGWB with fundamental high energy physics, and that will be important to keep on exploring in the near and far future, in parallel with the experimental progresses in GW physics. These investigations will strengthen the connections between GW astronomy and high energy physics.

1. Introduction. The detection of gravitational waves (GWs) from a black hole (BH) binary merger[1] is a milestone that represented the beginning of a new era in the exploration of the universe. Similarly, the detection of a neutron star (NS) binary merger[2] followed by electromagnetic signals established the beginning of multi-messenger astronomy. During the past several years the LIGO and Virgo collaborations increased their sensitivity and have detected compact binary coalescence events at the rate of approximately one per week.

Given that GWs couple very weakly to any form of matter, they travel basically undisturbed, storing information about the sources that produced them even if that occurred at high redshift. Hence, it is in principle possible to extract the relic GWs that were produced in the very early universe. Such a signal is a superposition of GW sources as characterized by the stochastic GW background (SGWB). This is intimately related to fundamental physics and cosmology, and provides information relevant to high-energy particle physics at temperatures not accessible at colliders. In the following, we consider a few scenarios with new physics beyond the Standard Model which lead to distinctive stochastic signals.

2. Cosmic strings. Cosmic strings[3–5] can either be the fundamental objects in the string theory or one-dimensional topological defects, which appear generically in extensions of the standard model[6], after a phase transition, followed by a spontaneous symmetry breaking characterized by a vacuum manifold with non-contractible closed curves. The energy scale associated with the new physics can be very high, far above the one reached by any terrestrial accelerator, such as the Large Hadron Collider. The dynamics of a cosmic string network is driven by the formation of loops and the emission of GWs[7,8]. Hence a detection of GWs from cosmic strings provides a unique window into new physics beyond the standard model.

Cusps and kinks[9] propagating on strings and kink-kink collisions[10,11] lead to powerful bursts of GWs. They can be observed as either individual bursts or as the SGWB composed of many unresolvable bursts throughout the history of the cosmic string network. Both channels are studied by the LIGO/Virgo Collaboration[12,13] and the LISA consortium[14]. While all current searches have been based on semi-analytical models[15,16] or numerical simulations [16,17], it is also worth investigating predictions of an agnostic model[18]. Subsequently, one can investigate signatures of cosmic superstrings, coherent macroscopic states of fundamental strings and Dirichlet branes extended in one macroscopic direction. Such objects are expected in superstring inspired inflationary models[19] and offer a unique way of testing string theories.

3. Strong first order phase transitions. Strong first order phase transitions (PT) occurring in the early Universe can trigger sizeable production of a SGWB[20–24]. There are three contributions to the SGWB produced during a strong first order phase transition: bubble collisions, sound waves, and turbulence in the thermal plasma. The precise modelling of these contributions is a topic of active investigations[25,26]. The resulting GW power spectrum is a broken power law with a peak frequency set by the symmetry breaking scale. For instance, this SGWB signal is peaked at a frequency which is detectable by LIGO-Virgo for symmetry breaking scales in the range $O(1-100)$PeV[27] (or even higher if there is supercooling). There are many motivated extensions of the SM that include new symmetries broken at high energy scales, beyond the reach of current experiments and colliders. This provides a unique and novel opportunity to explore high energy physics through a SGWB.

Given that the PT SGWB depends on a few parameters characterizing the phase transitions, an (almost) model independent analysis can be performed. With the current (O3) sensitivities, Advanced LIGO-Virgo detectors can already probe SGWB signals that are not constrained by other indirect measurements (such as CMB and BBN), and a dedicated PT analysis is ongoing. In the future, third generation observatories (such as the Einstein Telescope and Cosmic Explorer) will probe a considerably larger portion of models with phase transitions leading to a SGWB, establishing a new strategy to look for new physics at high scale.

4. Dark matter. The origin of dark matter remains an open question, despite numerous theoretical proposals and experimental searches. Primordial black holes (PBHs) are promising ultra heavy DM candidates. They are produced from the gravitational collapse of inhomogeneities in the early universe[28], or as recently proposed, they can be formed by the collapse of cusps on cosmic strings[29]. Binary PBHs are interesting potential sources of gravitational waves, and a possible formation channel for the massive black hole binaries observed by Advanced LIGO and Advanced Virgo[30,31]. They can also give rise to a SGWB detectable by future GW detectors[32]. In a very recent paper, it was shown that (30-100) solar masses PBHs evade previously calculated bounds on their abundance, re-opening the possibility of dark matter in the form of LIGO-mass PBHs[33].

Opposite to the ultraheavy DM candidate like a PBH, a GW detector can also be useful to look for ultralight DM particles. There are two natural and promising ultralight DM candidates, axions and dark photons. Axions, or in general pseudo-scalar particles with many of the same properties as the QCD axion, might be the dark matter or comprise a significant fraction of it[34–37]. Such particles, particularly well-motivated in extensions of the Standard Model, lead to new forces and sources of radiation, and can be probed in several gravitational waves signatures. Advanced LIGO could detect new light scalar particles through their influence on the gravitational waveform produced in NS-NS and NS-BH binary mergers [38]. If the axion is coupled to a dark photon, it could have also generated a SGWB through exponential particle production[39]. Furthermore, if the $U(1)_B$ or $U(1)_{B-L}$ dark photon plays the role of DM, it can induce correlated signals at GW detectors[40]. The LIGO O1 data has imposed strong constraints on such DM candidate[41]. With an improved sensitivity and accumulated data, more and more unexplored parameter space will be probed.

Finally, recent studies have proposed novel ideas for the use of interferometers in direct searches for low-mass DM candidates[42], in the form of an oscillating classical dilaton field or topological defects. The interaction of the DM candidates with the interferometer would lead to the modification of the core optics, producing a new signature with frequency proportional to the DM mass.

5. Inflation. Period of rapid expansion of the very early universe, known as inflation, is a likely explanation for the observed flatness and isotropy of the universe, for the lack of magnetic monopoles today, and other questions in the Standard Model of Cosmology. The physics of inflation, i.e., the particle physics mechanism that drove inflation, is currently not understood. Furthermore, due to the exceedingly high energy scales of inflation, it is not possible to explore such physics in the laboratory. Gravitational waves therefore offer a unique opportunity to probe the physical laws that apply at the highest energy scales.

Multiple mechanisms for generating gravitational waves during inflation have been proposed. Amplification of vacuum fluctuations in the standard slow-roll inflationary model is expected to result in an almost frequency-independent SGWB spectrum[43,44] that is likely below the sensitivity of future, 3G terrestrial detectors and LISA. Other processes could lead to significant SGWB amplification in the frequency band of both LISA and terrestrial detectors. For example, axion inflation models that include couplings to gauge fields could extend inflation and results in an SGWB with a strong and detectable blue tilt[45–48]. Similar effects are also possible if inflation is followed by another (presently unknown) phase with a stiff equation of state, again resulting in possible detectability with 3G detectors[49–51].

6. Discussion. GW experiments provide a novel and powerful method to study high energy physics, especially through SGWB measurements. The GW field will experience a rapid development in the following decades, with an increased ground-based network including KAGRA[52] in Japan and LIGO-India[53], the preparation of 3G detectors (Einstein Telescope and Cosmic Explorer) with orders of magnitude of improvement in sensitivity, and the start of the LISA space program. Such progresses will significantly advance our capability of probing the existence of new particles beyond the Standard Model and a new era in cosmology.

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