



**HAL**  
open science

## Detection of Early-Universe Gravitational Wave Signatures and Fundamental Physics

Robert Caldwell, Yanou Cui, Huai-Ke Guo, Vuk Mandic, Alberto Mariotti, Jose Miguel No, Michael J. Ramsey-Musolf, Mairi Sakellariadou, Kuver Sinha, Lian-Tao Wang, et al.

► **To cite this version:**

Robert Caldwell, Yanou Cui, Huai-Ke Guo, Vuk Mandic, Alberto Mariotti, et al.. Detection of Early-Universe Gravitational Wave Signatures and Fundamental Physics. Snowmass 2021, Jul 2022, Seattle, United States. pp.156, 10.1007/s10714-022-03027-x . hal-03629834

**HAL Id: hal-03629834**

**<https://hal.science/hal-03629834>**

Submitted on 10 Mar 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



# Detection of early-universe gravitational-wave signatures and fundamental physics

Robert Caldwell<sup>1</sup> · Yanou Cui<sup>2</sup> · Huai-Ke Guo<sup>3</sup> · Vuk Mandic<sup>4</sup> · Alberto Mariotti<sup>5</sup> · Jose Miguel No<sup>6</sup> · Michael J. Ramsey-Musolf<sup>7,8</sup> · Mairi Sakellariadou<sup>9</sup> · Kuver Sinha<sup>10</sup> · Lian-Tao Wang<sup>11</sup> · Graham White<sup>12</sup> · Yue Zhao<sup>3</sup> · Haipeng An<sup>13,14,15</sup> · Ligong Bian<sup>15,16</sup> · Chiara Caprini<sup>17,18</sup> · Sebastien Clesse<sup>19</sup> · James M. Cline<sup>20</sup> · Giulia Cusin<sup>17,21</sup> · Bartosz Fornal<sup>22</sup> · Ryusuke Jinno<sup>6</sup> · Benoit Laurent<sup>20</sup> · Noam Levi<sup>23</sup> · Kun-Feng Lyu<sup>4</sup> · Mario Martinez<sup>24</sup> · Andrew L. Miller<sup>25</sup> · Diego Redigolo<sup>26</sup> · Claudia Scarlata<sup>4</sup> · Alexander Sevrin<sup>5</sup> · Barmak Shams Es Haghi<sup>3</sup> · Jing Shu<sup>27,28,29,30</sup> · Xavier Siemens<sup>31</sup> · Danièle A. Steer<sup>32</sup> · Raman Sundrum<sup>33</sup> · Carlos Tamarit<sup>34</sup> · David J. Weir<sup>35</sup> · Ke-Pan Xie<sup>36</sup> · Feng-Wei Yang<sup>3</sup> · Siyi Zhou<sup>37</sup>

Received: 23 April 2022 / Accepted: 20 October 2022 / Published online: 30 November 2022  
© The Author(s) 2022

## Abstract

Detection of a gravitational-wave signal of non-astrophysical origin would be a landmark discovery, potentially providing a significant clue to some of our most basic, big-picture scientific questions about the Universe. In this white paper, we survey the leading early-Universe mechanisms that may produce a detectable signal—including inflation, phase transitions, topological defects, as well as primordial black holes—and highlight the connections to fundamental physics. We review the complementarity with collider searches for new physics, and multimessenger probes of the large-scale structure of the Universe.

**Keywords** Primordial gravitational waves · Inflation · Topological defects · Phase transitions · Dark matter · Collider and gravitational wave complementarity · Gravitational wave and EM correlation

---

All authors contributed equally to this work.

Based on a Snowmass 2021 White Paper.

✉ Huai-Ke Guo  
huaike.guo@gmail.com

✉ Mairi Sakellariadou  
mairi.sakellariadou@kcl.ac.uk

Extended author information available on the last page of the article

## Contents

1	Introduction	2
2	Early phases in the evolution of the universe	4
3	Phase transitions	7
4	Topological defects	12
5	Dark matter	15
6	Complementarity between collider and GW observations	19
6.1	Electroweak phase transition	19
6.2	Theoretical robustness	24
6.3	Other phase transitions	24
7	Correlating GW background with EM observations	25
8	Conclusions	28
	References	30

## 1 Introduction

Despite their remarkable successes, both the Standard Model of Particle Physics and the Standard Model of Cosmology face multiple open questions. Examples include the origin and composition of dark matter, the origin of dark energy, the evolution of the Universe during the first minute after the Big Bang (including the inflationary phase as well as possible other phase transitions), the particle physics at the TeV and higher energy scales, the mechanism of electroweak symmetry breaking, and others. Many of these phenomena could have left measurable imprints in the form of gravitational waves (GWs) coming from the early Universe, providing a unique connection between GW physics and fundamental physics. Given the very high energies associated with many of these phenomena, often unachievable in laboratories and accelerators, GWs may provide the only experimental handle to probe these domains for new physics. (Snowmass white paper “Future Gravitational-Wave Detector Facilities” [1] gives an extensive survey of planned and proposed GW observatories. Snowmass white paper “Spacetime Symmetries and Gravitational Physics” [2] provides an overview of high-sensitivity small experiments that can be used for GW detections.)

The connection between high energy physics, cosmology, and GW physics has been investigated through many facets, and can be illustrated using different perspectives. On one hand, there are open questions that are inevitably linked with the cosmology of our Universe and that may be partially decoupled from the Standard Model of Particle Physics. We dedicate two individual Sections to such questions. Section 2 is dedicated to the questions about the origin of our Universe. This includes the inflationary and other early phases in the evolution of the Universe that could have generated a stochastic GW background (SGWB). (For synergy, see Snowmass white papers on inflation [3] and high energy physics model-building of the early Universe [4, 5].) Later, Section 5 is dedicated to the open problem of dark matter. (Many of the open problems in cosmology are presented in the Snowmass white paper “Cosmology Intertwined: A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies” [6].) Since there are many possible strategies to address the dark matter problem, the dark matter mechanisms that generate GW signals are necessarily diverse. For instance, a dark matter particle could leave an

imprint in GW signals by distorting the binary merger dynamics, while dark matter in the form of primordial black holes would provide a new source of binary mergers GW signals. (For synergy, see the Snowmass white paper “Observational Facilities to Study Dark Matter” [7]. See also the Snowmass white paper “Primordial Black Hole Dark Matter” [8] for a detailed discussion of the implications of primordial black holes. There are also significant overlaps with the Snowmass white papers “Astrophysical and Cosmological Probes of Dark Matter” [9] and Snowmass white paper: “Cosmic Probes of Fundamental Physics Probing dark matter with small-scale astrophysical observations” [10].)

Many fundamental questions in particle physics – the electroweak hierarchy problem and the mechanism behind electroweak symmetry breaking, the strong CP problem, the matter-antimatter asymmetry, neutrino masses, to some extent also dark matter – are typically addressed by introducing new particles and symmetries to the Standard Model (SM), with new, and possibly dark, sectors. These new symmetries may break through phase transitions during the evolution of the Universe, possibly constituting important new sources of a SGWB. GW production mechanisms include both the dynamics of the phase transition if it is first order, as discussed in Section 3, or topological defects if they are created during the phase transition, as covered in Section 4.

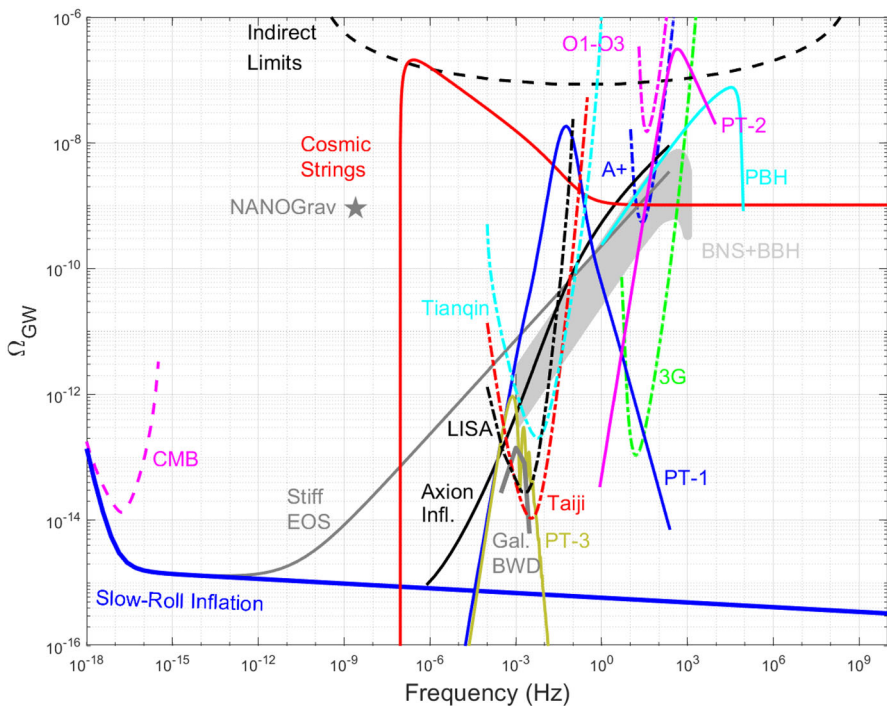
Finally, there is a great potential for multimessenger complementarity between GW observations and the standard techniques for probing cosmology and particle physics. In Section 6, we explore such complementarity between GW observations and the future collider experiments in the context of probing TeV-scale physics. This includes studies of the electroweak symmetry breaking in colliders and associated GWs from phase transitions in the early Universe. It also includes other possible symmetries and associated phase transitions, such as those related to supersymmetry. (For synergy with collider-based probes, see the Snowmass white paper “Probing the Electroweak Phase Transition with Exotic Higgs Decays” [11]. Further GW probes of fundamental physics are described in the Snowmass white paper “Fundamental Physics and Beyond the Standard Model” [12].) In Section 7 we explore complementarity between GW observations and traditional electromagnetic observations of the large-scale structure, such as the cosmic microwave background (CMB) or weak gravitational lensing. Directional correlations between these observations, codified in angular cross-correlation spectra, may offer unique information about the early phases in the evolution of the Universe and perhaps shed additional information on the dark matter problem. (Snowmass white papers “Cosmology and Fundamental Physics from the Three-Dimensional Large Scale Structure” [13] and “Cosmic Microwave Background Measurements” [14] provide a deeper study of the connections of large scale structure and CMB measurements to fundamental physics.) We offer concluding remarks in Section 8.

We note that SGWB could also be generated by astrophysical sources such as mergers of binary black hole and binary neutron star systems. This astrophysical SGWB can act as a foreground to the cosmological (early universe) SGWB. Suppression or removal of the astrophysical stochastic GW foreground is an active area of research, with multiple techniques being explored [15–18]. These efforts have only had partial success to date and further studies in this direction are needed. We will not discuss this problem any further in this paper.

## 2 Early phases in the evolution of the universe

A variety of physical processes in the early Universe may generate GWs. As the universe expands and the temperature drops, phase transitions may take place followed by spontaneously broken symmetries.

First order phase transitions may generate GWs [34] within the frequency range of present [35] or future [36] interferometers, providing a way to test particle physics models beyond the SM. Phase transitions followed by spontaneous symmetry breaking may lead to the production of topological defects as relics of the previous more symmetric phase of the Universe; they are characterised by the homotopy group of the false vacuum. One-dimensional topological defects, called cosmic strings [37–39], were shown [40] to be generically formed at the end of hybrid inflation within the context of grand unified theories. Cosmic strings, analogues of vortices in condensed matter systems, leave several observational signatures, opening up a new window to fundamental physics at energy scales much above the ones reached by accelerators. The production of GWs by cosmic strings [41, 42] is one of the most promising obser-



**Fig. 1** Landscape of gravitational wave cosmology. Experimental results include: O1-O3 LIGO-Virgo upper limits [19], indirect limits from big bang nucleosynthesis [20], CMB limits [20], and NANOGrav pulsar timing measurement [21], as well as projected sensitivities of the third generation (3G) terrestrial GW detectors [22, 23] and space-borne LISA [24], Taiji [25], and Tianqin [26]. Theoretical models include examples of slow-roll inflation [27], first-order phase transitions (PT-1 [28], PT-2 [29], and PT-3 [30]), Axion Inflation [31], Primordial Black Hole model [32], hypothetical stiff equation of state in the early universe [33], and foregrounds due to binary black hole/neutron stars [19] and galactic binary white dwarfs [24]

vational signatures; they can be accessed by interferometers [43–45], as illustrated in Fig. 1. Domain walls, [42, 46–50], textures [51], and indirectly monopoles [50] can also source GWs; they are hitherto less studied than cosmic strings. A cosmic string network is mainly characterised by the string tension  $G\mu(c = 1)$ , where  $G$  is Newton's constant and  $\mu$  the mass per unit length. Observational data constrain the  $G\mu$  parameter, which is related to the energy scale of the phase transition leading to cosmic string formation, and therefore it may also be related to the energy scale of inflation. Cosmic superstrings, predicted [52, 53] in superstring inspired inflationary models with spacetime-wrapping D-branes, are coherent macroscopic states of fundamental superstrings and D-branes extended in one macroscopic direction. For cosmic superstrings, there is an additional parameter, namely the intercommutation probability. The dynamics of either a cosmic string or a cosmic superstring network is driven by the formation of loops and the emission of GWs.

Following the inflationary paradigm, vacuum fluctuations of the inflaton field may generate a scale-invariant spectrum of GWs imprinted on the CMB B-mode polarization. Inflationary models generally predict very small values of the ratio of the power spectra of the tensor and scalar modes ( $r \ll 1$ ). Combining Planck with BICEP2/Keck 2015 data yields an upper limit of  $r < 0.044$  [54]. Inflationary scenarios in which the inflaton couples to a gauge field may predict strongly blue-tilted GW spectra that may be consistent with CMB bounds at long wavelengths but within reach of direct detection experiments at short wavelengths. (See Ref. [55] for examples, or the forthcoming “Cosmology with the Laser Interferometer Space Antenna,” by the LISA Cosmology Working Group [56], for further discussion.) Effective Field Theory inflationary models that do not respect the null-energy condition are also characterized by a blue tensor tilt [57], as well as inflationary models with violation of slow roll [58], and potentially inflationary models within modified gravity. Finally, there are inflationary models that predict features in the stochastic GW background, for instance as the result of particle production during inflation [59].

Despite its success, inflation does face drawbacks [60–65], hence various alternatives have been proposed and worked out. Within bouncing cosmologies [66], the pre-Big Bang [67] or ekpyrotic model [68], the string gas cosmology [69, 70] and the matter bounce scenario [71, 72], have been long discussed in the literature.

The pre-Big Bang scenario [67, 73] assumes that gravity and cosmology are based on some particular version of superstring theory. According to this model, the Universe emerges from a highly perturbative initial state preceding the Big Bang. In string theory, the dilaton is an additional massless mode, which while at late times may be assumed fixed, is dynamical in the very early Universe. Hence, the massless sector of string theory to which the graviton belongs is given by dilaton gravity. This model leads to the production of an amplified quasi-thermal spectrum of gravitons during the dilaton-driven phase. While the slope of the GW spectrum may change for modes crossing the horizon during the subsequent string phase, it remains characterized by an enhanced production of high frequency gravitons, irrespective of the particular value of the spectral index [74]. For a wide region of the parameter space of the pre-Big Bang model, one can simultaneously generate a spectrum of scalar metric perturbations in agreement with Planck data and a stochastic background of primordial GWs within reach of the design sensitivity of aLIGO/Virgo and/or LISA [75].

The ekpyrotic model [68] is motivated by a specific realization of M-theory in which spacetime is 11-dimensional [76]. In this model, whereas the equation of motion of the cosmological perturbations depends on the potential of the scalar field, that of the GWs does not. The spectrum of GWs turns out to be very blue, implying that primordial GWs are negligible on scales of cosmological interest today.

String gas cosmology is based on degrees of freedom and symmetries of superstring theory which are absent in an effective field theory approach to early Universe cosmology. This model has two fundamental elements. The first is the Hagedorn temperature defined as the maximal temperature which a gas of strings in thermal equilibrium can achieve. The second is the T-duality symmetry of the spectrum of string states. This string gas cosmology model (tested also via numerical experiments [77]) leads to an almost scale-invariant spectrum of primordial GWs [78]. However, whereas inflation typically leads to a red spectrum, string gas cosmology generically yields a slightly blue spectrum.

The matter bounce model [71, 72] is based on the duality between the evolution of the canonical fluctuation variables in an exponentially expanding period and in a contracting phase with vanishing pressure. In this model, the amplitude of the GW spectrum is generically larger than that in inflationary models ( $r$  can be close to 1).

Having indicated the many possibilities during the expansion phase in the very early Universe, we now turn to the role that GWs play in the subsequent eras. GWs, because they free-stream through the entirety of cosmological history, provide us a way of probing cosmic history before Big Bang Nucleosynthesis (BBN).

(i) Long-lasting GW sources as cosmic witnesses: The vast stretch of energies between the initial expansion phase of the Universe and BBN can accommodate a range of non-standard cosmological histories with equations of state parameter  $w$  different from  $w = 1/3$ . The GW spectrum of long-lasting sources such as inflation and networks of cosmic strings spans a wide range of frequencies and has been studied as cosmic witnesses [79, 80], especially to extract information about  $w$ . Scenarios with  $1/3 \leq w \leq 1$  develop a blue tilt for the tensor perturbations at large frequencies and certain portions of the parameter space may be detectable by LISA and/or terrestrial GW detectors [33, 80–82], c.f. Fig. 1. Matter-dominated era with  $w = 0$  may cause kinks in the spectrum at frequencies corresponding to the onset of matter and radiation domination, which may be observable in the future at BBO and other experiments. If the change in the equation of state is sudden enough, rapidly oscillating scalar perturbations may enhance the primordial GW spectrum from inflation; this effect has been pursued in the context of primordial black holes [83] and Q-balls [84].

(ii) Phase transitions as cosmic witnesses: It is challenging to use shorter-lasting sources like phase transitions as a witness to  $w$  in the early universe, although some effort has been made in this direction [85–88]. If the phase transition occurs during a phase dominated by an entity with a general equation of state  $w$  that is not radiation, expressions for the parameters defining the phase transition should take into account the new dominant contribution to the energy density; if the phase transition is followed by an era dominated by an entity with state  $w$ , the modified redshifting changes the spectrum. In the deep infrared, super-horizon modes scale as  $\propto k^{3+2\frac{3w-1}{3w+1}}$ . A special case of phase transitions serving as a probe of inflationary physics is when the transition



occurs *during* inflation itself, possibly triggered by inflaton couplings to spectator fields. For such a source, the GW spectrum always contains a unique oscillatory feature, which can be used to identify the GW source [89].

A different avenue is to use GWs from phase transitions as a record of temperature anisotropies coming from a previous era, for example from inflation. Since the phase transition inherits primordial temperature anisotropies, it effectively serves as a copy of the CMB, but in an earlier, more pristine form [90]. While this matching is true for adiabatic fluctuations, if the primordial fluctuations carry an isocurvature component then a richer scenario can emerge [91].

(iii) GWs from inflationary reheating/preheating: The large time-dependent field inhomogeneities that are characteristic of rapid particle production through parametric resonances during a preheating phase [92–94] can be a well-motivated source of GW production. Topics that have been explored in this context include gauge preheating after axion inflation [95, 96], self-resonance after single-field inflation and oscillon formation [97–102], as well as tachyonic preheating from a waterfall transition [103–105]. The frequency of the resultant GW signal is typically too high, or the amplitude too small, to be detectable with near future GW detectors, although several ideas have been proposed recently [106, 107]. (See also the Snowmass White Paper [108].) The recent work of [109] demonstrates a promising GW detection prospect based on a preheating scenario in the framework of hybrid inflation, where a prolonged waterfall phase allows for an efficient transfer of energy from the scalar sector to an Abelian gauge field. For particular reheating mechanisms, the study of [110] has investigated the phases of early and late time reheating through imprints on primordial GWs.

### 3 Phase transitions

GWs from first order phase transitions (FOPTs) in the early Universe offer a unique way of probing particle physics models at energy scales otherwise inaccessible. The GW spectrum, with examples shown in Fig. 1, is sensitive to the shape of the effective potential, which depends on the symmetry breaking pattern and the particle content of the theory. This provides access to regions of parameter space unexplored so far in various extensions of the SM. GWs from a strong FOPT have a plethora of motivations in the early universe. For instance, new physics at the electroweak scale can lead to a strongly first order electroweak phase transition [111–138] and large lepton asymmetries or different quark masses can make the QCD transition strong [139–142]. Beyond this, a strong transition can occur in multistep phase transitions<sup>1</sup> [148–153], B-L breaking [28, 154–161] (or B/L breaking [162]), flavour physics [163, 164], axions [29, 165, 166], GUT symmetry breaking chains [167–171], supersymmetry breaking [172–175], hidden sector involving scalars [176–180, 180–185], neutrino mass models [186–188] and confinement [189, 189–196].

Such phase transitions could occur at nearly any time during or after inflation. For example, the environment in which an electroweak-scale phase transition takes place, where bubbles expand in a plasma of relativistic SM particles, is very different to that

<sup>1</sup> See Refs. [143–147] for the viability of a multistep phase transition.



prior to reheating. Much of what is discussed in this section relates in particular to what one might call *thermal phase transitions*, in which the bubbles typically nucleate thermally through the three-dimensional bounce action. Despite the name, not all thermal transitions efficiently transfer kinetic energy to the plasma, as will be discussed below. Nevertheless, as a class of scenarios they represent the most likely source of an observable SGWB due to a FOPT, and have the richest complementarity with other particle physics and cosmological observables.

A thermal phase transition begins with the nucleation of bubbles where the walls expand in a plasma of ultrarelativistic particles, and the interactions of the particles with the walls in large part determine the terminal wall velocity of the bubbles. GWs are first sourced by the colliding bubble walls [197–200] and the fluid shock configurations, detonation or deflagrations, accompanying them [201], although for a thermal transition the shear stress in the walls and shocks is unlikely to be a substantial source of GWs [202]. For deflagrations, pressure may build up in front of the walls, deforming them and delaying completion of the transition through the formation of hot droplets [203]. After the bubbles have merged, a bulk fluid velocity will remain in the plasma. At first the velocity perturbations will typically be longitudinal, unless the bubbles have been deformed during the transition due to hydrodynamic instabilities or deformations of the shape. In weak transitions, the fluid perturbation will take the form of longitudinal acoustic waves – sound waves [204]. If the shock formation timescale  $\tau_{\text{sh}} \sim L_*/v_{\text{rms}}$ , where  $L_*$  is a typical length scale in the fluid linked to the mean bubble separation, and  $v_{\text{rms}}$  is the root mean square fluid 3-velocity, is smaller than the Hubble time, shocks will form [205]. This is expected to occur for strong transitions, and to lead to turbulence [206]. Sound waves, acoustic, and vortical turbulence are all sources of GWs, lasting until the kinetic energy is dissipated by the plasma viscosity [207]. These different processes source GWs with different spectral shapes (see e.g. [207–212]), which would allow us in principle to reconstruct the conditions in the Universe during and after a sufficiently strong FOPT.

The starting point in the calculation is the effective potential  $V_{\text{eff}}$  of a given model, consisting of three contributions: tree-level, one-loop Coleman-Weinberg, and finite temperature part. The  $V_{\text{eff}}$  initially admits a vacuum at high temperature, typically at the origin of the field space, and starts to develop another one which becomes more and more energetically preferable as temperature drops. Provided that the two vacua are separated by a potential barrier, the Universe then undergoes a FOPT to the lower-energy state. This is realized through nucleating bubbles of true vacuum, which then expand and collide with each other, eventually leaving the Universe in the new vacuum state. Four parameters characterizing this picture dictate the resulting GWs: the nucleation temperature  $T_*$ , the bubble wall velocity  $v_w$ , the FOPT's strength  $\alpha$  and its inverse duration  $\beta$ . We note the following issues and recent developments regarding their calculations.

**1. Issues in perturbation theory.** A perturbative treatment of the finite temperature potential is known to breakdown. The central problem is that the expansion parameter at finite temperature involves a mode occupation which diverges when the mass vanishes [213]. This can be partially addressed by resumming the most dangerous “daisy” diagrams. However, the usual resummation prescriptions have the issues that ( $T$  dependent) UV divergences do not cancel at the same order [214] and anyway

does not address the issue of the slow convergence of perturbation theory. Including next to leading order corrections can change the predictions of the GW amplitude by many orders of magnitude [116, 215]. At present, only the technique of dimensional reduction [216, 217] performed at NLO using an  $\hbar$  expansion provides a prescription to calculate thermodynamic parameters at  $O(g^4)$  in a gauge independent way [116, 215]. This method is challenging to use and has been applied to benchmarks in very few models. There are proposed alternatives to dimensional reduction [218, 219]. However, these are in need of development and testing and it is not yet obvious how to apply such techniques in a gauge invariant way. Finally, for very weak transitions, the tachyonic mass of the physical Higgs is cancelled by thermal mass near the origin, leading to an unresolved infrared divergence which is probably captured by large differences in predictions of perturbation theory and Monte-Carlo simulations [220, 221]. It is generally assumed that perturbation theory in its most sophisticated form should give accurate results provided a transition is strong enough, however this needs to be proven by careful comparison with Monte-Carlo simulations.

**2. Calculation of the bubble nucleation rate.** An accurate evaluation of the nucleation rate  $\Gamma_{\text{nuc}}$  and its evolution with temperature is of paramount importance to defining the characteristic time scales of the transition. For sufficiently fast transitions,  $T_*$  and  $\beta$  can be obtained by linearizing the rate near  $T_*$ .

This breaks down for slow transitions, which can be of great phenomenological interest, where the next order corrections must be accounted for [222]. Various components contribute to  $\Gamma_{\text{nuc}}$ , each meriting a separate discussion. Firstly, analytical solutions of the bounce EOM exist only for specific single field potentials [223–226], with progress made in the study of approximate single field potentials for light scalars [227–231]. Often, however, the underlying theory implies highly nonlinear equations of motion, or the existence of multiple scalar directions, where the bounce solution describes the motion of a soliton along a complicated manifold, requiring the use of numerical tools, such as [232–238]. Secondly, the stationary phase approximation used to derive the bounce action holds well for weakly-coupled theories, including radiative corrections [239–243], which assumes the existence of a hierarchy of scales, with UV and IR modes well separated in energy scales. This assumption breaks down at strong coupling, where novel methods for generalizing the saddle point treatment are necessary, as discussed in [116, 219, 244]. Thirdly, the nucleation prefactor, often taken to be a simple  $\mathcal{O}(1)$  times mass dimension 4 prefactor, can have a non-trivial form when more carefully evaluated, and has been shown to substantially alter the nucleation rate in some cases, as its contribution may become exponential. This prefactor can be split into two independent pieces, a dynamical part, related to the inverse timescale of critical bubble growth, depending on the evolution of fluctuation of the bubble radius, as well as the thermal bath [245–250], and a statistical part, which depends on functional determinants of the second-order fluctuations around the critical bubble and the symmetric phase [85, 116, 208, 251–253], both requiring a different formalism in order to obtain a complete treatment.

**3. Bubble wall velocity.** Different formalisms have been developed for the calculation of  $v_w$ , whose applicability depends on the relative strengths of the transition, which determines whether the terminal speed will be only mildly relativistic, or on the other hand ultrarelativistic. For not-too-fast moving walls, a standard approach is

to split the distribution functions for the various particle species in the plasma into an equilibrium part, plus a perturbation due to the interaction between the wall and the particles. Recently, progress has been made in characterizing the importance of the equilibrium part of the distribution function, where variation of the plasma temperature, which is a function of the position relative to the wall and  $v_w$ , plays a role. These variations are tied to hydrodynamic effects in the plasma, which can induce a backreaction force on the wall [133, 254–257]. For ultrarelativistic bubble walls, with a Lorentz factor  $\gamma(v_w) = 1/\sqrt{1 - v_w^2} \gtrsim 10$ , equilibration cannot be maintained across the bubble wall. Nevertheless, one can assume that all the particles ahead of the advancing bubble, featuring equilibrium distributions, are absorbed by the new phase, without any reflections. The absorbed particles can then exchange momentum with the wall, which gives rise to friction. The leading effect is caused by the variation in the particles' masses across the wall due to the changing scalar condensate [258]. This gives rise to a friction force that remains independent of  $v_w$ , and thus cannot in general prevent a runaway behaviour towards  $v_w = 1$ . Additionally, the particles can also emit radiation, mainly in the form of gauge bosons, which leads to a  $v_w$ -dependent friction effect that grows with  $v_w$  and thus can prevent runaways. Single-particle emissions yield a force proportional to  $\gamma(v_w)mT^3$  [259], where  $m$  is the mass of emitted gauge bosons inside the bubble, while a resummation of multi-particle emissions leads to an enhanced force proportional to  $\gamma(v_w)^2T^4$  [260], or  $\gamma(v_w)mT^3$  times a log [261]. Possible open issues include the difference between these two results and the lack of mass dependence [262] of the force in [260], and the impact of radiated bosons that are reflected [261]. Nevertheless, independent of the specific form of the friction term, the efficiency factor for the bubble wall motion can be calculated in general [263].

With the above transition parameters  $T_*$ ,  $v_w$ ,  $\alpha$  and  $\beta$  determined, one can go on to calculate GWs. For a weak thermal phase transition, the dominant contribution is due to sound waves, with the GW spectrum obtained from large scale numerical simulations [202, 208]. The sound shell model [209, 264] has been proposed to understand these numerical results, with a generalization to the expanding Universe given in [85]. In this model, the velocity field of the perturbed plasma is modelled by a linear superposition of individual disturbance from each bubble which in turn can be solved from a hydrodynamic analysis [265]. The resulting spectrum agrees reasonably well with that from large scale numerical calculations [208]. Aside from the spectral shape, which does not agree perfectly with numerical result, the amplitude is also different due to several reasons. Firstly, the amplitude depends on the root mean square fluid velocity  $\bar{U}_f$ , calculable from the hydrodynamic analysis. However,  $\bar{U}_f$  calculated this way gives an overestimation as observed in numerical simulations for strong phase transition where  $\alpha \sim 1$  with small  $v_w$  [203]. This reduction is more pronounced for increasingly smaller  $v_w$  for fixed  $\alpha$ , due presumably to the formation of bubble droplets ahead of the wall which then slows down the wall. Secondly, the original widely used GW spectrum (see, e.g., [205]) actually enforces an infinite lifetime,  $\tau_{sw}$ , of sound waves, as found out in [85, 222]. For a finite  $\tau_{sw}$ , an additional multiplication factor needs to be added to account for the increasingly reduced GW production due to the increasingly diluted energy density as the universe expands. This factor depends on the expansion rate of the universe during the transition, and for radiation domination it is  $(1 - 1/\sqrt{1 + 2\tau_{sw}H})$  with  $H$  the Hubble rate at  $T_*$  [85], which approaches the

asymptotic value of 1 as  $\tau_{\text{sw}} \rightarrow \infty$  recovering the old result, and reduces to  $\tau_{\text{sw}} H$  [222, 266] for short transitions. There remains the question of what exactly the value of  $\tau_{\text{sw}}$  is. It is usually chosen to be the time scale corresponding to the onset of turbulence [206, 208], which needs to be improved based on insights gained from numerical simulations and analytical studies. Besides, there are attempts [267, 268] of going beyond the bag model [267].

We now return to the less-thermal transitions, where the vacuum energy released in phase transitions can far exceed the surrounding radiation energy (see, e.g., [269, 270]). Here the bubble expansion mode has two possibilities [265]: strong detonation, where the wall reaches a terminal velocity due to balancing between the outward pressure and the friction, and runaway, where the wall continues to accelerate until it collides. In determining which of the two is relevant, the friction from the thermal plasma splitting upon impinging onto the ultrarelativistic walls plays a crucial role [259–261]. Since this friction increases as the wall accelerates, runaway is now known to require a stronger transition than previously thought. The main contribution to the energy budget of these transitions comes from a highly relativistic and concentrated fluid around the bubbles in strong detonations, while it comes from relativistic walls in runaway [28]. The GW production for the latter has long been estimated with the so-called envelope approximation, in which the walls immediately dump upon collision [198–200, 271–274]. However, numerical calculations revealed that the energy accumulated on the bubble surface propagates inside other bubbles even after collision [275–279]. To incorporate the long lifetime of these walls, a modelling now called the bulk flow model is proposed [280–282], and it is found that GWs at low frequencies are amplified, reflecting the expanding spherical structure after collision. On the other hand, the GW production in strong detonations leaves much room for study. While the sound shell model [209, 264] is expected to describe the GW production if the system turns into weak compression waves  $\gamma \lesssim \mathcal{O}(1)$  at an early stage, it should be noted that strong concentration of the fluid may take some time to get dispersed [283], or the system may develop vortical and/or acoustic turbulence at an early stage [205, 211, 266, 284].

In addition, both purely hydrodynamic and magneto-hydrodynamic (MHD) turbulence are expected to source GWs [201]. Past analyses have evaluated the GW production using semi-analytical modelling [207, 210, 285–289]. The results of these analyses have been combined with the prediction of the GW signal from the acoustic phase, leading to a GW spectrum where the acoustic contribution dominates at the peak while turbulence, believed to be sub-leading, dominates at high frequencies (see e.g. [205]). Simulations featuring the scalar field evolution coupled to the relativistic fluid dynamics started only recently to explore the non-linear regime, where vorticity and turbulent generation is expected to occur [203]. Simulations of MHD turbulence carried out with the Pencil code have improved on previous analytical estimates, but have shown that the initial conditions of the turbulence onset affect the GW spectral shape around the peak region [211, 290, 291]. A ready-to-use prediction of the GW signal from MHD turbulence, validated by numerical simulations but assuming fully-developed turbulence as initial condition, has been provided in [292]. Simulating the onset of turbulence directly from the PT dynamics, and thereby providing a thorough

and reliable estimate of the GW power spectrum, remains a key challenge of the next decade.

Direct experimental searches for GWs from FOPTs have recently been carried out by several experimental collaborations. A subgroup of the LIGO-Virgo-KAGRA collaboration has performed the first search using its data from the O1, O2 and O3 observing runs [35], being sensitive to FOPT at the energy scale of  $\sim(\text{PeV-EeV})$ , and found no evidence for such signals, with upper limits thus placed on the FOPT parameters. Searches have also been performed by the NANOGrav collaboration, based on its 12.5 year data set [293], corresponding to the QCD energy scale [141, 294], after the detection of a common-noise possibly due to a SGWB [295]: it concludes that a FOPT signal would be degenerate with that from supermassive black hole binary mergers. A search on Parkes PTA data is also reported [296] with no positive detection and with upper limits set. Continued searches by these efforts will give improved results in the near future, while in a longer term, future third generation ground-based detectors such as Cosmic Explorer [297, 298] and Einstein Telescope [299, 300] will probe much more weaker GW signals, and future space interferometers LISA [205, 301], Taiji [25, 302, 303] and Tianqin [26, 304, 305] will operate in a frequency range suitable to test FOPTs at the electroweak scale. Once the GW signal from a FOPT is detected, recent analyses suggest that all four parameters determining its spectral shape can be reconstructed from the power spectrum, within the sound shell model [306].

## 4 Topological defects

**Motivation.** Topological defects are generically predicted in field theories with symmetry breaking [40] as well as superstring theories [52, 53].

When a symmetry is spontaneously broken in the early Universe, the homotopy groups of the resultant vacuum manifold can be non-trivial. Consequently, topological defects of different forms can form [37, 38]. Three types of topological defects have been shown to produce SGWB signals: domain walls [42, 46–50], textures [51] and cosmic strings [307–316]. Monopoles can also indirectly produce GWs, particularly when combined with other defects [50]. What makes such signals particularly interesting, is that, in all cases the amplitude of the GW signal grows with the symmetry breaking scale. This makes topological defects an effective probe of high energy physics.

The type together with the detailed properties of defects which are formed depends on the underlying theory. Domain walls can in principle arise wherever there is reason to expect a discrete symmetry — from Pecci Quinn [317, 318], R-Parity [319] to neutrino masses [320] for a non-exhaustive list. Discrete symmetries also appear naturally in the center of symmetry breaking chains — for example D parity and matter parity [321, 322]. Global strings can originate from axion dark matter models where a  $U(1)$  is broken to a vacuum with a discrete symmetry [323]. Local strings, monopoles and textures are ubiquitous in the symmetry breaking chains that result from  $SO(10)$  breaking to the SM [50]. Considering all possible spontaneous symmetry breaking patterns from the GUT down to the SM gauge group, it was shown [40] that cosmic

string formation is unavoidable. The strings which form at the end of inflation have a mass which is proportional to the inflationary scale. Sometimes, a second network of strings form at a lower scale.

In the context of string theory, cosmic superstrings [324] can form as the result of brane interactions. While solitonic cosmic strings are classical objects, cosmic superstrings are quantum ones, hence one expects several differences between the two (see, e.g., [325] and references therein).

**Gravitational wave signals.** The GW spectrum resulting from the topological defect will have different features depending upon whether the symmetry broken is local or global. For instance, GW spectrum from local textures has an infrared suppression compared to global textures [326], GW signal strength from global strings features a more dramatic scaling with the symmetry breaking scale compared to the linear scaling of local strings [323] and local domain walls require destruction via strings in order to be viable, in contrast with global domain walls [50]. In the following we summarize the current status on GW signal from topological defects, with an emphasis on cosmic strings, which are most studied.

*1. GW from local cosmic strings.* For local strings, and particularly thin strings with no internal structure which can be described by the Nambu-Goto action, once the string network is formed, it is expected to quickly reach the scaling regime [38]. The predicted GW spectrum is then contingent on two crucial quantities: the dimensionless power spectrum for a loop of a given length; and the number density of loops. Regarding the power spectrum, either one can motivate an averaged power spectrum (where the average is over different configurations of loops of the same length) using simulation data as input [308], or one can assume a high frequency domination [310, 327]. Regarding the number density, a (rather crude) analytic estimate can be made using the ‘velocity dependent one scale model’ that takes only the loop size at formation as an input [328, 329]. This agrees quite well with some models of simulations [330, 331], but disagrees with others [332–334] which predict a greater fraction of energy density in smaller loops. The reasons for these differences are not yet fully understood, but may be related to the effects of gravitational backreaction. Besides their differences, these string models all predict a roughly constant GW spectrum over many decades of frequency, assuming standard cosmological history (see e.g. [44]). This makes it a useful witness to any departures from a standard cosmological picture [335–337]. Nambu-Goto dynamics may not apply to all types of cosmic strings, in particular the case with field theory strings is unclear. Some simulation results [338, 339] show that the field theory strings decay predominantly into particles rather than gravitational radiation, although the literature did not yet converge [340–343]. Such discrepancies lead to different observational predictions. Therefore it is important to further investigate this open question and better understand the difference between Nambu-Goto and field theory results.

*2. GW from global/axion cosmic strings/domain walls.* While most of literature focused on the evolution of local cosmic strings, motivated by the close connection to axion physics, recent years have seen increasing interest in global or axion strings/topological defects and the GW signature sourced by them [47, 323, 344–349]. Although the GW signal from global strings is suppressed relative to local strings due to the dominant



emission of Goldstone bosons, it has been shown to be detectable with upcoming experiments, and feature a logarithmic declining spectrum towards high frequency [323, 348, 349]. Clarification of the GW spectrum from global strings will require further investigations in simulation studies, which so far have not converged well.

3. *GW from superstrings.* Evolution of cosmic superstring networks, is a rather involved issue, which has been addressed by numerical [350–355] as well as analytical [356–359] approaches. Cosmic superstrings can also lead to gravitational waves (see, e.g., [360, 361]), hence GW experiments can provide a novel and powerful way to test string theory.

**Probe for non-standard cosmology.** The state and particle content of our Universe prior to the BBN era remains unknown as the “primordial dark age” [362, 363], despite the standard paradigm we often assume. Potential deviations from the standard cosmology scenario are well motivated and attracted increasing interest in recent years. GW background spectrum from a cosmic string network typically spans over a wide frequency range with detectable amplitude, making it a unique tool for “cosmic archaeology” based on a time-frequency correspondence [335, 336]. In the following we review a few representative cases on how the GW signal from strings may be used to probe the pre-BBN cosmology.

1. *Probe new equation of state of the early universe.* In standard cosmology, the Universe undergoes a prolonged radiation dominated era from the end of inflation till the recent transition to matter domination at redshift  $\sim 3000$ . However, well-motivated theories suggest that the evolution of the Universe’s equation of state may deviate from this paradigm, e.g. the presence of an early matter-domination or kination phase [364–368]. Such an alternative cosmic history can sharply modify the GW spectrum from cosmic strings via its effect on Hubble expansion rate. Specifically, an early period of kination results in a period where the GW frequency spectrum grows as  $f^1$ , whereas an early period of matter domination results in a spectrum that depletes in the UV, obeying a  $f^{-1/3}$  power law [336, 369, 370]. A string network can also be “consumed” through the nucleation of monopoles [371] or domain walls if there is a small hierarchy between symmetry breaking steps, or if not they can be destroyed by a connected domain wall in a later symmetry breaking step [50]. Importantly, all of these signals can be distinguished.

2. *Probe new particle species.* While the high frequency range of the GW spectrum from strings is largely flat (corresponding to GW emission during radiation domination), it is modified by changes in the number of relativistic degrees of freedom,  $g_*$  [44, 335], which modifies the standard Hubble expansion history, and can therefore be used as a probe of high energy degrees of freedom that are beyond the reach of terrestrial colliders or CMB observatories.

3. *Probe (pre-)inflationary universe.* Cosmic defects generally dilute more slowly than radiation. Even if a large number of e-foldings during inflation largely washes out a pre-existing string network, it can regrow back into the horizon and replenish itself to become a non-trivial component of the late Universe energy budget. In particular, replenished strings can leave a unique SGWB spectrum that can be probed by nanoHz



detectors, along with GW burst signals [369]. This provides a unique example that cosmology before the end of inflation can be probed with GWs from cosmic defects.

**Probe for new particle physics.** As the amplitude of the GW spectrum produced by a string network grows with the symmetry breaking scale, they provide a unique way of probing high scale physics. For example, since there is typically a hierarchy between the seesaw scale and the GUT scale, it is natural to protect the seesaw scale with gauge symmetry. Symmetry breaking chains predict strings more often than not and the entire range of scales relevant to thermal leptogenesis is projected to be testable by future detectors [326]. More generally, GUT symmetry breaking chains more often than not allow for observable signals from some set of defects [50].<sup>2</sup> Searches for proton decay provide a complimentary probe of symmetry breaking chains, as chains that allow for proton decay can be chains that do not predict strings [373, 374]. Furthermore, there has been a growing interest in GWs from global/axion topological defects due to the close connection to axion or axion-like (ALP) dark matter physics [323, 337, 348, 349, 375, 376]: when PQ symmetry breaking occurs after inflation, these topological defects are an indispensable companion of axion particles. While there have been extensive studies on axion particle detection which strongly depend on whether/how axions couple to SM particles in an observable manner, the GW signature from axion strings/domain walls is universal and could be a highly complementary probe for axion physics. In addition, as mentioned earlier, the GW spectrum from cosmic strings may reveal new particle species via the effect on the Hubble expansion rate due to changes in relativistic degrees of freedom.

**Prospect for experimental detection.** Current limits on cosmic strings from GW signals are:  $G\mu \lesssim 9.6 \times 10^{-9}$  by LIGO-Virgo [43], and  $G\mu \lesssim 10^{-10}$  by pulsar timing arrays [377, 378]. Fig. 1 shows an example of a cosmic string GW spectrum in comparison with existing and future detector sensitivities. Note that considering the expected astrophysical background and a galactic foreground, a cosmic string tension in the range of  $G\mu \approx 10^{-16} - 10^{-15}$  or bigger could be detectable by LISA, with the galactic foreground affecting this limit more than the astrophysical background [44, 45].

Future experiments covering a wide frequency range will further improve the sensitivity to GW signals from cosmic strings, including: e.g. Einstein Telescope, Cosmic Explorer, AEDGE, DECIGO, BBO,  $\mu$ Ares and Theia [299, 379–383]. An exciting possibility is that NANOGrav may have already seen a hint of cosmic strings [295]. The suggested hint is consistent with a shallow power law as one would expect from strings [193, 370, 373, 377, 384–386] though to fully verify one way or another, the Hellings-Downs curve needs to be constructed [387].

## 5 Dark matter

There are multiple strong and independent lines of evidences on the existence of dark matter (DM). However its identity remains as one of the greatest mysteries in the

<sup>2</sup> See also Snowmass white paper [372].

modern physics. For example, the mass of DM can range for almost 100 orders of magnitude. Understanding the DM identity provides invaluable information about the early Universe as well as the extension of the particle Standard Model.

Decades of effort have been devoted to searches of DM. Motivated by the gauge hierarchy problem, experimental efforts has been focused on the mass window around the electroweak energy scale, i.e.  $\sim 100$  GeV. Null results to date have led to strong constraints in this part of the parameter space and have prompted a re-examination of the possibilities of other well-motivated mass windows.

Besides conventional DM search methods, GW experiments may provide completely novel opportunities to search for DM. Interestingly, it has been demonstrated that GW experiments can be used to study DM in both ultraheavy and ultralight mass regimes, for an indirect as well as a direct detection. (For synergy, see Snowmass white paper “New Horizons: Scalar and Vector Ultralight Dark Matter” [388], and “Ultraheavy particle dark matter” [389].)

● **Primordial black holes (PBHs):** GW observations [390–399] have revealed intriguing properties of BH mergers and have rekindled suggestions that PBHs may exist and constitute a fraction of the DM [400–404]. Advanced LIGO and Virgo, and future ground-based GW observatories, e.g. Cosmic Explorer (CE) [297, 405] and Einstein Telescope (ET) [300, 381, 406], will probe the origin of BHs (stellar or primordial) through different methods and observations:

1. *Subsolar black holes mergers.* Detecting a black hole of mass below the Chandrasekhar mass would almost unambiguously point towards a primordial origin. Subsolar searches have been carried out in the first three runs of LIGO/Virgo [407–413], with a few candidates recently found [411], while CE and ET will reach the sensitivity at cosmological distances.

2. *BHs in the NS mass range, low mass gap and pair-instability mass gap.* Multimessenger astronomy could probe the origin of compact objects in the possible mass-gap between NS and astrophysical BHs [398, 399], eventually revealing their possibly primordial origin by detecting EM counterparts [414]. CE and ET could also detect their different merging phase. PBHs in this range are motivated by a boosted formation at the QCD transition [415, 416].

Above  $60M_{\odot}$ , pair-instability should prevent BHs to form while PBHs could explain recent observations [416–418], though hierarchal mergers remain a more natural explanation [419]. Accurate spin reconstructions allow distinguishing them from secondary mergers in dense environments [420]. CE will probe intermediate-mass black hole binaries up to  $10^4M_{\odot}$ , which will reveal a possible primordial origin of the seeds of the super-massive BHs at galactic centers [416, 421].

3. *BH mergers at high redshift.* The third generation of GW detectors like CE and ET will have an astrophysical reach  $20 \lesssim z + 1 \lesssim 100$ , prior to the formation of stars. Any BH merger detection would therefore almost certainly point to a primordial origin [422].

4. *Distinguishing PBH vs stellar BHs with statistical methods.* Bayesian statistical methods and model selection [423] applied to the rate, mass, spin and redshift distributions will also help to distinguish PBHs from the stellar scenarios [416, 424–443]. They can be used to set new limits on PBH models and reveal the existence of different black hole populations (PBH binaries with merging rates large enough to be

detected may have formed by tidal capture in clusters [400, 401, 444, 445] and before recombination [425, 446–449]).

5. *GW backgrounds.* If PBHs contribute to a non-negligible fraction of DM, their binaries generate a detectable GW background [32, 447, 450–454], as well as close encounters [455]. Its spectral shape depends on the PBH mass distribution and binary formation channel, with its amplitude comparable or higher than astrophysical sources. The number of sources contributing may also help to identify a SGWB from PBHs [456]. Other SGWBs may come from Hawking radiation [457, 458], from the density fluctuations at the origin of PBH formation [414, 459–470] or from their distribution [471, 472]. The density fluctuations also give rise to anisotropies and deformation in SGWBs of other cosmological origins through propagation effects [473–478].

6. *Continuous waves (CWs).* Very light ( $\lesssim \mathcal{O}(10^{-10} M_{\odot} - 10^{-3} M_{\odot})$ ) PBH binaries would generate long-lived GWs during inspiraling, lasting at least  $\mathcal{O}(\text{hours-days})$  and potentially up to thousands or million years. A method has been designed to search for these GWs [479], and those from mini-EMRI ones [480], with constraints placed using upper limits from searching for quasi-monochromatic, persistent GWs in O3 from planetary and asteroid-mass PBHs [481, 482]. CE and ET could even detect such binaries in the solar system vicinity.

7. *GW bursts.* These may be produced by hyperbolic encounters in dense halos [483, 484]. The signal frequency can lie in the frequency range of ground-based detectors for stellar-mass BHs, with a duration of order of milliseconds. Finally, the absence of GW from kilonovae may point to neutron stars (NS) destroyed by sublunar PBHs [485].

8. *Phase transition GWs.* PBHs can form during a first-order phase transition via trapping fermions in the false vacuum [486–490], bubble collisions [491, 492] or postponed vacuum decay [493, 494]. In such scenarios, there could be correlated signals between PBHs (e.g. merger/evaporation/microlensing) and phase transition GWs.

• **Dark photon DM:** If DM is made up of ultralight bosons, it will behave as an oscillating classical wave, with dark photon (DPDM) being a good candidate. If DPDM is further charged under  $U(1)_B$  gauge group, the DPDM background field will induce displacements on the GW interferometer's test masses, resulting in a time dependent variation on the arm length and thus a GW-like signal [495]. The DPDM signal in the frequency domain is quasi-monochromatic, centered at the mass of dark photon  $m_A$ , with a very narrow frequency width  $\Delta f/f \sim 10^{-6}$  from the velocity dispersion of DM halo in the Milky Way. Thus, the search amounts to bump hunting in the frequency domain with Fourier analysis.

Searches have been performed at LIGO, which is most sensitive to a DPDM mass of  $m_A \sim 4 \times 10^{-13} \text{eV}$  at its most sensitive frequency  $\sim 100 \text{Hz}$ , using data from the first observation run (O1) [496] and the third (O3) [497]. The long coherence length of the DPDM means the signal is correlated in multiple interferometers of LIGO and Virgo, which then allows cross-correlating the strain channels of data from pairs of interferometers to significantly reduce the noises [498], while in the O3 search, a band sampled data method is also used [499].

No evidence of DPDM signal has been found in O1 and O3 data and upper limits are placed on the DPDM coupling with baryon number. The O3 upper limit of squared

coupling  $\epsilon^2$  is best constrained to be  $1.2(1.31) \times 10^{-47}$  at  $5.7(4.2) \times 10^{-13} \text{eV}/c^2$  for the two methods used, which is improved by a factor of  $\sim 100$  for  $m_A \sim (2 - 4) \times 10^{-13} \text{eV}/c^2$  compared with the O1 result, with most of the gain in sensitivity coming from taking into account of the finite travel time of the light [500]. The GW data have already probed the unexplored DPDM parameter space, and direct DPDM search using GW data became competitive compared with other fifth-force experiments at this particular mass region.

- **Dilaton:** The dilaton is a promising ultralight dark matter candidate. It is naturally predicted in theories with extra dimensions, and it couples to the SM particles through the trace of the energy momentum tensor. If the dilaton plays the role of DM, its oscillation will lead to time-dependent variations of fundamental constants, such as the electron mass and the fine structure constant.

If the GW interferometers are embedded in the background of the dilaton, the oscillation of the dilaton DM would manifest as changes in the length and index of refraction of materials [501–503]. Similarly to DPDM, dilatons would behave as a classically oscillating field, and would impart a quasi-monochromatic, persistent signal onto the detectors by physically changing the size of the beam splitter, resulting in different travel times for light coming from the x- and y-arms [504]. Therefore, the arm-length of the interferometers does not matter; instead, it is necessary to have high sensitivity to optical phase differences between the two arms. In GEO 600, the squeezed light vacuum states of light allow for a large quantum noise reduction, more than LIGO/Virgo/KAGRA, meaning that GEO 600 is the most sensitive GW interferometer to dilaton DM. A search for dilaton DM was conducted using about a week of data from GEO 600, resulting in extremely competitive constraints on the couplings of dilatons to electrons and photons [505]. The analysis was optimally sensitive to each logarithmically-spaced mass of the dilaton, since it employed LPSD to confine the frequency modulation induced by the dilaton on the detector to one frequency bin. This modulation results from the superposition of plane waves that compose a packet of dilatons that interacts with the detector [506].

- **Axions:** Axions are scalar particles that generally appear in various extensions of the SM [507, 508]. These hypothetical particles can be constrained in several ways. If axions play the role of DM, constraints can be imposed using techniques sensitive to different interaction channels and appropriate mass ranges [509]. Stellar energy-loss arguments can also lead to constraints [510]. Axions with weak self-interactions could lead to black hole superradiance, and thus be constrained through black hole spin measurements [511–516], polarimetric observations [517], and GWs emitted by the superradiance cloud [518–522].

Light scalar fields can be sourced by neutron stars due to their coupling to nuclear matter, and affect the dynamics of binary neutron star coalescence leaving potentially detectable fingerprints in the inspiral waveform. Calculating the first post-Newtonian corrections to the orbital dynamics, radiated power, and gravitational waveform for binary neutron star mergers in the presence of an axion field, it was shown [523] that Advanced LIGO at designed sensitivity can potentially exclude axions with mass  $m_a \lesssim 10^{-11} \text{eV}$  and decay constant  $f_a \sim (10^{14} - 10^{17}) \text{GeV}$ . Analyzing the GWs from the binary neutron star inspiral GW170817 allowed to impose constraints on axions with masses below  $10^{-11} \text{eV}$  by excluding the ones with decay constants ranging

from  $1.6 \times 10^{16}$  GeV to  $10^{18}$  GeV at a  $3\sigma$  confidence level [524]. This parameter space, excluded from neutron star inspirals, has not been probed by other existing experiments.

## 6 Complementarity between collider and GW observations

As discussed in previous sections, GW signals from the early Universe offer a new probe of physics beyond the SM. In particular, a phase transition in the early Universe in the 100 GeV - 100 TeV energy range will lead to a GW signal with a peak frequency in the mHz - Hz range, potentially accessible at future GW observatories such as LISA, Taiji, Tianqin. This range will also be scrutinized by the LHC (including its High Luminosity upgrade) in combination with proposed future high-energy colliders like ILC, CLIC, CEPC, FCC, SppC or a multi-TeV muon smasher. GW observatories and high-energy colliders are then highly complementary in the search for physics beyond the SM: the discovery of a GW signal from a phase transition in the early Universe could then guide searches for new physics at future colliders; conversely, new physics discovered at colliders could provide hints of early Universe phase transitions producing GW signals. We here discuss this complementarity, highlighting that the respective sensitivities may be very different depending on the specific incarnation of new physics, and each of the two approaches could in principle cover the “blind spots” of the other.

We first focus on the possibility of an electroweak phase transition (EWPT) as a prime example leading to potential signatures both at colliders and next-generation GW detectors. Then, we also discuss other phase transitions in the early Universe for which such complementarity could be very important.

### 6.1 Electroweak phase transition

Unravelling the physics behind electroweak symmetry breaking (EWSB) is central to particle physics. It will be a leading aspect of the upcoming LHC and HL-LHC physics runs, as well as a main physics driver for future high-energy colliders. There are compelling theoretical arguments to expect new physics coupled to the SM Higgs and not far from the TeV energy scale, e.g. in order to address the origin of the electroweak scale. Among the many questions surrounding EWSB, the thermal history of EWSB is of particular interest. In the SM with a 125 GeV Higgs boson, the EWSB transition occurs via a smooth cross-over rather than a *bona fide* phase transition [525]. This transition takes place at a temperature  $T_{EW} \sim 140$  GeV. Importantly, new physics coupled to the Higgs could alter the nature of the EWSB transition, possibly making it a first order EWPT. The existence of such a transition is a necessary ingredient for electroweak baryogenesis (see Ref. [526] and references therein as well as Snowmass white papers [5, 527]) and could provide a source for observable gravitational radiation. To significantly alter the SM thermal history, the new physics mass scale cannot lie too far above  $T_{EW}$ , nor can its interactions with the SM Higgs boson be too feeble[111].

Thus, it will be generally possible to measure its effects at the LHC or future high-energy colliders.

Collider probes rely on two classes of signatures. On the one hand, it should be possible to directly produce and study the new particles at some of these facilities, given that their reach in energy spans one/two orders of magnitude beyond the electroweak scale.

On the other hand, new physics coupled to the Higgs tends to lead to deviations  $\delta_i$  of the Higgs couplings or other properties from their SM values, including:

- The Higgs trilinear self-coupling,  $\lambda_3$ . Although the HL-LHC will only be mildly sensitive to this coupling ( $\delta_{\lambda_3} \sim 50\%$ ), future colliders could significantly improve on its measurement. In particular, 100 TeV hadron colliders (e.g. FCC-hh or SppC) and TeV scale lepton colliders could reach a sensitivity  $\delta_{\lambda_3} \sim 5 - 10\%$ .
- The Higgs-Z boson coupling [114, 528], which could be measured with exquisite precision (down to  $\delta_{Zh} \sim 0.1\%$ ) in future Higgs factories like ILC, CEPC or FCC-ee.
- Higgs boson signal strengths, which depend on the product of the Higgs production cross section and decay branching ratios. Mixing between the Higgs boson and a new neutral scalar that catalyzes a first order EWPT may lead to deviations accessible at future Higgs factories [529].
- The Higgs-to-diphoton decay rate. If a new neutral scalar is part of an electroweak multiplet, its charged partners will contribute to this loop-induced decay, with a magnitude governed by the scalar mass and the same Higgs portal coupling responsible for a first order EWPT. Order 1-10% deviations from the SM prediction are possible, yielding potentially observable signatures at next generation colliders.
- Possible new or “exotic” Higgs decay modes into new light particles responsible for a first order EWPT.

For a generic assessment of the discovery reach for direct and indirect signals associated with a first order EWPT – along with an extensive set of references to model-specific studies – see Ref. [111].

The two types of collider probes of new physics that may catalyze a first order EWPT, direct production of the new particle states and precision measurements of Higgs properties, are complementary to each other and to GW probes of the EWSB thermal history. In the following, we discuss several concrete examples of such interplay, which illustrate the reach when combining collider searches and GW observations to probe the properties of a possible first order EWPT.

*Singlet-driven EWPT scenarios.* The interactions of a SM gauge singlet scalar with the Higgs open up significant possibilities for a first order EWPT. A singlet may be either real (the “xSM”) or complex (the “cxSM”) and involve adding to the SM one or two new degrees of freedom, respectively.

We focus on the EWPT in the xSM (see, e.g., [112, 114, 529–531]).

In the absence of a  $\mathbb{Z}_2$ -symmetry for the singlet scalar field  $S$ , the Higgs and the singlet will generally mix. On general grounds, one expects  $|\sin \theta| \gtrsim 0.01$  when a first order EWPT is sufficiently strong as to accommodate electroweak baryogenesis [111]. The presence of the singlet, both via the mixing angle  $\theta$  and via its contribution to the Higgs two-point function at loop level, leads to a universal suppression of



Higgs couplings to gauge bosons and fermions w.r.t. their SM values. Precision studies of Higgs boson properties provide multiple avenues for observing these effects. For example, it has been shown in [114, 532] (see also [533]) that the resulting modification of the Higgs coupling to the  $Z$  boson would allow one to probe a large fraction of the parameter space region yielding a strongly first-order EWPT at FCC-ee, CEPC or ILC-500. Measurements of the Higgs boson signal strengths at the LHC or future Higgs factories could provide a similarly powerful probe, as shown in Ref. [529]. The Higgs self-coupling  $\lambda_3$  could be measured at a future 100 TeV hadron collider or a multi-TeV lepton collider (e.g. CLIC or a muon smasher) with 10% precision or better, which yields a comparable constraint on the singlet parameter space in the small-mixing limit  $\sin \theta \ll 1$  [529, 532].

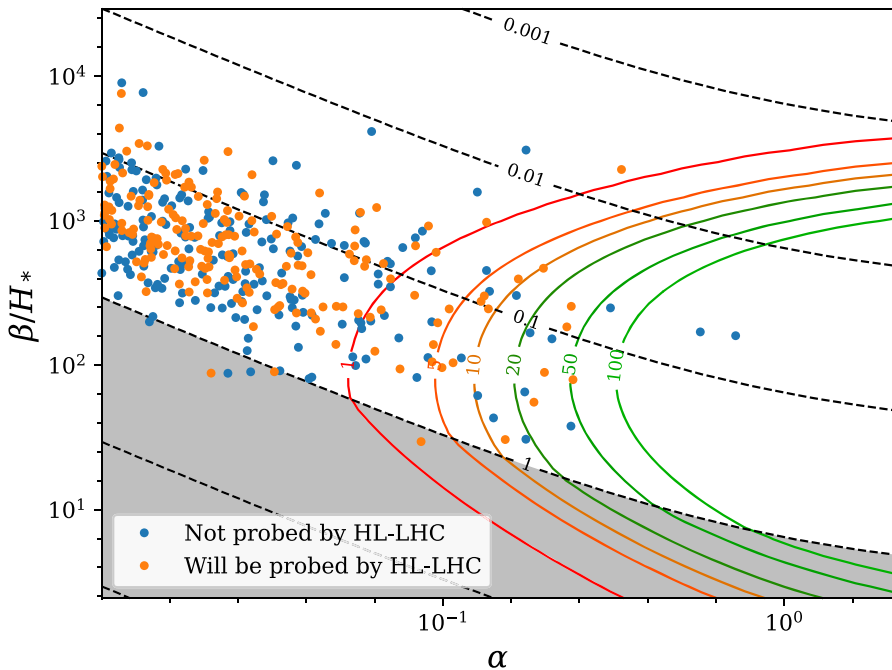
On the other hand, it is possible that the degree of singlet-Higgs mixing needed for a first order EWPT may not be entirely accessible with future precision Higgs studies. In this case, direct production via the “resonant di-Higgs” process (for  $m_s > 2m_h$ ) provides a complementary approach. It was shown in Ref. [534] that searches for this process in the channels  $pp \rightarrow s \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$  and  $pp \rightarrow s \rightarrow hh \rightarrow 4\tau$  at a 100 TeV hadron collider could cover the entire first order EWPT parameter space, including portions not accessible through precision Higgs studies. (See also Refs. [535, 536] for resonant di-Higgs probes of the EWPT in the xSM with the  $bbWW$  and  $4b$  channels at the HL-LHC.) Additional direct production possibilities include vector boson fusion (VBF) production of the singlet at 3 TeV CLIC [537, 538] or a multi-TeV muon collider [538, 539] with its subsequent decay to a Higgs boson pair ( $s \rightarrow hh \rightarrow b\bar{b}b\bar{b}$ ) or  $Z$  boson pair ( $s \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ ) (with higher collision energy setups giving higher reach).

Conversely, for small singlet scalar masses  $m_s < m_h/2$ , exotic Higgs decays  $h \rightarrow ss$  will also allow to probe the corresponding first-order EWPT region [540, 541] at the HL-LHC (in the  $b\bar{b}\tau\tau$  final state) and future lepton colliders (in the  $4b$  final state). When combined with the projected sensitivity to the EWPT via GWs of the future LISA detector, (almost) the entire parameter space yielding detectable GW signals would be probed by future multi-TeV lepton colliders [539] (and also by 100 TeV hadron colliders). Thus, if a stochastic GW signal from a phase transition were to be detected by LISA, these future collider facilities would provide a key cross-check to identify the underlying new physics. The complementarity between GW probes with the future LISA detector and new physics searches at colliders (in this case the HL-LHC) is shown explicitly for the xSM in Fig. 2, in the plane of EWPT strength  $\alpha$  and inverse duration (in Hubble units)  $\beta/H^*$  (see section 3), using PTPLOT [542].

For the  $\mathbb{Z}_2$ -symmetric singlet extension of the SM [112, 533] the direct signatures<sup>3</sup> at colliders differ from the ones discussed above: the singlet field does not mix with the Higgs, has to be produced in pairs and does not decay to SM particles, escaping the detector as missing transverse energy  $E_T^{\text{miss}}$ . For  $m_s > m_h/2$ , the sensitivity of the HL-LHC (in the VBF process  $pp \rightarrow 2j + ss$  via an off-shell Higgs) will be very limited, and the parameter space yielding a first-order EWPT will only be accessible at a future 100 TeV hadron collider [533, 543] or multi-TeV lepton colliders [538, 544,

<sup>3</sup> Indirect signatures of the singlet through the modifications of Higgs couplings would be similar to the non- $\mathbb{Z}_2$ -symmetric case discussed above in the limit of vanishing Higgs-singlet mixing.





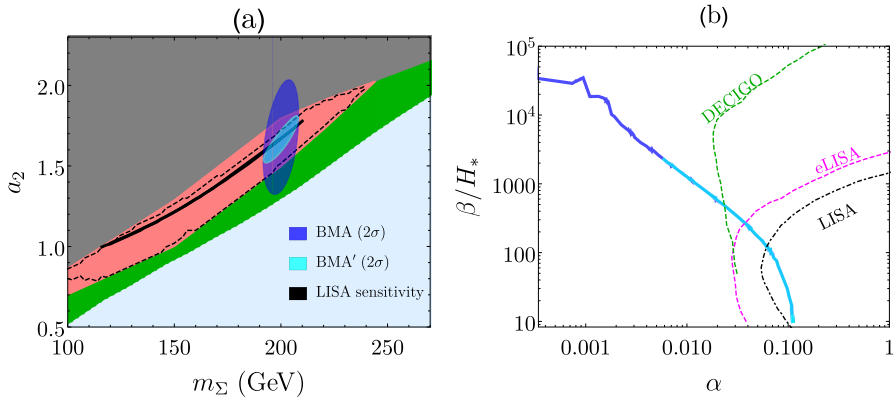
**Fig. 2** EWPT strength  $\alpha$  versus inverse duration (in Hubble units)  $\beta/H^*$  for xSM benchmark scenarios. The orange benchmarks feature a singlet mixing  $|\sin \theta| \gtrsim 0.1$ , thus within reach of the HL-LHC, while the HL-LHC will not be able to probe the blue points (some of which are within reach of LISA). The red-orange-green curves correspond to the LISA sensitivity with a certain signal-to-noise ratio (indicated in the figure). The black dashed lines correspond to constant values of  $(\tau_{\text{sw}} H)^{-1}$  (see section 3), with  $\tau_{\text{sw}} H < 1$  for the grey region. Figure adapted from [36] using PTPLOT [542]

[545] (also possibly at a high-energy  $\gamma\gamma$  collider based on such lepton colliders [546]). A space-based GW observatory like LISA would then have the first chance to probe the parameter space with a first-order EWPT in the  $\mathbb{Z}_2$ -symmetric scenario (as discussed in section 6.1 of [36]).

For other (non-singlet) extensions of the SM yielding a strong first-order EWPT, e.g. with new scalar electroweak multiplets, the non-singlet nature of the new fields helps making them more accessible at high-energy colliders. This strengthens the interplay between LHC studies and the generation of GWs from the EWPT. Important cases of recent interest include:

*Two-Higgs-doublet models (2HDM).* In this scenario, a first-order EWPT favours a sizable mass splitting among the new states  $A_0$  and  $H_0$  from the second Higgs doublet, and LHC searches for  $pp \rightarrow A_0 \rightarrow H_0 Z$  yield important constraints on the corresponding EWPT parameter space [547, 548]. The HL-LHC will completely probe the first-order EWPT parameter space in the 2HDM of Type-II (see e.g. section 9.4 of [549]), while for Type-I, LISA will be able to explore parameter regions beyond the LHC.

*Extension of the SM by a (real) scalar  $SU(2)_L$  triplet.* This scenario [145, 147, 148, 550], which entails adding three new degrees of freedom to the SM, allows for a very



**Fig. 3** Real triplet extension of the SM. Panel (a) gives the phase diagram in terms of the triplet mass  $m_\Sigma$  and Higgs portal coupling  $a_2$ . The light blue, green, red, and grey areas correspond to singlet step crossover transition, single step first order transition, two step thermal history, and unstable electroweak minimum, respectively. The interior of the black dashed contour corresponds to an EWPT that would complete. The thin black band is the allowed region for a hypothetical LISA observation. The dark (light) ellipses give prospective collider allowed regions for scenarios BMA (BMA'): determination of the triplet mass and Higgs diphoton decay rate (adds a measurement of the neutral triplet decay to two Z bosons). The blue bands in panel (b) show projection of the hypothetical collider allowed parameter space into the plane of GW-relevant inputs. Figures adapted from Ref. [153]

strong first-order EWPT through a two-step process [145] within the reach of LISA. It also predicts various distinct collider signatures, including the modification of the  $h \rightarrow \gamma\gamma$  branching fraction and disappearing track signatures [551] associated with the compressed triplet scalar spectrum.

Recent work on the triplet model that draws on the use of effective field theory and lattice simulations, illustrates how the combination of GW and collider observations could test the model and identify the values of the relevant parameters [153]. Illustrative results are shown in Fig. 3. Panel (a) shows the phase diagram (see caption for details), with the thin black band giving the portion region that a hypothetical GW signal would identify. The dark and light blue ellipses correspond to the results of prospective future collider observations. An overlap between the collider and GW-allowed regions could enable a precise determination of the model parameters in a way that is unlikely to occur with either GW or Collider measurements alone. Panel (b) shows how a hypothetical collider-allowed region in the plane of GW input parameters. Some portions of that parameter space would lie within the range of currently envisioned GW probes, while a complete coverage would require development of more sensitive probes.

Finally, some scenarios envision the dark matter actually plays a role in modifying the nature of the EWPT. An example in this class is the so called lepton portal dark matter model, with Majorana fermionic dark matter candidate [552] which has negligible direct and indirect signals. Therefore, the only hope to probe such a WIMP scenario is the collider searches. The scalar portal interactions between the charged mediator and the SM Higgs are first considered in Ref. [135], which shows that the EWPT can be modified to a first-order one, providing an extra detecting channel, i.e. the first order EWPT GWs. It is shown that the precision measurement at the future

CEPC on Higgs exotic decay and Higgs coupling to lepton can be complementary to the GW signals in probing the scalar and lepton portal couplings.

## 6.2 Theoretical robustness

When exploring the EWPT sensitivity of future GW and collider probes, it is important to assess the reliability of the theoretical computations. To date, the bulk of such studies have relied on the use of perturbation theory to analyze the EWPT thermodynamics and bubble nucleation dynamics (in the case of a first order EWPT). However, it has long been known, if not widely appreciated in recent times, that exclusive reliance on perturbation theory can yield quantitatively and qualitatively misleading results. The most significant impediment arises from bosonic contributions to thermal loops. While non-perturbative lattice computations are free from this difficulty, exclusive reliance on the lattice is not practical for a wide survey of BSM scenarios and the relevant parameter space therein. A reasonable middle ground is to pair the lattice with state-of-the-art perturbative computations, using the former to “benchmark” the latter. The latter now relies on the use of the dimensionally-reduced, three-dimensional effective field theory (DR 3DEFT). For recent applications to the singlet, 2HDM, and real triplet models, see Refs. [148, 220, 221, 553, 554].

A recent application of this benchmarking approach to the GW-collider interplay is given in Ref. [220]. In that study, it was observed that if a new scalar is sufficiently heavy to be integrated out of the DR 3DEFT, yielding a high-temperature effective theory that is SM like, then the resulting GW signal is unlikely to be accessible with LISA. Only for a sufficiently light or dynamical new scalar could one expect a signal in the LISA detector. On the other hand, future collider searches could still probe the first order EWPT-viable models that would be inaccessible to LISA. Looking to the future, the use of lattice-EFT methods to investigate the prospects for next generation GW probes is a clear theoretical forefront.

## 6.3 Other phase transitions

Other phase transitions close to the weak scale can also leave both collider and GW signal. One of the well motivated scenarios is Supersymmetry, which could be probed with GWs, complementing the existing efforts in collider physics.

First, the presence of light supersymmetric particles (specifically the stops) coupled to the SM Higgs could affect the properties of the EW symmetry breaking, rendering it strongly first order [555, 556]. However such light stop scenario is in tension with LHC data [557–560]. Within the same strategy, one could consider non minimal SUSY extension of the SM including extra scalars which further favour a strong FOPT, without being excluded by the LHC (see e.g. [561–563]). The phenomenology of such models possesses features similar to the singlet extensions of the SM which have been previously discussed.

A promising scenario for GW signatures in the MSSM has been investigated recently in [172]. In this realization the MSSM scalars have a non-standard thermal evolution at high temperatures, passing through a phase of symmetry non-restoration.

The associated phase transition at high temperature can be a source of GWs, possibly detectable in future interferometers.

Futhermore, viable SUSY models should include a sector where SUSY is spontaneously broken, and SUSY breaking is tied to spontaneous R-symmetry breaking [564]. In [173] the SUSY and R-symmetry phase transition in simple SUSY breaking hidden sectors has been investigated, and it has been shown under which conditions this can be strong and first order, leading to a SGWB. Constraints from gravitino cosmology set bounds on the SUSY breaking scales resulting in a GW spectrum in the frequency ranges accessible to current and future interferometers. Moreover, once the SUSY breaking mediation scheme is specified, the peak of the GW spectrum is correlated with the typical scale of the SM superpartners, and a visible GW signal would imply superpartners within reach of future colliders.

As a generic remark, we emphasize that SUSY gauge theories typically include large scalar manifolds where phase transitions could have occurred during the evolution of the Universe, opening the possibilities for novel mechanisms to generate GW signatures and to test high energy SUSY breaking scales.

### 7 Correlating GW background with EM observations

As discussed above, a SGWB arises as an incoherent superposition of many 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 [565, 566]. These models often yield predictions for other cosmological observables, such as the CMB, the distribution of galaxies across the sky and redshift, and the distribution of dark matter throughout the universe. It is therefore expected that cross-correlating the spatial structure in the SGWB with spatial structures in other cosmological observables would enable new probes of the underlying physical models and of the earliest phases of the evolution of the universe.

The SGWB is typically described in terms of its energy density [567, 568]:

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

where  $d\rho_{\text{GW}}$  is the energy density of gravitational radiation stored in the frequency band  $[f, f + df]$ ,  $\hat{e}$  is the direction on the sky, and  $\rho_c$  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  $\delta\Omega_{\text{GW}}(\hat{e}, f) = \sum_{lm} a_{lm}(f) Y_{lm}(\hat{e})$ , from which the angular power spectrum can be computed as  $C_l(f) \propto \sum_m \langle a_{lm}(f) a_{lm}^*(f) \rangle$ , under the assumption of statistical isotropy.

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 [569–594]. Some of them have also investigated the possibility of cor-

relating the SGWB anisotropy with the anisotropy observed in electromagnetic (EM) tracers of the large scale structure, such as galaxy counts and weak lensing [576–578, 580, 582, 583, 585, 595–597], or the CMB [569, 586–588, 590, 592–594]. In such cases, one can also expand the EM observable (such as galaxy count distribution) in spherical harmonics (with coefficients  $b_{lm}$ ) and define the angular cross-correlation spectrum  $D_l(f) \propto \sum_m \langle a_{lm}(f) b_{lm}^*(f) \rangle$ . These SGWB-EM anisotropy correlations carry unique potential to probe different aspects of high-energy physics, as we outline in the following examples.

**SGWB-CMB Correlations:** While most cosmological SGWB models predict isotropic backgrounds [27, 31, 33, 598–602], 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 [603–611]. 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 [611], as discussed in Section 4. A PT is expected to occur at the time of the electroweak symmetry breaking, at  $\sim 1$  TeV scale, resulting in a potentially strong SGWB in both LISA and third-generation (3G) terrestrial detector bands [610, 612]. Possible PTs at higher temperatures ( $\sim 10^3 - 10^6$  TeV) would also be accessible to 3G detectors [612]. 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:  $C_l^{\text{GW}} \sim [l(l+1)]^{-1}$  [586]. 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 [586]. The degree and nature of correlations between the two backgrounds would provide valuable insight into inflation and the “dark ages” of cosmic history.

While SGWB anisotropy can be generated at the time of the SGWB production, as in the above phase transition example, it is also possible for the SGWB anisotropy to be generated while GWs propagate through a non-uniform universe. This effect is common for all isotropic early-universe SGWB models: as GWs propagate through large-scale density perturbations that are correlated with the CMB temperature and E-mode polarization, they too become correlated with the CMB [569, 587, 588, 592, 593]. Multiple examples of extensions of  $\Lambda$ CDM universe model have been examined, all featuring new pre-recombination physics. This includes models with extra relativistic degrees of freedom, a massless non-minimally coupled scalar field, and an Early Dark Energy component [594]. SGWB-CMB correlations help constrain these models at various levels of significance, depending on the specific model and on the strength of the SGWB monopole.

**Cosmic strings:** As discussed in Section 5, cosmic strings, either as fundamental strings or as topological defects formed during PTs in the early universe, are expected to support cusps [327, 613–615] and kinks [616], 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 [324]. 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 [617–619]. While the isotropic (monopole) component of this SGWB may be within reach of the advanced or 3G detectors [620], 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 [570, 621]. 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):** As discussed in Section 6, 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 sky-map of the SGWB due to binary black hole (BBH) signals with the sky-maps of galaxy distribution or dark matter distribution could provide additional insights on the origin of black holes [622–625]. 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 [626–628], and efforts to combine well-resolved sources with the SGWB hold promise as well [629].

**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 [630, 631]. Similar techniques for measuring SGWB anisotropy in the 1 mHz band using LISA are being developed [632]. 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 [633]). 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 [634, 635]. 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.

## 8 Conclusions

This white paper highlights the strong scientific potential in using GW observations to probe fundamental particle physics and the physics of the early universe. Processes that took place in the Universe within one minute after the Big Bang are often associated with high energies that cannot be reproduced in laboratories, making GW observations unique opportunities to probe the new physics at such energies. In some cases, combining GW observations with accelerator-based experiments or with cosmological observations in the electromagnetic spectrum allows even more powerful probes of the new physics.

The standard inflationary paradigm results in a scale-invariant GW spectrum. A novel coupling between the inflaton and gauge fields could result in a strongly blue-tilted spectrum. At the end of inflation, a variety of mechanisms for transferring energy from the inflaton to other particles, including reheating and preheating phases, could result in a boost of the GW spectrum at relatively high frequencies. The presence of additional phases in the Universe, especially if characterized by stiff equations of state, could also result in a significant blue GW spectrum observable by future GW detectors. Alternative cosmologies, such as pre-Big-Bang and ekpyrotic models, could also leave observable blue GW spectra, hence providing new windows into the origins of the universe.

As the Universe cools, multiple symmetries are expected to be broken at different energy scales, resulting in phase transitions in the early universe. The electroweak phase transition is of particular interest, but others are also possible, including QCD, supersymmetry, and others. If they are first-order, these phase transitions could result in GW production with a spectrum typically peaked around the frequency corresponding to the energy scale of the phase transition. GW production mechanisms include collisions of bubble walls, sound waves in the plasma, and magnetohydrodynamic turbulence. In the case of electroweak phase transitions, existence of new physics slightly above the electroweak scale could cause the transition to be first-order. Such new physics would be within reach of future collider experiments, including the ILC, FCC, CEPC, and others, hence raising the distinct possibility of combining collider experiments with GW observations to probe the physics of electroweak symmetry breaking. Similar collider-GW complementarity could also be used to study other symmetries and corresponding phase transitions, with supersymmetry as a notable example.

Furthermore, phase transitions in the early universe could result in topological defects, such as strings or domain walls. Among these, cosmic strings have received much attention as possible GW sources: the dynamics in cosmic string loops is expected to produce a broad GW spectrum, spanning decades in frequency, with the amplitude strongly dependent on the string tension. More recently, axion strings and



topological defects have been studied as sources of GWs, likely with a spectrum with logarithmic decline at high frequencies. Cosmic superstrings are also a possible GW source, turning GW experiments into novel ways to test string theory.

Dark matter could result in GW production with a broad variety of morphologies. Dark matter in the form of primordial black holes could be detected in individual binary black hole merger events, for example if involving subsolar black holes or if taking place at high redshift ( $> 20$ ), or by observing the SGWB due to binary black holes whose spectrum would depend on the fraction of black holes that are of primordial origin. Dark matter in the form of dark photons would induce quasi-monochromatic displacements in the GW detector test masses, at the frequency set by the dark photon mass, and could be searched for using Fourier techniques. Dark matter in the form of a dilaton would cause changes in the length and index of refraction in a GW detector's mirrors, hence inducing phase differences in the detector's two arms. Dark matter in the form of axions could generate GW signatures through the black hole superradiance process or by modifying the inspiral signal in neutron star binary mergers.

Finally, we note that cross-correlations of the anisotropy in GW energy density and the anisotropy in electromagnetic tracers of the structure in the universe (cosmic microwave and infrared backgrounds), weak lensing, galaxy counts) could also serve as powerful probes of the early universe physics. As an example, if a phase transition happened after inflation, the primordial density fluctuations that led to the CMB angular spectrum would also have been present during the phase transition, imprinting anisotropy in the SGWB at least as large as (and correlated with) the CMB anisotropy. Other applications include cosmic string probes and probes of dark matter in the form of primordial black holes.

This tremendous breadth of fundamental particle physics and cosmology phenomena will be accessible to future GW observations, including terrestrial and space-borne detectors, pulsar timing observations, and experiments targeting the B-mode CMB polarization. Realizing this scientific potential requires not only development and completion of the next generation of GW and collider detectors, but also theoretical developments that would define effective probes of the phenomena using the upcoming data.

**Acknowledgements** RC is supported in part by U.S. Department of Energy Award No. DE-SC0010386. YC is supported in part by the U.S. Department of Energy under award number DE-SC0008541. HG, FY and YZ are supported by U.S. Department of Energy under Award No. DESC0009959. VM is supported by NSF grant PHY2110238. VM and CS are also supported by NSF grant PHY-2011675. AM and AS are supported by the SRP High-Energy Physics and the Research Council of the VUB, AM is also supported by the EOS - be.h project n.30820817, and AS by the FWO project G006119N. JMN is supported by Ramón y Cajal Fellowship contract RYC-2017-22986, and by grant PGC2018-096646-A-I00 from the Spanish Proyectos de I+D de Generación de Conocimiento. MJRM is supported in part under U.S. Department of Energy contract DE-SC0011095, and was also supported in part under National Natural Science Foundation of China grant No. 19Z103010239. MS is supported in part by the Science and Technology Facility Council (STFC), United Kingdom, under the research grant ST/P000258/1. KS is supported in part by the U.S. Department of Energy under award number DE-SC0009956. LTW is supported by the U.S. Department of Energy grant DE-SC0013642. GW is supported by World Premier International Research Center Initiative (WPI), MEXT, Japan. HA is supported in part by the National Key R&D Program of China under Grant No. 2021YFC2203100 and 2017YFA0402204, the National Natural Science Foundation under Grant No. 11975134, and the Tsinghua University Initiative Scientific Research Program. LB is supported in part by the National Key Research and Development Program of China Grant No. 2021YFC2203004, the National

Natural Science Foundation of China under the grants Nos.12075041, 12047564, and the Fundamental Research Funds for the Central Universities of China (No. 2021CDJQY-011 and No. 2020CDJQY-Z003), and Chongqing Natural Science Foundation (Grants No.cstc2020jcyj-msxmX0814). SC is supported by a Starting Grant from the Belgian Francqui Foundation. JMC and BL are supported by NSERC (Natural Sciences and Engineering Research Council), Canada. GC is funded by Swiss National Science Foundation (Ambizione Grant). RJ is supported by the grants IFT Centro de Excelencia Severo Ochoa SEV-2016-0597, CEX2020-001007-S and by PID2019-110058GB-C22 funded by MCIN/AEI/10.13039/501100011033 and by ERDF. NL is grateful for the support of the Milner Foundation via the Milner Doctoral Fellowship. KFL is partially supported by the U.S. Department of Energy grant DE-SC0022345. MM is partially supported by the Spanish MCIN/AEI/10.13039/501100011033 under the grant PID2020-113701GB-I00, which includes ERDF funds from the European Union. IFAE is partially funded by the CERCA program of the Generalitat de Catalunya. ALM is a beneficiary of a FSR Incoming Postdoctoral Fellowship. BS is supported in part by NSF grant PHY-2014075. JS is supported by the National Natural Science Foundation under Grants No. 12025507, No. 12150015, No.12047503; and is also supported by the Strategic Priority Research Program and Key Research Program of Frontier Science of the Chinese Academy of Sciences under Grants No. XDB21010200, No. XDB23010000, and No. ZDBS-LY-7003 and CAS project for Young Scientists in Basic Research YSBR-006. XS was supported by NSF's NANOGrav Physics Frontier Center (NSF grants PHY-1430284 and PHY-2020265). RS is supported by the NSF grant PHY-1914731 and by the US-Israeli BSF Grant 2018236. CT acknowledges financial support by the DFG through the ORIGINS cluster of excellence. DJW was supported by Academy of Finland grant nos. 324882 and 328958. KPX is supported by the University of Nebraska-Lincoln. SYZ is supported in part by JSPS KAKENHI Grant Number 21F21026.

**Data Availability** Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

## Declarations

**Conflict of interest** The author M.S. is Editor-in-Chief of the journal *General Relativity and Gravitation*; the article underwent a standard single-blind peer review process.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

1. Ballmer, S.W., et al.: Snowmass2021 Cosmic Frontier White Paper: Future Gravitational-Wave Detector Facilities. arXiv e-prints (2022) [arXiv:2203.08228](https://arxiv.org/abs/2203.08228) [gr-qc]
2. Adelberger, E., et al.: Snowmass white paper: precision studies of spacetime symmetries and gravitational physics. In: 2022 Snowmass Summer Study (2022) [arXiv:2203.09691](https://arxiv.org/abs/2203.09691) [hep-ex]
3. Achúcarro, A., et al.: Inflation: Theory and Observations. arXiv e-prints (2022) [arXiv:2203.08128](https://arxiv.org/abs/2203.08128) [astro-ph.CO]
4. Flauger, R., Gorbenco, V., Joyce, A., McAllister, L., Shiu, G., Silverstein, E.: Snowmass White Paper: Cosmology at the Theory Frontier. arXiv e-prints (2022) [arXiv:2203.07629](https://arxiv.org/abs/2203.07629) [hep-th]
5. Asadi, P., et al.: Early-Universe Model Building (2022) [arXiv:2203.06680](https://arxiv.org/abs/2203.06680) [hep-ph]
6. Abdalla, E., et al.: Cosmology Intertwined: A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies. arXiv e-prints (2022) [arXiv:2203.06142](https://arxiv.org/abs/2203.06142) [astro-ph.CO]

7. Chakrabarti, S., et al.: Snowmass2021 cosmic frontier white paper: observational facilities to study dark matter. In: 2022 Snowmass Summer Study (2022) [arXiv:2203.06200](https://arxiv.org/abs/2203.06200) [astro-ph.CO]
8. Bird, S., et al.: Snowmass2021 Cosmic Frontier White Paper: Primordial Black Hole Dark Matter. arXiv e-prints (2022) [arXiv:2203.08967](https://arxiv.org/abs/2203.08967) [hep-ph]
9. Boddy, K.K., et al.: Astrophysical and Cosmological Probes of Dark Matter. arXiv e-prints (2022) [arXiv:2203.06380](https://arxiv.org/abs/2203.06380) [hep-ph]
10. Brito, R., et al.: Snowmass2021 Cosmic Frontier White Paper: Cosmic probes of fundamental physics probing dark matter with small-scale astrophysical observations. arXiv e-prints (2022) [arXiv:2203.15954](https://arxiv.org/abs/2203.15954)
11. Carena, M., Kozaczuk, J., Liu, Z., Ou, T., Ramsey-Musolf, M.J., Shelton, J., Wang, Y., Xie, K.-P.: Probing the electroweak phase transition with exotic higgs decays. In: 2022 Snowmass Summer Study (2022) [arXiv:2203.08206](https://arxiv.org/abs/2203.08206) [hep-ph]
12. Berti, E., Cardoso, V., Haiman, Z., Holz, D.E., Mottola, E., Mukherjee, S., Sathyaprakash, B., Siemens, X., Yunes, N.: Snowmass2021 Cosmic Frontier White Paper: Fundamental Physics and Beyond the Standard Model. arXiv e-prints (2022) [arXiv:2203.06240](https://arxiv.org/abs/2203.06240) [hep-ph]
13. Ferraro, S., Sailer, N., Slosar, A., White, M.: Snowmass2021 Cosmic Frontier White Paper: Cosmology and Fundamental Physics from the three-dimensional Large Scale Structure. arXiv e-prints (2022) [arXiv:2203.07506](https://arxiv.org/abs/2203.07506) [astro-ph.CO]
14. Chang, C.L., et al.: Snowmass2021 Cosmic Frontier: Cosmic Microwave Background Measurements White Paper. arXiv e-prints (2022) [arXiv:2203.07638](https://arxiv.org/abs/2203.07638) [astro-ph.CO]
15. Regimbau, T., Evans, M., Christensen, N., Katsavounidis, E., Sathyaprakash, B., Vitale, S.: Digging deeper: observing primordial gravitational waves below the binary-black-hole-produced stochastic background. *Phys. Rev. Lett.* **118**, 151105 (2017). <https://doi.org/10.1103/PhysRevLett.118.151105>
16. Sachdev, S., Regimbau, T., Sathyaprakash, B.S.: Subtracting compact binary foreground sources to reveal primordial gravitational-wave backgrounds. *Phys. Rev. D* **102**, 024051 (2020). <https://doi.org/10.1103/PhysRevD.102.024051>
17. Sharma, A., Harms, J.: Searching for cosmological gravitational-wave backgrounds with third-generation detectors in the presence of an astrophysical foreground. *Phys. Rev. D* **102**, 063009 (2020). <https://doi.org/10.1103/PhysRevD.102.063009>
18. Biscoveanu, S., Talbot, C., Thrane, E., Smith, R.: Measuring the primordial gravitational-wave background in the presence of astrophysical foregrounds. *Phys. Rev. Lett.* **125**, 241101 (2020). <https://doi.org/10.1103/PhysRevLett.125.241101>
19. Abbott, R., et al.: Upper limits on the isotropic gravitational-wave background from advanced ligo and advanced virgo's third observing run. *Phys. Rev. D* **104**, 022004 (2021). <https://doi.org/10.1103/PhysRevD.104.022004>
20. Lasky, P.D., et al.: Gravitational-wave cosmology across 29 decades in frequency. *Phys. Rev. X* **6**, 011035 (2016). <https://doi.org/10.1103/PhysRevX.6.011035>
21. Arzoumanian, Z., et al.: The NANOGrav 125 yr data set: search for an isotropic stochastic gravitational-wave background. *Astrophys. J. Lett.* **905**(2), 34 (2020). <https://doi.org/10.3847/2041-8213/abd401>
22. ET science team: Einstein gravitational wave Telescope (ET) conceptual design study, number = ET-0106C-10. Technical report, ET consortium (2011). <https://apps.et-gw.eu/tds/ql/>
23. Abbott, B.P., et al.: Exploring the sensitivity of next generation gravitational wave detectors. *Class. Quant. Gravit.* **34**, 044001 (2017)
24. Danzmann, K., et al.: LISA, Laser Interferometer Space Antenna. [https://www.elisascience.org/files/publications/LISA\\_L3\\_20170120.pdf](https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf) (2017)
25. Hu, W.-R., Wu, Y.-L.: The Taiji Program in Space for gravitational wave physics and the nature of gravity. *Natl. Sci. Rev.* **4**(5), 685–686 (2017). <https://doi.org/10.1093/nsr/nwx116>
26. Luo, J., et al.: TianQin: a space-borne gravitational wave detector. *Class. Quant. Gravit.* **33**(3), 035010 (2016). <https://doi.org/10.1088/0264-9381/33/3/035010>. [arXiv:1512.02076](https://arxiv.org/abs/1512.02076) [astro-ph.IM]
27. Turner, M.S.: Detectability of inflation-produced gravitational waves. *Phys. Rev. D* **55**, 435 (1997)
28. Ellis, J., Lewicki, M., No, J.M., Vaskonen, V.: Gravitational wave energy budget in strongly supercooled phase transitions. *JCAP* **06**, 024 (2019). <https://doi.org/10.1088/1475-7516/2019/06/024>. [arXiv:1903.09642](https://arxiv.org/abs/1903.09642) [hep-ph]
29. Delle Rose, L., Panico, G., Redi, M., Tesi, A.: Gravitational waves from supercool axions. *JHEP* **04**, 025 (2020). [https://doi.org/10.1007/JHEP04\(2020\)025](https://doi.org/10.1007/JHEP04(2020)025). [arXiv:1912.06139](https://arxiv.org/abs/1912.06139) [hep-ph]

30. An, H., Lyu, K.-F., Wang, L.-T., Zhou, S.: Gravitational waves from an inflation triggered first-order phase transition. [arXiv:2201.05171](https://arxiv.org/abs/2201.05171) (2022)
31. Barnaby, N., Pajer, E., Peloso, M.: Gauge field production in axion inflation: consequences for monodromy, non-gaussianity in the cmb, and gravitational waves at interferometers. *Phys. Rev. D* **85**, 023525 (2012)
32. Wang, S., Wang, Y.-F., Huang, Q.-G., Li, T.G.F.: Constraints on the primordial black hole abundance from the first advanced LIGO observation run using the stochastic gravitational-wave background. *Phys. Rev. Lett.* **120**(19), 191102 (2018). <https://doi.org/10.1103/PhysRevLett.120.191102>. [arXiv:1610.08725](https://arxiv.org/abs/1610.08725) [astro-ph.CO]
33. Boyle, L.A., Buonanno, A.: Relating gravitational wave constraints from primordial nucleosynthesis, pulsar timing, laser interferometers, and the cmb: implications for the early universe. *Phys. Rev. D* **78**, 043531 (2008)
34. Kosowsky, A., Turner, M.S., Watkins, R.: Gravitational waves from first-order cosmological phase transitions. *Phys. Rev. Lett.* **69**, 2026–2029 (1992). <https://doi.org/10.1103/PhysRevLett.69.2026>
35. Romero, A., Martinovic, K., Callister, T.A., Guo, H.-K., Martínez, M., Sakellariadou, M., Yang, F.-W., Zhao, Y.: Implications for first-order cosmological phase transitions from the third LIGO-Virgo Observing. Run. *Phys. Rev. Lett.* **126**(15), 151301 (2021). <https://doi.org/10.1103/PhysRevLett.126.151301>. [arXiv:2102.01714](https://arxiv.org/abs/2102.01714) [hep-ph]
36. Caprini, C., et al.: Detecting gravitational waves from cosmological phase transitions with LISA: an update. *JCAP* **03**, 024 (2020). <https://doi.org/10.1088/1475-7516/2020/03/024>. [arXiv:1910.13125](https://arxiv.org/abs/1910.13125) [astro-ph.CO]
37. Vilenkin, A., Shellard, E.P.S.: *Cosmic Strings and Other Topological Defects*. Cambridge University Press, Cambridge (2000)
38. Kibble, T.W.B.: Topology of cosmic domains and strings. *J. Phys. A* **9**, 1387–1398 (1976). <https://doi.org/10.1088/0305-4470/9/8/029>
39. Sakellariadou, M.: Cosmic strings. *Lect. Notes Phys.* **718**, 247–288 (2007). [https://doi.org/10.1007/3-540-70859-6\\_10](https://doi.org/10.1007/3-540-70859-6_10). [arXiv:hep-th/0602276](https://arxiv.org/abs/hep-th/0602276)
40. Jeannerot, R., Rocher, J., Sakellariadou, M.: How generic is cosmic string formation in SUSY GUTs. *Phys. Rev. D* **68**, 103514 (2003). <https://doi.org/10.1103/PhysRevD.68.103514>. [arXiv:hep-ph/0308134](https://arxiv.org/abs/hep-ph/0308134)
41. Vachaspati, T., Vilenkin, A.: Gravitational radiation from cosmic strings. *Phys. Rev. D* **31**, 3052–3058 (1985). <https://doi.org/10.1103/PhysRevD.31.3052>
42. Sakellariadou, M.: Gravitational waves emitted from infinite strings. *Phys. Rev. D* **42**, 354–360 (1990). <https://doi.org/10.1103/PhysRevD.42.354>. [Erratum: *Phys. Rev. D* **43**, 4150 (1991)]
43. Abbott, R., et al.: Constraints on cosmic strings using data from the third advanced LIGO-virgo observing. Run. *Phys. Rev. Lett.* **126**(24), 241102 (2021). <https://doi.org/10.1103/PhysRevLett.126.241102>. [arXiv:2101.12248](https://arxiv.org/abs/2101.12248) [gr-qc]
44. Auclair, P., et al.: Probing the gravitational wave background from cosmic strings with LISA. *JCAP* **04**, 034 (2020). <https://doi.org/10.1088/1475-7516/2020/04/034>. [arXiv:1909.00819](https://arxiv.org/abs/1909.00819) [astro-ph.CO]
45. Boileau, G., Jenkins, A.C., Sakellariadou, M., Meyer, R., Christensen, N.: Ability of LISA to detect a gravitational-wave background of cosmological origin: the cosmic string case (2021) [arXiv:2109.06552](https://arxiv.org/abs/2109.06552) [gr-qc]
46. Vilenkin, A.: Gravitational field of vacuum domain walls and strings. *Phys. Rev. D* **23**, 852–857 (1981). <https://doi.org/10.1103/PhysRevD.23.852>
47. Sakellariadou, M.: Radiation of Nambu-Goldstone bosons from infinitely long cosmic strings. *Phys. Rev. D* **44**, 3767–3773 (1991). <https://doi.org/10.1103/PhysRevD.44.3767>
48. Gleiser, M., Roberts, R.: Gravitational waves from collapsing vacuum domains. *Phys. Rev. Lett.* **81**, 5497–5500 (1998). <https://doi.org/10.1103/PhysRevLett.81.5497>. [arXiv:astro-ph/9807260](https://arxiv.org/abs/astro-ph/9807260)
49. Hiramatsu, T., Kawasaki, M., Saikawa, K.: Gravitational waves from collapsing domain walls. *JCAP* **05**, 032 (2010). <https://doi.org/10.1088/1475-7516/2010/05/032>. [arXiv:1002.1555](https://arxiv.org/abs/1002.1555) [astro-ph.CO]
50. Dunskey, D.I., Ghoshal, A., Murayama, H., Sakakihara, Y., White, G.: Gravitational Wave Gastronomy (2021) [arXiv:2111.08750](https://arxiv.org/abs/2111.08750) [hep-ph]
51. Fenu, E., Figueroa, D.G., Durrer, R., Garcia-Bellido, J.: Gravitational waves from self-ordering scalar fields. *JCAP* **10**, 005 (2009). <https://doi.org/10.1088/1475-7516/2009/10/005>. [arXiv:0908.0425](https://arxiv.org/abs/0908.0425) [astro-ph.CO]
52. Sarangi, S., Tye, S.H.H.: Cosmic string production towards the end of brane inflation. *Phys. Lett. B* **536**, 185–192 (2002). [https://doi.org/10.1016/S0370-2693\(02\)01824-5](https://doi.org/10.1016/S0370-2693(02)01824-5). [arXiv:hep-th/0204074](https://arxiv.org/abs/hep-th/0204074)

53. Jones, N.T., Stoica, H., Tye, S.H.H.: Brane interaction as the origin of inflation. *JHEP* **07**, 051 (2002). <https://doi.org/10.1088/1126-6708/2002/07/051>. arXiv:hep-th/0203163
54. Tristram, M., et al.: Planck constraints on the tensor-to-scalar ratio. *Astron. Astrophys.* **647**, 128 (2021). <https://doi.org/10.1051/0004-6361/202039585>. arXiv:2010.01139 [astro-ph.CO]
55. Thorne, B., Fujita, T., Hazumi, M., Katayama, N., Komatsu, E., Shiraishi, M.: Finding the chiral gravitational wave background of an axion-SU(2) inflationary model using CMB observations and laser interferometers. *Phys. Rev. D* **97**(4), 043506 (2018). <https://doi.org/10.1103/PhysRevD.97.043506>. arXiv:1707.03240 [astro-ph.CO]
56. Auclair, P., et al.: Cosmology with the Laser Interferometer Space Antenna (2022) arXiv:2204.05434 [astro-ph.CO]
57. Capurri, G., Bartolo, N., Maino, D., Matarrese, S.: Let Effective Field Theory of Inflation flow: stochastic generation of models with red/blue tensor tilt. *JCAP* **11**, 037 (2020). <https://doi.org/10.1088/1475-7516/2020/11/037>. arXiv:2006.10781 [astro-ph.CO]
58. Wang, Y., Xue, W.: Inflation and Alternatives with Blue Tensor Spectra. *JCAP* **10**, 075 (2014). <https://doi.org/10.1088/1475-7516/2014/10/075>. arXiv:1403.5817 [astro-ph.CO]
59. Fumagalli, J., Renaux-Petel, S., Witkowski, L.T.: Oscillations in the stochastic gravitational wave background from sharp features and particle production during inflation. *JCAP* **08**, 030 (2021). <https://doi.org/10.1088/1475-7516/2021/08/030>. arXiv:2012.02761 [astro-ph.CO]
60. Goldwirth, D.S., Piran, T.: Inhomogeneity and the Onset of Inflation. *Phys. Rev. Lett.* **64**, 2852–2855 (1990). <https://doi.org/10.1103/PhysRevLett.64.2852>
61. Calzetta, E., Sakellariadou, M.: Inflation in inhomogeneous cosmology. *Phys. Rev. D* **45**, 2802–2805 (1992). <https://doi.org/10.1103/PhysRevD.45.2802>
62. Calzetta, E., Sakellariadou, M.: Semiclassical effects and the onset of inflation. *Phys. Rev. D* **47**, 3184–3193 (1993). <https://doi.org/10.1103/PhysRevD.47.3184>. arXiv:gr-qc/9209007
63. Borde, A., Guth, A.H., Vilenkin, A.: Inflationary space-times are incomplete in past directions. *Phys. Rev. Lett.* **90**, 151301 (2003). <https://doi.org/10.1103/PhysRevLett.90.151301>. arXiv:gr-qc/0110012
64. Ijjas, A., Steinhardt, P.J., Loeb, A.: Inflationary schism. *Phys. Lett. B* **736**, 142–146 (2014). <https://doi.org/10.1016/j.physletb.2014.07.012>. arXiv:1402.6980 [astro-ph.CO]
65. Brandenberger, R.H.: A Status review of inflationary cosmology. In: Sasaki, M., et al. (eds.) Proceedings of the 10th Workshop on General Relativity and Gravitation in Japan (JGR10), p. 268 (2000) arXiv:hep-ph/0101119
66. Brandenberger, R., Peter, P.: Bouncing cosmologies: progress and problems. *Found. Phys.* **47**(6), 797–850 (2017). <https://doi.org/10.1007/s10701-016-0057-0>. arXiv:1603.05834 [hep-th]
67. Gasperini, M., Veneziano, G.: Pre-big-bang in string cosmology. *Astropart. Phys.* **1**, 317–339 (1993). [https://doi.org/10.1016/0927-6505\(93\)90017-8](https://doi.org/10.1016/0927-6505(93)90017-8). arXiv:hep-th/9211021
68. Khoury, J., Ovrut, B.A., Steinhardt, P.J., Turok, N.: The Ekpyrotic universe: Colliding branes and the origin of the hot big bang. *Phys. Rev. D* **64**, 123522 (2001). <https://doi.org/10.1103/PhysRevD.64.123522>. arXiv:hep-th/0103239
69. Brandenberger, R.H., Vafa, C.: Superstrings in the early universe. *Nucl. Phys. B* **316**, 391–410 (1989). [https://doi.org/10.1016/0550-3213\(89\)90037-0](https://doi.org/10.1016/0550-3213(89)90037-0)
70. Battefeld, D., Peter, P.: A critical review of classical bouncing cosmologies. *Phys. Rept.* **571**, 1–66 (2015). <https://doi.org/10.1016/j.physrep.2014.12.004>. arXiv:1406.2790 [astro-ph.CO]
71. Finelli, F., Brandenberger, R.: On the generation of a scale invariant spectrum of adiabatic fluctuations in cosmological models with a contracting phase. *Phys. Rev. D* **65**, 103522 (2002). <https://doi.org/10.1103/PhysRevD.65.103522>. arXiv:hep-th/0112249
72. Brandenberger, R.H.: The matter bounce alternative to inflationary cosmology (2012) arXiv:1206.4196 [astro-ph.CO]
73. Gasperini, M., Veneziano, G.: The pre-big-bang scenario in string cosmology. *Phys. Rept.* **373**, 1–212 (2003). [https://doi.org/10.1016/S0370-1573\(02\)00389-7](https://doi.org/10.1016/S0370-1573(02)00389-7). arXiv:hep-th/0207130
74. Brustein, R., Gasperini, M., Giovannini, M., Veneziano, G.: Relic gravitational waves from string cosmology. *Phys. Lett. B* **361**, 45–51 (1995). [https://doi.org/10.1016/0370-2693\(95\)01128-D](https://doi.org/10.1016/0370-2693(95)01128-D). arXiv:hep-th/9507017
75. Gasperini, M.: Observable gravitational waves in pre-big bang cosmology: an update. *JCAP* **12**, 010 (2016). <https://doi.org/10.1088/1475-7516/2016/12/010>. arXiv:1606.07889 [gr-qc]
76. Horava, P., Witten, E.: Heterotic and type I string dynamics from eleven-dimensions. *Nucl. Phys. B* **460**, 506–524 (1996). [https://doi.org/10.1016/0550-3213\(95\)00621-4](https://doi.org/10.1016/0550-3213(95)00621-4). arXiv:hep-th/9510209



77. Sakellariadou, M.: Numerical experiments on string cosmology. *Nucl. Phys. B* **468**, 319–335 (1996). [https://doi.org/10.1016/0550-3213\(96\)00123-X](https://doi.org/10.1016/0550-3213(96)00123-X). [arXiv:hep-th/9511075](https://arxiv.org/abs/hep-th/9511075)
78. Brandenberger, R.H., Nayeri, A., Patil, S.P., Vafa, C.: String gas cosmology and structure formation. *Int. J. Mod. Phys. A* **22**, 3621–3642 (2007). <https://doi.org/10.1142/S0217751X07037159>. [arXiv:hep-th/0608121](https://arxiv.org/abs/hep-th/0608121)
79. D'Eramo, F., Schmitz, K.: Imprint of a scalar era on the primordial spectrum of gravitational waves. *Phys. Rev. Res.* **1**, 013010 (2019). <https://doi.org/10.1103/PhysRevResearch.1.013010>. [arXiv:1904.07870](https://arxiv.org/abs/1904.07870) [hep-ph]
80. Figueroa, D.G., Tanin, E.H.: Ability of LIGO and LISA to probe the equation of state of the early Universe. *JCAP* **08**, 011 (2019). <https://doi.org/10.1088/1475-7516/2019/08/011>. [arXiv:1905.11960](https://arxiv.org/abs/1905.11960) [astro-ph.CO]
81. Giovannini, M.: Gravitational waves constraints on post-inflationary phases stiffer than radiation. *Phys. Rev. D* **58**, 083504 (1998)
82. Giovannini, M.: Primordial backgrounds of relic gravitons. *Prog. Part. Nucl. Phys.* **112**, 103774 (2020)
83. Inomata, K., Kawasaki, M., Mukaida, K., Terada, T., Yanagida, T.T.: Gravitational wave production right after a primordial black hole evaporation. *Phys. Rev. D* **101**(12), 123533 (2020). <https://doi.org/10.1103/PhysRevD.101.123533>. [arXiv:2003.10455](https://arxiv.org/abs/2003.10455) [astro-ph.CO]
84. White, G., Pearce, L., Vagie, D., Kusenko, A.: Detectable gravitational wave signals from affleck-dine baryogenesis. *Phys. Rev. Lett.* **127**(18), 181601 (2021). <https://doi.org/10.1103/PhysRevLett.127.181601>. [arXiv:2105.11655](https://arxiv.org/abs/2105.11655) [hep-ph]
85. Guo, H.-K., Sinha, K., Vagie, D., White, G.: Phase transitions in an expanding universe: stochastic gravitational waves in standard and non-standard histories. *JCAP* **01**, 001 (2021). <https://doi.org/10.1088/1475-7516/2021/01/001>. [arXiv:2007.08537](https://arxiv.org/abs/2007.08537) [hep-ph]
86. Hook, A., Marques-Tavares, G., Racco, D.: Causal gravitational waves as a probe of free streaming particles and the expansion of the Universe. *JHEP* **02**, 117 (2021). [https://doi.org/10.1007/JHEP02\(2021\)117](https://doi.org/10.1007/JHEP02(2021)117). [arXiv:2010.03568](https://arxiv.org/abs/2010.03568) [hep-ph]
87. Barenboim, G., Park, W.-I.: Gravitational waves from first order phase transitions as a probe of an early matter domination era and its inverse problem. *Phys. Lett. B* **759**, 430–438 (2016). <https://doi.org/10.1016/j.physletb.2016.06.009>. [arXiv:1605.03781](https://arxiv.org/abs/1605.03781) [astro-ph.CO]
88. Cai, R.-G., Pi, S., Sasaki, M.: Universal infrared scaling of gravitational wave background spectra. *Phys. Rev. D* **102**(8), 083528 (2020). <https://doi.org/10.1103/PhysRevD.102.083528>. [arXiv:1909.13728](https://arxiv.org/abs/1909.13728) [astro-ph.CO]
89. An, H., Lyu, K.-F., Wang, L.-T., Zhou, S.: A unique gravitational wave signal from phase transition during inflation (2020) [arXiv:2009.12381](https://arxiv.org/abs/2009.12381) [astro-ph.CO]
90. Geller, M., Hook, A., Sundrum, R., Tsai, Y.: Primordial anisotropies in the gravitational wave background from cosmological phase transitions. *Phys. Rev. Lett.* **121**(20), 201303 (2018). <https://doi.org/10.1103/PhysRevLett.121.201303>. [arXiv:1803.10780](https://arxiv.org/abs/1803.10780) [hep-ph]
91. Kumar, S., Sundrum, R., Tsai, Y.: Non-Gaussian stochastic gravitational waves from phase transitions. *JHEP* **11**, 107 (2021). [https://doi.org/10.1007/JHEP11\(2021\)107](https://doi.org/10.1007/JHEP11(2021)107). [arXiv:2102.05665](https://arxiv.org/abs/2102.05665) [astro-ph.CO]
92. Kofman, L., Linde, A.D., Starobinsky, A.A.: Towards the theory of reheating after inflation. *Phys. Rev. D* **56**, 3258–3295 (1997). <https://doi.org/10.1103/PhysRevD.56.3258>. [arXiv:hep-ph/9704452](https://arxiv.org/abs/hep-ph/9704452)
93. Kofman, L., Linde, A.D., Starobinsky, A.A.: Reheating after inflation. *Phys. Rev. Lett.* **73**, 3195–3198 (1994). <https://doi.org/10.1103/PhysRevLett.73.3195>. [arXiv:hep-th/9405187](https://arxiv.org/abs/hep-th/9405187)
94. Amin, M.A., Hertzberg, M.P., Kaiser, D.I., Karouby, J.: Nonperturbative dynamics of reheating after inflation: a review. *Int. J. Mod. Phys. D* **24**, 1530003 (2014). <https://doi.org/10.1142/S0218271815300037>. [arXiv:1410.3808](https://arxiv.org/abs/1410.3808) [hep-ph]
95. Adshed, P., Giblin, J.T., Pieroni, M., Weiner, Z.J.: Constraining axion inflation with gravitational waves from preheating. *Phys. Rev. D* **101**(8), 083534 (2020). <https://doi.org/10.1103/PhysRevD.101.083534>. [arXiv:1909.12842](https://arxiv.org/abs/1909.12842) [astro-ph.CO]
96. Adshed, P., Giblin, J.T., Weiner, Z.J.: Gravitational waves from gauge preheating. *Phys. Rev. D* **98**(4), 043525 (2018). <https://doi.org/10.1103/PhysRevD.98.043525>. [arXiv:1805.04550](https://arxiv.org/abs/1805.04550) [astro-ph.CO]
97. Zhou, S.-Y., Copeland, E.J., Easter, R., Finkel, H., Mou, Z.-G., Saffin, P.M.: Gravitational waves from oscillon preheating. *JHEP* **10**, 026 (2013). [https://doi.org/10.1007/JHEP10\(2013\)026](https://doi.org/10.1007/JHEP10(2013)026). [arXiv:1304.6094](https://arxiv.org/abs/1304.6094) [astro-ph.CO]
98. Lozanov, K.D., Amin, M.A.: Gravitational perturbations from oscillons and transients after inflation. *Phys. Rev. D* **99**(12), 123504 (2019). <https://doi.org/10.1103/PhysRevD.99.123504>. [arXiv:1902.06736](https://arxiv.org/abs/1902.06736) [astro-ph.CO]

99. Antusch, S., Cefala, F., Orani, S.: Gravitational waves from oscillons after inflation. *Phys. Rev. Lett.* **118**(1), 011303 (2017). <https://doi.org/10.1103/PhysRevLett.118.011303>. arXiv:1902.06736 [astro-ph.CO]. [Erratum: *Phys. Rev. Lett.* **120**, 219901 (2018)]
100. Amin, M.A., Braden, J., Copeland, E.J., Giblin, J.T., Solorio, C., Weiner, Z.J., Zhou, S.-Y.: Gravitational waves from asymmetric oscillon dynamics? *Phys. Rev. D* **98**, 024040 (2018). <https://doi.org/10.1103/PhysRevD.98.024040>. arXiv:1803.08047 [astro-ph.CO]
101. Hiramatsu, T., Sfakianakis, E.I., Yamaguchi, M.: Gravitational wave spectra from oscillon formation after inflation. *JHEP* **03**, 021 (2021). [https://doi.org/10.1007/JHEP03\(2021\)021](https://doi.org/10.1007/JHEP03(2021)021). arXiv:2011.12201 [hep-ph]
102. Kou, X.-X., Mertens, J.B., Tian, C., Zhou, S.-Y.: Gravitational Waves from Fully General Relativistic Oscillon Preheating (2021) arXiv:2112.07626 [gr-qc]
103. Garcia-Bellido, J., Figueroa, D.G.: A stochastic background of gravitational waves from hybrid preheating. *Phys. Rev. Lett.* **98**, 061302 (2007). <https://doi.org/10.1103/PhysRevLett.98.061302>. arXiv:astro-ph/0701014
104. Garcia-Bellido, J., Figueroa, D.G., Sastre, A.: A Gravitational Wave Background from Reheating after Hybrid Inflation. *Phys. Rev. D* **77**, 043517 (2008). <https://doi.org/10.1103/PhysRevD.77.043517>. arXiv:0707.0839 [hep-ph]
105. Dufaux, J.-F., Figueroa, D.G., Garcia-Bellido, J.: Gravitational waves from abelian gauge fields and cosmic strings at preheating. *Phys. Rev. D* **82**, 083518 (2010). <https://doi.org/10.1103/PhysRevD.82.083518>. arXiv:1006.0217 [astro-ph.CO]
106. Berlin, A., Blas, D., Tito D' Agnolo, R., Ellis, S.A.R., Harnik, R., Kahn, Y., Schütte-Engel, J.: Detecting High-Frequency Gravitational Waves with Microwave Cavities (2021) arXiv:2112.11465 [hep-ph]
107. Domcke, V., Garcia-Cely, C., Rodd, N.L.: A novel search for high-frequency gravitational waves with low-mass axion haloscopes (2022) arXiv:2202.00695 [hep-ph]
108. Berlin, A., et al.: Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities (2022) arXiv:2203.12714 [hep-ph]
109. Cui, Y., Sfakianakis, E.I.: Detectable Gravitational Wave Signals from Inflationary Preheating (2021) arXiv:2112.00762 [hep-ph]
110. Haque, M.R., Maity, D., Paul, T., Sriramkumar, L.: Decoding the phases of early and late time reheating through imprints on primordial gravitational waves. *Phys. Rev. D* **104**(6), 063513 (2021). <https://doi.org/10.1103/PhysRevD.104.063513>. arXiv:2105.09242 [astro-ph.CO]
111. Ramsey-Musolf, M.J.: The electroweak phase transition: a collider target. *JHEP* **09**, 179 (2020). [https://doi.org/10.1007/JHEP09\(2020\)179](https://doi.org/10.1007/JHEP09(2020)179). arXiv:1912.07189 [hep-ph]
112. Profumo, S., Ramsey-Musolf, M.J., Shaughnessy, G.: Singlet Higgs phenomenology and the electroweak phase transition. *JHEP* **08**, 010 (2007). <https://doi.org/10.1088/1126-6708/2007/08/010>. arXiv:0705.2425 [hep-ph]
113. Delaunay, C., Grojean, C., Wells, J.D.: Dynamics of non-renormalizable electroweak symmetry breaking. *JHEP* **04**, 029 (2008). <https://doi.org/10.1088/1126-6708/2008/04/029>. arXiv:0711.2511 [hep-ph]
114. Huang, P., Long, A.J., Wang, L.-T.: Probing the electroweak phase transition with higgs factories and gravitational waves. *Phys. Rev. D* **94**(7), 075008 (2016). <https://doi.org/10.1103/PhysRevD.94.075008>. arXiv:1608.06619 [hep-ph]
115. Chala, M., Krause, C., Nardini, G.: Signals of the electroweak phase transition at colliders and gravitational wave observatories. *JHEP* **07**, 062 (2018). [https://doi.org/10.1007/JHEP07\(2018\)062](https://doi.org/10.1007/JHEP07(2018)062). arXiv:1802.02168 [hep-ph]
116. Croon, D., Gould, O., Schicho, P., Tenkanen, T.V.I., White, G.: Theoretical uncertainties for cosmological first-order phase transitions. *JHEP* **04**, 055 (2021). [https://doi.org/10.1007/JHEP04\(2021\)055](https://doi.org/10.1007/JHEP04(2021)055). arXiv:2009.10080 [hep-ph]
117. Grojean, C., Servant, G.: Gravitational waves from phase transitions at the electroweak scale and beyond. *Phys. Rev. D* **75**, 043507 (2007). <https://doi.org/10.1103/PhysRevD.75.043507>. arXiv:hep-ph/0607107
118. Alves, A., Ghosh, T., Guo, H.-K., Sinha, K., Vagie, D.: Collider and gravitational wave complementarity in exploring the singlet extension of the standard model. *JHEP* **04**, 052 (2019). [https://doi.org/10.1007/JHEP04\(2019\)052](https://doi.org/10.1007/JHEP04(2019)052). arXiv:1812.09333 [hep-ph]
119. Alves, A., Gonçalves, D., Ghosh, T., Guo, H.-K., Sinha, K.: Di-Higgs blind spots in gravitational wave signals. *Phys. Lett. B* **818**, 136377 (2021). <https://doi.org/10.1016/j.physletb.2021.136377>. arXiv:2007.15654 [hep-ph]



120. Vaskonen, V.: Electroweak baryogenesis and gravitational waves from a real scalar singlet. *Phys. Rev. D* **95**(12), 123515 (2017). <https://doi.org/10.1103/PhysRevD.95.123515>. arXiv:1611.02073 [hep-ph]
121. Dorsch, G.C., Huber, S.J., Konstandin, T., No, J.M.: A second higgs doublet in the early universe: baryogenesis and gravitational waves. *JCAP* **05**, 052 (2017). <https://doi.org/10.1088/1475-7516/2017/05/052>. arXiv:1611.05874 [hep-ph]
122. Chao, W., Guo, H.-K., Shu, J.: Gravitational wave signals of electroweak phase transition triggered by dark matter. *JCAP* **09**, 009 (2017). <https://doi.org/10.1088/1475-7516/2017/09/009>. arXiv:1702.02698 [hep-ph]
123. Wang, X., Huang, F.P., Zhang, X.: Gravitational wave and collider signals in complex two-Higgs doublet model with dynamical CP-violation at finite temperature. *Phys. Rev. D* **101**(1), 015015 (2020). <https://doi.org/10.1103/PhysRevD.101.015015>. arXiv:1909.02978 [hep-ph]
124. Demidov, S.V., Gorbunov, D.S., Kirpichnikov, D.V.: Gravitational waves from phase transition in split NMSSM. *Phys. Lett. B* **779**, 191–194 (2018). <https://doi.org/10.1016/j.physletb.2018.02.007>. arXiv:1712.00087 [hep-ph]
125. Ahriche, A., Hashino, K., Kanemura, S., Nasri, S.: Gravitational waves from phase transitions in models with charged singlets. *Phys. Lett. B* **789**, 119–126 (2019). <https://doi.org/10.1016/j.physletb.2018.12.013>. arXiv:1809.09883 [hep-ph]
126. Huang, F.P., Yu, J.-H.: Exploring inert dark matter blind spots with gravitational wave signatures. *Phys. Rev. D* **98**(9), 095022 (2018). <https://doi.org/10.1103/PhysRevD.98.095022>. arXiv:1704.04201 [hep-ph]
127. Mohamadnejad, A.: Gravitational waves from scale-invariant vector dark matter model: probing below the neutrino-floor. *Eur. Phys. J. C* **80**(3), 197 (2020). <https://doi.org/10.1140/epjc/s10052-020-7756-6>. arXiv:1907.08899 [hep-ph]
128. Baldes, I., Servant, G.: High scale electroweak phase transition: baryogenesis & symmetry non-restoration. *JHEP* **10**, 053 (2018). [https://doi.org/10.1007/JHEP10\(2018\)053](https://doi.org/10.1007/JHEP10(2018)053). arXiv:1807.08770 [hep-ph]
129. Huang, F.P., Qian, Z., Zhang, M.: Exploring dynamical CP violation induced baryogenesis by gravitational waves and colliders. *Phys. Rev. D* **98**(1), 015014 (2018). <https://doi.org/10.1103/PhysRevD.98.015014>. arXiv:1804.06813 [hep-ph]
130. Ellis, S.A.R., Ipek, S., White, G.: Electroweak baryogenesis from temperature-varying couplings. *JHEP* **08**, 002 (2019). [https://doi.org/10.1007/JHEP08\(2019\)002](https://doi.org/10.1007/JHEP08(2019)002). arXiv:1905.11994 [hep-ph]
131. Alves, A., Ghosh, T., Guo, H.-K., Sinha, K.: Resonant di-higgs production at gravitational wave benchmarks: a collider study using machine learning. *JHEP* **12**, 070 (2018). [https://doi.org/10.1007/JHEP12\(2018\)070](https://doi.org/10.1007/JHEP12(2018)070). arXiv:1808.08974 [hep-ph]
132. Alves, A., Gonçalves, D., Ghosh, T., Guo, H.-K., Sinha, K.: Di-higgs production in the  $4b$  channel and gravitational wave complementarity. *JHEP* **03**, 053 (2020). [https://doi.org/10.1007/JHEP03\(2020\)053](https://doi.org/10.1007/JHEP03(2020)053). arXiv:1909.05268 [hep-ph]
133. Cline, J.M., Friedlander, A., He, D.-M., Kainulainen, K., Laurent, B., Tucker-Smith, D.: Baryogenesis and gravity waves from a UV-completed electroweak phase transition. *Phys. Rev. D* **103**(12), 123529 (2021). <https://doi.org/10.1103/PhysRevD.103.123529>. arXiv:2102.12490 [hep-ph]
134. Chao, W., Guo, H.-K., Li, X.-F.: First Order Color Symmetry Breaking and Restoration Triggered by Electroweak Symmetry Non-restoration (2021) arXiv:2112.13580 [hep-ph]
135. Liu, J., Wang, X.-P., Xie, K.-P.: Searching for lepton portal dark matter with colliders and gravitational waves. *JHEP* **06**, 149 (2021). [https://doi.org/10.1007/JHEP06\(2021\)149](https://doi.org/10.1007/JHEP06(2021)149). arXiv:2104.06421 [hep-ph]
136. Zhang, Z., Cai, C., Jiang, X.-M., Tang, Y.-L., Yu, Z.-H., Zhang, H.-H.: Phase transition gravitational waves from pseudo-Nambu-Goldstone dark matter and two Higgs doublets. *JHEP* **05**, 160 (2021). [https://doi.org/10.1007/JHEP05\(2021\)160](https://doi.org/10.1007/JHEP05(2021)160). arXiv:2102.01588 [hep-ph]
137. Cai, R.-G., Hashino, K., Wang, S.-J., Yu, J.-H.: Gravitational waves from patterns of electroweak symmetry breaking: an effective perspective (2022) arXiv:2202.08295 [hep-ph]
138. Liu, J., Wang, X.-P., Xie, K.-P.: Scalar-mediated dark matter model at colliders and gravitational wave detectors—a white paper for snowmass 2021. In: 2022 Snowmass Summer Study (2022) arXiv:2203.10046 [hep-ph]
139. Schwarz, D.J., Stuke, M.: Lepton asymmetry and the cosmic QCD transition. *JCAP* **11**, 025 (2009). <https://doi.org/10.1088/1475-7516/2009/11/025>. arXiv:0906.3434 [hep-ph]. [Erratum: *JCAP* **10**, E01 (2010)]
140. Middeldorf-Wygas, M.M., Oldengott, I.M., Bödeker, D., Schwarz, D.J.: The cosmic QCD transition for large lepton flavour asymmetries (2020) arXiv:2009.00036 [hep-ph]

141. Caprini, C., Durrer, R., Siemens, X.: Detection of gravitational waves from the QCD phase transition with pulsar timing arrays. *Phys. Rev. D* **82**, 063511 (2010). <https://doi.org/10.1103/PhysRevD.82.063511>. arXiv:1007.1218 [astro-ph.CO]
142. von Harling, B., Servant, G.: QCD-induced electroweak phase transition. *JHEP* **01**, 159 (2018). [https://doi.org/10.1007/JHEP01\(2018\)159](https://doi.org/10.1007/JHEP01(2018)159). arXiv:1711.11554 [hep-ph]
143. Weinberg, S.: Gauge and global symmetries at high temperature. *Phys. Rev. D* **9**, 3357–3378 (1974). <https://doi.org/10.1103/PhysRevD.9.3357>
144. Land, D., Carlson, E.D.: Two stage phase transition in two Higgs models. *Phys. Lett. B* **292**, 107–112 (1992). [https://doi.org/10.1016/0370-2693\(92\)90616-C](https://doi.org/10.1016/0370-2693(92)90616-C). arXiv:hep-ph/9208227
145. Patel, H.H., Ramsey-Musolf, M.J.: Stepping into electroweak symmetry breaking: phase transitions and higgs phenomenology. *Phys. Rev. D* **88**, 035013 (2013). <https://doi.org/10.1103/PhysRevD.88.035013>. arXiv:1212.5652 [hep-ph]
146. Patel, H.H., Ramsey-Musolf, M.J., Wise, M.B.: Color breaking in the early universe. *Phys. Rev. D* **88**(1), 015003 (2013). <https://doi.org/10.1103/PhysRevD.88.015003>. arXiv:1303.1140 [hep-ph]
147. Blinov, N., Kozaczuk, J., Morrissey, D.E., Tamarit, C.: Electroweak baryogenesis from exotic electroweak symmetry breaking. *Phys. Rev. D* **92**(3), 035012 (2015). <https://doi.org/10.1103/PhysRevD.92.035012>. arXiv:1504.05195 [hep-ph]
148. Niemi, L., Patel, H.H., Ramsey-Musolf, M.J., Tenkanen, T.V.I., Weir, D.J.: Electroweak phase transition in the real triplet extension of the SM: Dimensional reduction. *Phys. Rev. D* **100**(3), 035002 (2019). <https://doi.org/10.1103/PhysRevD.100.035002>. arXiv:1802.10500 [hep-ph]
149. Croon, D., White, G.: Exotic gravitational wave signatures from simultaneous phase transitions. *JHEP* **05**, 210 (2018). [https://doi.org/10.1007/JHEP05\(2018\)210](https://doi.org/10.1007/JHEP05(2018)210). arXiv:1803.05438 [hep-ph]
150. Morais, A.P., Pasechnik, R., Vieu, T.: Multi-peaked signatures of primordial gravitational waves from multi-step electroweak phase transition. *PoS EPS-HEP2019*, 054 (2020). <https://doi.org/10.22323/1.364.0054>. arXiv:1802.10109 [hep-ph]
151. Morais, A.P., Pasechnik, R.: Probing multi-step electroweak phase transition with multi-peaked primordial gravitational waves spectra. *JCAP* **04**, 036 (2020). <https://doi.org/10.1088/1475-7516/2020/04/036>. arXiv:1910.00717 [hep-ph]
152. Angelescu, A., Huang, P.: Multistep Strongly First Order Phase Transitions from New Fermions at the TeV Scale. *Phys. Rev. D* **99**(5), 055023 (2019). <https://doi.org/10.1103/PhysRevD.99.055023>. arXiv:1812.08293 [hep-ph]
153. Friedrich, L., Ramsey-Musolf, M.J., Tenkanen, T.V.I., Tran, V.Q.: Addressing the Gravitational Wave-Collider Inverse Problem. arXiv e-prints (2022) arXiv:2203.05889 [hep-ph]
154. Jinno, R., Takimoto, M.: Probing a classically conformal B-L model with gravitational waves. *Phys. Rev. D* **95**(1), 015020 (2017). <https://doi.org/10.1103/PhysRevD.95.015020>. arXiv:1604.05035 [hep-ph]
155. Chao, W., Cui, W.-F., Guo, H.-K., Shu, J.: Gravitational wave imprint of new symmetry breaking. *Chin. Phys. C* **44**(12), 123102 (2020). <https://doi.org/10.1088/1674-1137/abb4cb>. arXiv:1707.09759 [hep-ph]
156. Brdar, V., Helmboldt, A.J., Kubo, J.: Gravitational Waves from First-Order Phase Transitions: LIGO as a Window to Unexplored Seesaw Scales. *JCAP* **02**, 021 (2019). <https://doi.org/10.1088/1475-7516/2019/02/021>. arXiv:1810.12306 [hep-ph]
157. Okada, N., Seto, O.: Probing the seesaw scale with gravitational waves. *Phys. Rev. D* **98**(6), 063532 (2018). <https://doi.org/10.1103/PhysRevD.98.063532>. arXiv:1807.00336 [hep-ph]
158. Marzo, C., Marzola, L., Vaskonen, V.: Phase transition and vacuum stability in the classically conformal B-L model. *Eur. Phys. J. C* **79**(7), 601 (2019). <https://doi.org/10.1140/epjc/s10052-019-7076-x>. arXiv:1811.11169 [hep-ph]
159. Bian, L., Cheng, W., Guo, H.-K., Zhang, Y.: Cosmological implications of a  $B - L$  charged hidden scalar: leptogenesis and gravitational waves. *Chin. Phys. C* **45**(11), 113104 (2021). <https://doi.org/10.1088/1674-1137/ac1e09>. arXiv:1907.13589 [hep-ph]
160. Hasegawa, T., Okada, N., Seto, O.: Gravitational waves from the minimal gauged  $U(1)_{B-L}$  model. *Phys. Rev. D* **99**(9), 095039 (2019). <https://doi.org/10.1103/PhysRevD.99.095039>. arXiv:1904.03020 [hep-ph]
161. Okada, N., Seto, O., Uchida, H.: Gravitational waves from breaking of an extra  $U(1)$  in  $SO(10)$  grand unification. *PTEP* **2021**(3), 033–100 (2021). <https://doi.org/10.1093/ptep/ptab003>. arXiv:2006.01406 [hep-ph]

162. Fornal, B., Shams Es Haghi, B.: Baryon and Lepton Number Violation from Gravitational Waves. *Phys. Rev. D* **102**(11), 115037 (2020). <https://doi.org/10.1103/PhysRevD.102.115037>. [arXiv:2008.05111](https://arxiv.org/abs/2008.05111) [hep-ph]
163. Greljo, A., Opferkuch, T., Stefanek, B.A.: Gravitational imprints of flavor hierarchies. *Phys. Rev. Lett.* **124**(17), 171802 (2020). <https://doi.org/10.1103/PhysRevLett.124.171802>. [arXiv:1910.02014](https://arxiv.org/abs/1910.02014) [hep-ph]
164. Fornal, B.: Gravitational wave signatures of lepton universality violation. *Phys. Rev. D* **103**(1), 015018 (2021). <https://doi.org/10.1103/PhysRevD.103.015018>. [arXiv:2006.08802](https://arxiv.org/abs/2006.08802) [hep-ph]
165. Dev, P.S.B., Ferrer, F., Zhang, Y., Zhang, Y.: Gravitational waves from first-order phase transition in a simple axion-like particle model. *JCAP* **11**, 006 (2019). <https://doi.org/10.1088/1475-7516/2019/11/006>. [arXiv:1905.00891](https://arxiv.org/abs/1905.00891) [hep-ph]
166. Von Harling, B., Pomarol, A., Pujolàs, O., Rompineve, F.: Peccei-quinn phase transition at LIGO. *JHEP* **04**, 195 (2020). [https://doi.org/10.1007/JHEP04\(2020\)195](https://doi.org/10.1007/JHEP04(2020)195). [arXiv:1912.07587](https://arxiv.org/abs/1912.07587) [hep-ph]
167. Hashino, K., Kakizaki, M., Kanemura, S., Ko, P., Matsui, T.: Gravitational waves from first order electroweak phase transition in models with the  $U(1)_X$  gauge symmetry. *JHEP* **06**, 088 (2018). [https://doi.org/10.1007/JHEP06\(2018\)088](https://doi.org/10.1007/JHEP06(2018)088). [arXiv:1802.02947](https://arxiv.org/abs/1802.02947) [hep-ph]
168. Huang, F.P., Zhang, X.: Probing the gauge symmetry breaking of the early universe in 3–3–1 models and beyond by gravitational waves. *Phys. Lett. B* **788**, 288–294 (2019). <https://doi.org/10.1016/j.physletb.2018.11.024>. [arXiv:1701.04338](https://arxiv.org/abs/1701.04338) [hep-ph]
169. Croon, D., Gonzalo, T.E., White, G.: Gravitational Waves from a Pati-Salam Phase Transition. *JHEP* **02**, 083 (2019). [https://doi.org/10.1007/JHEP02\(2019\)083](https://doi.org/10.1007/JHEP02(2019)083). [arXiv:1812.02747](https://arxiv.org/abs/1812.02747) [hep-ph]
170. Brdar, V., Graf, L., Helmbold, A.J., Xu, X.-J.: Gravitational Waves as a Probe of Left-Right Symmetry Breaking. *JCAP* **12**, 027 (2019). <https://doi.org/10.1088/1475-7516/2019/12/027>. [arXiv:1909.02018](https://arxiv.org/abs/1909.02018) [hep-ph]
171. Huang, W.-C., Sannino, F., Wang, Z.-W.: Gravitational Waves from Pati-Salam Dynamics. *Phys. Rev. D* **102**(9), 095025 (2020). <https://doi.org/10.1103/PhysRevD.102.095025>. [arXiv:2004.02332](https://arxiv.org/abs/2004.02332) [hep-ph]
172. Fornal, B., Shams Es Haghi, B., Yu, J.-H., Zhao, Y.: Gravitational Waves from Mini-Split SUSY. *Phys. Rev. D* **104**, 115005 (2021) [arXiv:2104.00747](https://arxiv.org/abs/2104.00747) [hep-ph]. <https://doi.org/10.1103/PhysRevD.104.115005>
173. Craig, N., Levi, N., Mariotti, A., Redigolo, D.: Ripples in spacetime from broken supersymmetry. *JHEP* **21**, 184 (2020). [https://doi.org/10.1007/JHEP02\(2021\)184](https://doi.org/10.1007/JHEP02(2021)184). [arXiv:2011.13949](https://arxiv.org/abs/2011.13949) [hep-ph]
174. Apreda, R., Maggione, M., Nicolis, A., Riotto, A.: Gravitational waves from electroweak phase transitions. *Nucl. Phys. B* **631**, 342–368 (2002). [https://doi.org/10.1016/S0550-3213\(02\)00264-X](https://doi.org/10.1016/S0550-3213(02)00264-X). [arXiv:gr-qc/0107033](https://arxiv.org/abs/gr-qc/0107033)
175. Bian, L., Guo, H.-K., Shu, J.: Gravitational Waves, baryon asymmetry of the universe and electric dipole moment in the CP-violating NMSSM. *Chin. Phys. C* **42**(9), 093106 (2018) [arXiv:1704.02488](https://arxiv.org/abs/1704.02488) [hep-ph]. <https://doi.org/10.1088/1674-1137/42/9/093106>. [Erratum: *Chin.Phys.C* 43, 129101 (2019)]
176. Schwaller, P.: Gravitational waves from a dark phase transition. *Phys. Rev. Lett.* **115**(18), 181101 (2015). <https://doi.org/10.1103/PhysRevLett.115.181101>. [arXiv:1504.07263](https://arxiv.org/abs/1504.07263) [hep-ph]
177. Baldes, I., Garcia-Cely, C.: Strong gravitational radiation from a simple dark matter model. *JHEP* **05**, 190 (2019). [https://doi.org/10.1007/JHEP05\(2019\)190](https://doi.org/10.1007/JHEP05(2019)190). [arXiv:1809.01198](https://arxiv.org/abs/1809.01198) [hep-ph]
178. Breitbach, M., Kopp, J., Madge, E., Opferkuch, T., Schwaller, P.: Dark, cold, and noisy: constraining secluded hidden sectors with gravitational waves. *JCAP* **07**, 007 (2019). <https://doi.org/10.1088/1475-7516/2019/07/007>. [arXiv:1811.11175](https://arxiv.org/abs/1811.11175) [hep-ph]
179. Croon, D., Sanz, V., White, G.: Model discrimination in gravitational wave spectra from dark phase transitions. *JHEP* **08**, 203 (2018). [https://doi.org/10.1007/JHEP08\(2018\)203](https://doi.org/10.1007/JHEP08(2018)203). [arXiv:1806.02332](https://arxiv.org/abs/1806.02332) [hep-ph]
180. Hall, E., Konstandin, T., McGehee, R., Murayama, H., Servant, G.: Baryogenesis from a dark first-order phase transition. *JHEP* **04**, 042 (2020). [https://doi.org/10.1007/JHEP04\(2020\)042](https://doi.org/10.1007/JHEP04(2020)042). [arXiv:1910.08068](https://arxiv.org/abs/1910.08068) [hep-ph]
181. Baldes, I.: Gravitational waves from the asymmetric-dark-matter generating phase transition. *JCAP* **05**, 028 (2017). <https://doi.org/10.1088/1475-7516/2017/05/028>. [arXiv:1702.02117](https://arxiv.org/abs/1702.02117) [hep-ph]
182. Croon, D., Kusenko, A., Mazumdar, A., White, G.: Solitosynthesis and gravitational waves. *Phys. Rev. D* **101**(8), 085010 (2020). <https://doi.org/10.1103/PhysRevD.101.085010>. [arXiv:1910.09562](https://arxiv.org/abs/1910.09562) [hep-ph]

183. Hall, E., Konstandin, T., McGehee, R., Murayama, H.: Asymmetric matters from a dark first-order phase transition (2019) [arXiv:1911.12342](https://arxiv.org/abs/1911.12342) [hep-ph]
184. Chao, W., Li, X.-F., Wang, L.: Filtered pseudo-scalar dark matter and gravitational waves from first order phase transition. *JCAP* **06**, 038 (2021). <https://doi.org/10.1088/1475-7516/2021/06/038>. [arXiv:2012.15113](https://arxiv.org/abs/2012.15113) [hep-ph]
185. Dent, J.B., Dutta, B., Ghosh, S., Kumar, J., Runburg, J.: Sensitivity to Dark Sector Scales from Gravitational Wave Signatures (2022) [arXiv:2203.11736](https://arxiv.org/abs/2203.11736) [hep-ph]
186. Li, M., Yan, Q.-S., Zhang, Y., Zhao, Z.: Prospects of gravitational waves in the minimal left-right symmetric model. *JHEP* **03**, 267 (2021). [https://doi.org/10.1007/JHEP03\(2021\)267](https://doi.org/10.1007/JHEP03(2021)267). [arXiv:2012.13686](https://arxiv.org/abs/2012.13686) [hep-ph]
187. Di Bari, P., Marfatia, D., Zhou, Y.-L.: Gravitational waves from first-order phase transitions in Majoron models of neutrino mass. *JHEP* **10**, 193 (2021). [https://doi.org/10.1007/JHEP10\(2021\)193](https://doi.org/10.1007/JHEP10(2021)193). [arXiv:2106.00025](https://arxiv.org/abs/2106.00025) [hep-ph]
188. Zhou, R., Bian, L., Du, Y.: Electroweak Phase Transition and Gravitational Waves in the Type-II Seesaw Model (2022) [arXiv:2203.01561](https://arxiv.org/abs/2203.01561) [hep-ph]
189. Helmboldt, A.J., Kubo, J., van der Woude, S.: Observational prospects for gravitational waves from hidden or dark chiral phase transitions. *Phys. Rev. D* **100**(5), 055025 (2019). <https://doi.org/10.1103/PhysRevD.100.055025>. [arXiv:1904.07891](https://arxiv.org/abs/1904.07891) [hep-ph]
190. Aoki, M., Kubo, J.: Gravitational waves from chiral phase transition in a conformally extended standard model. *JCAP* **04**, 001 (2020). <https://doi.org/10.1088/1475-7516/2020/04/001>. [arXiv:1910.05025](https://arxiv.org/abs/1910.05025) [hep-ph]
191. Croon, D., Howard, J.N., Ipek, S., Tait, T.M.P.: QCD baryogenesis. *Phys. Rev. D* **101**(5), 055042 (2020). <https://doi.org/10.1103/PhysRevD.101.055042>. [arXiv:1911.01432](https://arxiv.org/abs/1911.01432) [hep-ph]
192. Croon, D., Houtz, R., Sanz, V.: Dynamical axions and gravitational waves. *JHEP* **07**, 146 (2019). [https://doi.org/10.1007/JHEP07\(2019\)146](https://doi.org/10.1007/JHEP07(2019)146). [arXiv:1904.10967](https://arxiv.org/abs/1904.10967) [hep-ph]
193. Garcia-Bellido, J., Murayama, H., White, G.: Exploring the early Universe with Gaia and Theia. *JCAP* **12**(12), 023 (2021). <https://doi.org/10.1088/1475-7516/2021/12/023>. [arXiv:2104.04778](https://arxiv.org/abs/2104.04778) [hep-ph]
194. Huang, W.-C., Reichert, M., Sannino, F., Wang, Z.-W.: Testing the dark SU(N) Yang-Mills theory confined landscape: From the lattice to gravitational waves. *Phys. Rev. D* **104**(3), 035005 (2021). <https://doi.org/10.1103/PhysRevD.104.035005>. [arXiv:2012.11614](https://arxiv.org/abs/2012.11614) [hep-ph]
195. Halverson, J., Long, C., Maiti, A., Nelson, B., Salinas, G.: Gravitational waves from dark Yang-Mills sectors. *JHEP* **05**, 154 (2021). [https://doi.org/10.1007/JHEP05\(2021\)154](https://doi.org/10.1007/JHEP05(2021)154). [arXiv:2012.04071](https://arxiv.org/abs/2012.04071) [hep-ph]
196. Kang, Z., Matsuzaki, S., Zhu, J.: Dark confinement-deconfinement phase transition: a roadmap from Polyakov loop models to gravitational waves. *JHEP* **09**, 060 (2021). [https://doi.org/10.1007/JHEP09\(2021\)060](https://doi.org/10.1007/JHEP09(2021)060). [arXiv:2101.03795](https://arxiv.org/abs/2101.03795) [hep-ph]
197. Kosowsky, A., Turner, M.S., Watkins, R.: Gravitational radiation from colliding vacuum bubbles. *Phys. Rev. D* **45**, 4514–4535 (1992). <https://doi.org/10.1103/PhysRevD.45.4514>
198. Kosowsky, A., Turner, M.S.: Gravitational radiation from colliding vacuum bubbles: envelope approximation to many bubble collisions. *Phys. Rev. D* **47**, 4372–4391 (1993). <https://doi.org/10.1103/PhysRevD.47.4372>. [arXiv:astro-ph/9211004](https://arxiv.org/abs/astro-ph/9211004)
199. Huber, S.J., Konstandin, T.: Gravitational wave production by collisions: more bubbles. *JCAP* **09**, 022 (2008). <https://doi.org/10.1088/1475-7516/2008/09/022>. [arXiv:0806.1828](https://arxiv.org/abs/0806.1828) [hep-ph]
200. Jinno, R., Takimoto, M.: Gravitational waves from bubble collisions: an analytic derivation. *Phys. Rev. D* **95**(2), 024009 (2017). <https://doi.org/10.1103/PhysRevD.95.024009>. [arXiv:1605.01403](https://arxiv.org/abs/1605.01403) [astro-ph.CO]
201. Kamionkowski, M., Kosowsky, A., Turner, M.S.: Gravitational radiation from first order phase transitions. *Phys. Rev. D* **49**, 2837–2851 (1994). <https://doi.org/10.1103/PhysRevD.49.2837>. [arXiv:astro-ph/9310044](https://arxiv.org/abs/astro-ph/9310044)
202. Hindmarsh, M., Huber, S.J., Rummukainen, K., Weir, D.J.: Numerical simulations of acoustically generated gravitational waves at a first order phase transition. *Phys. Rev. D* **92**(12), 123009 (2015). <https://doi.org/10.1103/PhysRevD.92.123009>. [arXiv:1504.03291](https://arxiv.org/abs/1504.03291) [astro-ph.CO]
203. Cutting, D., Hindmarsh, M., Weir, D.J.: Vorticity, kinetic energy, and suppressed gravitational wave production in strong first order phase transitions. *Phys. Rev. Lett.* **125**(2), 021302 (2020). <https://doi.org/10.1103/PhysRevLett.125.021302>. [arXiv:1906.00480](https://arxiv.org/abs/1906.00480) [hep-ph]

204. Hindmarsh, M., Huber, S.J., Rummukainen, K., Weir, D.J.: Gravitational waves from the sound of a first order phase transition. *Phys. Rev. Lett.* **112**, 041301 (2014). <https://doi.org/10.1103/PhysRevLett.112.041301>. arXiv:1304.2433 [hep-ph]
205. Caprini, C., et al.: Science with the space-based interferometer eLISA, II: gravitational waves from cosmological phase transitions. *JCAP* **04**, 001 (2016). <https://doi.org/10.1088/1475-7516/2016/04/001>. arXiv:1512.06239 [astro-ph.CO]
206. Pen, U.-L., Turok, N.: Shocks in the early universe. *Phys. Rev. Lett.* **117**(13), 131301 (2016). <https://doi.org/10.1103/PhysRevLett.117.131301>. arXiv:1510.02985 [astro-ph.CO]
207. Caprini, C., Durrer, R., Servant, G.: The stochastic gravitational wave background from turbulence and magnetic fields generated by a first-order phase transition. *JCAP* **12**, 024 (2009). <https://doi.org/10.1088/1475-7516/2009/12/024>. arXiv:0909.0622 [astro-ph.CO]
208. Hindmarsh, M., Huber, S.J., Rummukainen, K., Weir, D.J.: Shape of the acoustic gravitational wave power spectrum from a first order phase transition. *Phys. Rev. D* **96**(10), 103520 (2017). <https://doi.org/10.1103/PhysRevD.96.103520>. arXiv:1704.05871 [astro-ph.CO]. Erratum: *Phys. Rev. D* **101**, 089902 (2020)
209. Hindmarsh, M., Hijazi, M.: Gravitational waves from first order cosmological phase transitions in the Sound Shell Model. *JCAP* **12**, 062 (2019). <https://doi.org/10.1088/1475-7516/2019/12/062>. arXiv:1909.10040 [astro-ph.CO]
210. Niksa, P., Schliederer, M., Sigl, G.: Gravitational waves produced by compressible MHD turbulence from cosmological phase transitions. *Class. Quant. Gravit.* **35**(14), 144001 (2018). <https://doi.org/10.1088/1361-6382/aac89c>. arXiv:1803.02271 [astro-ph.CO]
211. Roper Pol, A., Mandal, S., Brandenburg, A., Kahnishvili, T., Kosowsky, A.: Numerical simulations of gravitational waves from early-universe turbulence. *Phys. Rev. D* **102**(8), 083512 (2020). <https://doi.org/10.1103/PhysRevD.102.083512>. arXiv:1903.08585 [astro-ph.CO]
212. Jinno, R., Konstandin, T., Rubira, H.: A hybrid simulation of gravitational wave production in first-order phase transitions. *JCAP* **04**, 014 (2021). <https://doi.org/10.1088/1475-7516/2021/04/014>. arXiv:2010.00971 [astro-ph.CO]
213. Linde, A.D.: Infrared problem in thermodynamics of the Yang-Mills Gas. *Phys. Lett. B* **96**, 289–292 (1980). [https://doi.org/10.1016/0370-2693\(80\)90769-8](https://doi.org/10.1016/0370-2693(80)90769-8)
214. Laine, M., Meyer, M., Nardini, G.: Thermal phase transition with full 2-loop effective potential. *Nucl. Phys. B* **920**, 565–600 (2017). <https://doi.org/10.1016/j.nuclphysb.2017.04.023>. arXiv:1702.07479 [hep-ph]
215. Gould, O., Tenkanen, T.V.I.: On the perturbative expansion at high temperature and implications for cosmological phase transitions. *JHEP* **06**, 069 (2021). [https://doi.org/10.1007/JHEP06\(2021\)069](https://doi.org/10.1007/JHEP06(2021)069). arXiv:2104.04399 [hep-ph]
216. Kajantie, K., Laine, M., Rummukainen, K., Shaposhnikov, M.E.: Generic rules for high temperature dimensional reduction and their application to the standard model. *Nucl. Phys. B* **458**, 90–136 (1996). [https://doi.org/10.1016/0550-3213\(95\)00549-8](https://doi.org/10.1016/0550-3213(95)00549-8). arXiv:hep-ph/9508379
217. Farakos, K., Kajantie, K., Rummukainen, K., Shaposhnikov, M.E.: 3-d physics and the electroweak phase transition: A Framework for lattice Monte Carlo analysis. *Nucl. Phys. B* **442**, 317–363 (1995). [https://doi.org/10.1016/0550-3213\(95\)80129-4](https://doi.org/10.1016/0550-3213(95)80129-4). arXiv:hep-lat/9412091
218. Curtin, D., Meade, P., Ramani, H.: Thermal Resummation and Phase Transitions. *Eur. Phys. J. C* **78**(9), 787 (2018). <https://doi.org/10.1140/epjc/s10052-018-6268-0>. arXiv:1612.00466 [hep-ph]
219. Croon, D., Hall, E., Murayama, H.: Non-perturbative methods for false vacuum decay (2021) arXiv:2104.10687 [hep-th]
220. Gould, O., Kozaczuk, J., Niemi, L., Ramsey-Musolf, M.J., Tenkanen, T.V.I., Weir, D.J.: Nonperturbative analysis of the gravitational waves from a first-order electroweak phase transition. *Phys. Rev. D* **100**(11), 115024 (2019). <https://doi.org/10.1103/PhysRevD.100.115024>. arXiv:1903.11604 [hep-ph]
221. Niemi, L., Ramsey-Musolf, M.J., Tenkanen, T.V.I., Weir, D.J.: Thermodynamics of a two-step electroweak phase transition. *Phys. Rev. Lett.* **126**(17), 171802 (2021). <https://doi.org/10.1103/PhysRevLett.126.171802>. arXiv:2005.11332 [hep-ph]
222. Ellis, J., Lewicki, M., No, J.M.: On the maximal strength of a first-order electroweak phase transition and its gravitational wave signal. *JCAP* **04**, 003 (2019). <https://doi.org/10.1088/1475-7516/2019/04/003>. arXiv:1809.08242 [hep-ph]
223. Fubini, S.: A new approach to conformal invariant field theories. *Nuovo Cim. A* **34**, 521 (1976). <https://doi.org/10.1007/BF02785664>



224. Coleman, S.R., De Luccia, F.: Gravitational effects on and of vacuum decay. *Phys. Rev. D* **21**, 3305 (1980). <https://doi.org/10.1103/PhysRevD.21.3305>
225. Duncan, M.J., Jensen, L.G.: Exact tunneling solutions in scalar field theory. *Phys. Lett. B* **291**, 109–114 (1992). [https://doi.org/10.1016/0370-2693\(92\)90128-Q](https://doi.org/10.1016/0370-2693(92)90128-Q)
226. Adams, F.C.: General solutions for tunneling of scalar fields with quartic potentials. *Phys. Rev. D* **48**, 2800–2805 (1993). <https://doi.org/10.1103/PhysRevD.48.2800>. [arXiv:hep-ph/9302321](https://arxiv.org/abs/hep-ph/9302321)
227. Dutta, K., Hector, C., Vaudrevange, P.M., Westphal, A.: More exact tunneling solutions in scalar field theory. *Phys. Lett. B* **708**, 309–313 (2012). <https://doi.org/10.1016/j.physletb.2012.01.026>. [arXiv:1110.2380](https://arxiv.org/abs/1110.2380) [hep-th]
228. Aravind, A., Lorschbough, D., Paban, S.: Lower bound for the multifield bounce action. In: *Phys. Rev. D* (2014). <https://doi.org/10.1103/PhysRevD.89.103535>. [arXiv:1401.1230](https://arxiv.org/abs/1401.1230) [hep-th]
229. Espinosa, J.R.: A fresh look at the calculation of tunneling actions. *JCAP* **07**, 036 (2018). <https://doi.org/10.1088/1475-7516/2018/07/036>. [arXiv:1805.03680](https://arxiv.org/abs/1805.03680) [hep-th]
230. Guada, V., Nemeššek, M.: Exact one-loop false vacuum decay rate. *Phys. Rev. D* **102**, 125017 (2020). <https://doi.org/10.1103/PhysRevD.102.125017>. [arXiv:2009.01535](https://arxiv.org/abs/2009.01535) [hep-th]
231. Amariti, A.: Analytic bounces in d dimensions (2020) [arXiv:2009.14102](https://arxiv.org/abs/2009.14102) [hep-th]
232. Konstandin, T., Huber, S.J.: Numerical approach to multi dimensional phase transitions. *JCAP* **06**, 021 (2006). <https://doi.org/10.1088/1475-7516/2006/06/021>. [arXiv:hep-ph/0603081](https://arxiv.org/abs/hep-ph/0603081)
233. Wainwright, C.L.: CosmoTransitions: computing cosmological phase transition temperatures and bubble profiles with multiple fields. *Comput. Phys. Commun.* **183**, 2006–2013 (2012). <https://doi.org/10.1016/j.cpc.2012.04.004>. [arXiv:1109.4189](https://arxiv.org/abs/1109.4189) [hep-ph]
234. Camargo-Molina, J.E., O’Leary, B., Porod, W., Staub, F.: *Vevacious*: a tool for finding the global minima of one-loop effective potentials with many scalars. *Eur. Phys. J. C* **73**(10), 2588 (2013). <https://doi.org/10.1140/epjc/s10052-013-2588-2>. [arXiv:1307.1477](https://arxiv.org/abs/1307.1477) [hep-ph]
235. Masoumi, A., Olum, K.D., Shlaer, B.: Efficient numerical solution to vacuum decay with many fields. *JCAP* **01**, 051 (2017). <https://doi.org/10.1088/1475-7516/2017/01/051>. [arXiv:1610.06594](https://arxiv.org/abs/1610.06594) [gr-qc]
236. Athron, P., Balázs, C., Bardsley, M., Fowlie, A., Harries, D., White, G.: BubbleProfiler: finding the field profile and action for cosmological phase transitions. *Comput. Phys. Commun.* **244**, 448–468 (2019). <https://doi.org/10.1016/j.cpc.2019.05.017>. [arXiv:1901.03714](https://arxiv.org/abs/1901.03714) [hep-ph]
237. Sato, R.: SimpleBounce: a simple package for the false vacuum decay. *Comput. Phys. Commun.* **258**, 107566 (2021). <https://doi.org/10.1016/j.cpc.2020.107566>. [arXiv:1908.10868](https://arxiv.org/abs/1908.10868) [hep-ph]
238. Guada, V., Nemeššek, M., Pintar, M.: FindBounce: package for multi-field bounce actions. *Comput. Phys. Commun.* **256**, 107480 (2020). <https://doi.org/10.1016/j.cpc.2020.107480>. [arXiv:2002.00881](https://arxiv.org/abs/2002.00881) [hep-ph]
239. Langer, J.S.: Statistical theory of the decay of metastable states. *Annals Phys.* **54**, 258–275 (1969). [https://doi.org/10.1016/0003-4916\(69\)90153-5](https://doi.org/10.1016/0003-4916(69)90153-5)
240. Weinberg, E.J.: Vacuum decay in theories with symmetry breaking by radiative corrections. *Phys. Rev. D* **47**, 4614–4627 (1993). <https://doi.org/10.1103/PhysRevD.47.4614>. [arXiv:hep-ph/9211314](https://arxiv.org/abs/hep-ph/9211314)
241. Buchmuller, W., Helbig, T., Walliser, D.: First order phase transitions in scalar electrodynamics. *Nucl. Phys. B* **407**, 387–411 (1993). [https://doi.org/10.1016/0550-3213\(93\)90064-V](https://doi.org/10.1016/0550-3213(93)90064-V)
242. Gleiser, M., Marques, G.C., Ramos, R.O.: On the evaluation of thermal corrections to false vacuum decay rates. *Phys. Rev. D* **48**, 1571–1584 (1993). <https://doi.org/10.1103/PhysRevD.48.1571>. [arXiv:hep-ph/9304234](https://arxiv.org/abs/hep-ph/9304234)
243. Alford, M.G., March-Russell, J.: Radiatively induced first order phase transitions: the necessity of the renormalization group. *Nucl. Phys. B* **417**, 527–552 (1994). [https://doi.org/10.1016/0550-3213\(94\)90483-9](https://doi.org/10.1016/0550-3213(94)90483-9). [arXiv:hep-ph/9308364](https://arxiv.org/abs/hep-ph/9308364)
244. Dupuis, N., Canet, L., Eichhorn, A., Metzner, W., Pawłowski, J.M., Tissier, M., Wschebor, N.: The nonperturbative functional renormalization group and its applications. *Phys. Rept.* **910**, 1–114 (2021). <https://doi.org/10.1016/j.physrep.2021.01.001>. [arXiv:2006.04853](https://arxiv.org/abs/2006.04853) [cond-mat.stat-mech]
245. Affleck, I.: Quantum statistical metastability. *Phys. Rev. Lett.* **46**, 388 (1981). <https://doi.org/10.1103/PhysRevLett.46.388>
246. Linde, A.D.: Decay of the False Vacuum at Finite Temperature. *Nucl. Phys. B* **216**, 421 (1983). [https://doi.org/10.1016/0550-3213\(83\)90072-X](https://doi.org/10.1016/0550-3213(83)90072-X). [Erratum: *Nucl. Phys. B* **223**, 544 (1983)]
247. Arnold, P.B., McLerran, L.D.: Sphalerons, small fluctuations and baryon number violation in electroweak theory. *Phys. Rev. D* **36**, 581 (1987). <https://doi.org/10.1103/PhysRevD.36.581>
248. Csernai, L.P., Kapusta, J.I.: Nucleation of relativistic first order phase transitions. *Phys. Rev. D* **46**, 1379–1390 (1992). <https://doi.org/10.1103/PhysRevD.46.1379>



249. Carrington, M.E., Kapusta, J.I.: Dynamics of the electroweak phase transition. *Phys. Rev. D* **47**, 5304–5315 (1993). <https://doi.org/10.1103/PhysRevD.47.5304>
250. Moore, G.D., Rummukainen, K.: Electroweak bubble nucleation, nonperturbatively. *Phys. Rev. D* **63**, 045002 (2001). <https://doi.org/10.1103/PhysRevD.63.045002>. arXiv:hep-ph/0009132
251. Baaeke, J., Kiselev, V.G.: One loop corrections to the bubble nucleation rate at finite temperature. *Phys. Rev. D* **48**, 5648–5654 (1993). <https://doi.org/10.1103/PhysRevD.48.5648>. arXiv:hep-ph/9308273
252. Brahm, D.E., Lee, C.L.Y.: The exact critical bubble free energy and the effectiveness of effective potential approximations. *Phys. Rev. D* **49**, 4094–4100 (1994). <https://doi.org/10.1103/PhysRevD.49.4094>. arXiv:hep-ph/9311353
253. Surig, A.: Selfconsistent treatment of bubble nucleation at the electroweak phase transition. *Phys. Rev. D* **57**, 5049–5063 (1998). <https://doi.org/10.1103/PhysRevD.57.5049>. arXiv:hep-ph/9706259
254. Konstandin, T., No, J.M.: Hydrodynamic obstruction to bubble expansion. *JCAP* **02**, 008 (2011). <https://doi.org/10.1088/1475-7516/2011/02/008>. arXiv:1011.3735 [hep-ph]
255. Barroso Mancha, M., Prokopec, T., Swiezewska, B.: Field-theoretic derivation of bubble-wall force. *JHEP* **01**, 070 (2021). [https://doi.org/10.1007/JHEP01\(2021\)070](https://doi.org/10.1007/JHEP01(2021)070). arXiv:2005.10875 [hep-th]
256. Balaji, S., Spannowsky, M., Tamarit, C.: Cosmological bubble friction in local equilibrium. *JCAP* **03**, 051 (2021). <https://doi.org/10.1088/1475-7516/2021/03/051>. arXiv:2010.08013 [hep-ph]
257. Ai, W.-Y., Garbrecht, B., Tamarit, C.: Bubble wall velocities in local equilibrium (2021) arXiv:2109.13710 [hep-ph]
258. Bodeker, D., Moore, G.D.: Can electroweak bubble walls run away? *JCAP* **05**, 009 (2009). <https://doi.org/10.1088/1475-7516/2009/05/009>. arXiv:0903.4099 [hep-ph]
259. Bodeker, D., Moore, G.D.: Electroweak bubble wall speed limit. *JCAP* **05**, 025 (2017). <https://doi.org/10.1088/1475-7516/2017/05/025>. arXiv:1703.08215 [hep-ph]
260. Höche, S., Kozaczuk, J., Long, A.J., Turner, J., Wang, Y.: Towards an all-orders calculation of the electroweak bubble wall velocity. *JCAP* **03**, 009 (2021). <https://doi.org/10.1088/1475-7516/2021/03/009>. arXiv:2007.10343 [hep-ph]
261. Gouttenoire, Y., Jinno, R., Sala, F.: Friction pressure on relativistic bubble walls (2021) arXiv:2112.07686 [hep-ph]
262. Azatov, A., Vanvlasselaer, M.: Bubble wall velocity: heavy physics effects. *JCAP* **01**, 058 (2021). <https://doi.org/10.1088/1475-7516/2021/01/058>. arXiv:2010.02590 [hep-ph]
263. Cai, R.-G., Wang, S.-J.: Effective picture of bubble expansion. *JCAP* **03**, 096 (2021). <https://doi.org/10.1088/1475-7516/2021/03/096>. arXiv:2011.11451 [astro-ph.CO]
264. Hindmarsh, M.: Sound shell model for acoustic gravitational wave production at a first-order phase transition in the early Universe. *Phys. Rev. Lett.* **120**(7), 071301 (2018). <https://doi.org/10.1103/PhysRevLett.120.071301>. arXiv:1608.04735 [astro-ph.CO]
265. Espinosa, J.R., Konstandin, T., No, J.M., Servant, G.: Energy budget of cosmological first-order phase transitions. *JCAP* **06**, 028 (2010). <https://doi.org/10.1088/1475-7516/2010/06/028>. arXiv:1004.4187 [hep-ph]
266. Ellis, J., Lewicki, M., No, J.M.: Gravitational waves from first-order cosmological phase transitions: lifetime of the sound wave source. *JCAP* **07**, 050 (2020). <https://doi.org/10.1088/1475-7516/2020/07/050>. arXiv:2003.07360 [hep-ph]
267. Giese, F., Konstandin, T., Schmitz, K., Van De Vis, J.: Model-independent energy budget for LISA. *JCAP* **01**, 072 (2021). <https://doi.org/10.1088/1475-7516/2021/01/072>. arXiv:2010.09744 [astro-ph.CO]
268. Wang, X., Huang, F.P., Zhang, X.: Energy budget and the gravitational wave spectra beyond the bag model. *Phys. Rev. D* **103**(10), 103520 (2021). <https://doi.org/10.1103/PhysRevD.103.103520>. arXiv:2010.13770 [astro-ph.CO]
269. Randall, L., Servant, G.: Gravitational waves from warped spacetime. *JHEP* **05**, 054 (2007). <https://doi.org/10.1088/1126-6708/2007/05/054>. arXiv:hep-ph/0607158
270. Espinosa, J.R., Konstandin, T., No, J.M., Quiros, M.: Some cosmological implications of hidden sectors. *Phys. Rev. D* **78**, 123528 (2008). <https://doi.org/10.1103/PhysRevD.78.123528>. arXiv:0809.3215 [hep-ph]
271. Kosowsky, A., Turner, M.S., Watkins, R.: Gravitational waves from first order cosmological phase transitions. *Phys. Rev. Lett.* **69**, 2026–2029 (1992). <https://doi.org/10.1103/PhysRevLett.69.2026>
272. Jinno, R., Lee, S., Seong, H., Takimoto, M.: Gravitational waves from first-order phase transitions: Towards model separation by bubble nucleation rate. *JCAP* **11**, 050 (2017). <https://doi.org/10.1088/1475-7516/2017/11/050>. arXiv:1708.01253 [hep-ph]

273. Zhong, H., Gong, B., Qiu, T.: Gravitational waves from bubble collisions in FLRW spacetime (2021). [https://doi.org/10.1007/JHEP02\(2022\)077](https://doi.org/10.1007/JHEP02(2022)077)
274. Megevand, A., Membiela, F.A.: Model-independent features of gravitational waves from bubble collisions. *Phys. Rev. D* **104**(12), 123532 (2021). <https://doi.org/10.1103/PhysRevD.104.123532>. [arXiv:2108.07034](https://arxiv.org/abs/2108.07034) [astro-ph.CO]
275. Weir, D.J.: Revisiting the envelope approximation: gravitational waves from bubble collisions. *Phys. Rev. D* **93**(12), 124037 (2016). <https://doi.org/10.1103/PhysRevD.93.124037>. [arXiv:1604.08429](https://arxiv.org/abs/1604.08429) [astro-ph.CO]
276. Cutting, D., Hindmarsh, M., Weir, D.J.: Gravitational waves from vacuum first-order phase transitions: from the envelope to the lattice. *Phys. Rev. D* **97**(12), 123513 (2018). <https://doi.org/10.1103/PhysRevD.97.123513>. [arXiv:1802.05712](https://arxiv.org/abs/1802.05712) [astro-ph.CO]
277. Jinno, R., Konstandin, T., Takimoto, M.: Relativistic bubble collisions—a closer look. *JCAP* **09**, 035 (2019). <https://doi.org/10.1088/1475-7516/2019/09/035>. [arXiv:1906.02588](https://arxiv.org/abs/1906.02588) [hep-ph]
278. Cutting, D., Escartin, E.G., Hindmarsh, M., Weir, D.J.: Gravitational waves from vacuum first order phase transitions II: from thin to thick walls. *Phys. Rev. D* **103**(2), 023531 (2021). <https://doi.org/10.1103/PhysRevD.103.023531>. [arXiv:2005.13537](https://arxiv.org/abs/2005.13537) [astro-ph.CO]
279. Lewicki, M., Vaskonen, V.: Gravitational waves from colliding vacuum bubbles in gauge theories. *Eur. Phys. J. C* **81**(5), 437 (2021). <https://doi.org/10.1140/epjc/s10052-021-09232-3>. [arXiv:2012.07826](https://arxiv.org/abs/2012.07826) [astro-ph.CO]
280. Jinno, R., Takimoto, M.: Gravitational waves from bubble dynamics: beyond the envelope. *JCAP* **01**, 060 (2019). <https://doi.org/10.1088/1475-7516/2019/01/060>. [arXiv:1707.03111](https://arxiv.org/abs/1707.03111) [hep-ph]
281. Konstandin, T.: Gravitational radiation from a bulk flow model. *JCAP* **03**, 047 (2018). <https://doi.org/10.1088/1475-7516/2018/03/047>. [arXiv:1712.06869](https://arxiv.org/abs/1712.06869) [astro-ph.CO]
282. Megevand, A., Membiela, F.A.: Gravitational waves from bubble walls. *JCAP* **10**, 073 (2021). <https://doi.org/10.1088/1475-7516/2021/10/073>. [arXiv:2108.05510](https://arxiv.org/abs/2108.05510) [astro-ph.CO]
283. Jinno, R., Seong, H., Takimoto, M., Um, C.M.: Gravitational waves from first-order phase transitions: Ultra-supercooled transitions and the fate of relativistic shocks. *JCAP* **10**, 033 (2019). <https://doi.org/10.1088/1475-7516/2019/10/033>. [arXiv:1905.00899](https://arxiv.org/abs/1905.00899) [astro-ph.CO]
284. Dahl, J., Hindmarsh, M., Rummukainen, K., Weir, D.: Decay of acoustic turbulence in two dimensions and implications for cosmological gravitational waves (2021) [arXiv:2112.12013](https://arxiv.org/abs/2112.12013) [gr-qc]
285. Kosowsky, A., Mack, A., Kahniashvili, T.: Gravitational radiation from cosmological turbulence. *Phys. Rev. D* **66**, 024030 (2002). <https://doi.org/10.1103/PhysRevD.66.024030>. [arXiv:astro-ph/0111483](https://arxiv.org/abs/astro-ph/0111483)
286. Dolgov, A.D., Grasso, D., Nicolis, A.: Relic backgrounds of gravitational waves from cosmic turbulence. *Phys. Rev. D* **66**, 103505 (2002). <https://doi.org/10.1103/PhysRevD.66.103505>. [arXiv:astro-ph/0206461](https://arxiv.org/abs/astro-ph/0206461)
287. Caprini, C., Durrer, R.: Gravitational waves from stochastic relativistic sources: primordial turbulence and magnetic fields. *Phys. Rev. D* **74**, 063521 (2006). <https://doi.org/10.1103/PhysRevD.74.063521>. [arXiv:astro-ph/0603476](https://arxiv.org/abs/astro-ph/0603476)
288. Gogoberidze, G., Kahniashvili, T., Kosowsky, A.: The spectrum of gravitational radiation from primordial turbulence. *Phys. Rev. D* **76**, 083002 (2007). <https://doi.org/10.1103/PhysRevD.76.083002>. [arXiv:0705.1733](https://arxiv.org/abs/0705.1733) [astro-ph]
289. Kahniashvili, T., Campanelli, L., Gogoberidze, G., Maravin, Y., Ratra, B.: Gravitational radiation from primordial helical inverse cascade MHD turbulence. *Phys. Rev. D* **78**, 123006 (2008). <https://doi.org/10.1103/PhysRevD.78.123006>. [arXiv:0809.1899](https://arxiv.org/abs/0809.1899) [astro-ph]. [Erratum: *Phys. Rev. D* **79**, 109901 (2009)]
290. Kahniashvili, T., Brandenburg, A., Gogoberidze, G., Mandal, S., Roper Pol, A.: Circular polarization of gravitational waves from early-Universe helical turbulence. *Phys. Rev. Res.* **3**(1), 013193 (2021). <https://doi.org/10.1103/PhysRevResearch.3.013193>. [arXiv:2011.05556](https://arxiv.org/abs/2011.05556) [astro-ph.CO]
291. Roper Pol, A., Mandal, S., Brandenburg, A., Kahniashvili, T.: Polarization of gravitational waves from helical MHD turbulent sources (2021) [arXiv:2107.05356](https://arxiv.org/abs/2107.05356) [gr-qc]
292. Roper Pol, A., Caprini, C., Neronov, A., Semikoz, D.: The gravitational wave signal from primordial magnetic fields in the Pulsar Timing Array frequency band (2022) [arXiv:2201.05630](https://arxiv.org/abs/2201.05630) [astro-ph.CO]
293. Arzoumanian, Z., *et al.*: Searching for Gravitational Waves from Cosmological Phase Transitions with the NANOGrav 12.5-Year Dataset. *Phys. Rev. Lett.* **127**(25), 251302 (2021) [arXiv:2104.13930](https://arxiv.org/abs/2104.13930) [astro-ph.CO]. <https://doi.org/10.1103/PhysRevLett.127.251302>

294. Witten, E.: Cosmic Separation of Phases. *Phys. Rev. D* **30**, 272–285 (1984). <https://doi.org/10.1103/PhysRevD.30.272>
295. Arzoumanian, Z., et al.: The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background. *Astrophys. J. Lett.* **905**(2), 34 (2020) [arXiv:2009.04496](https://arxiv.org/abs/2009.04496) [astro-ph.HE]. <https://doi.org/10.3847/2041-8213/abd401>
296. Xue, X., et al.: Constraining Cosmological Phase Transitions with the Parkes Pulsar Timing Array. *Phys. Rev. Lett.* **127**(25), 251303 (2021). <https://doi.org/10.1103/PhysRevLett.127.251303>
297. Reitze, D., et al.: Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO. *Bull. Am. Astron. Soc.* **51**(7), 035 (2019) [arXiv:1907.04833](https://arxiv.org/abs/1907.04833) [astro-ph.IM]
298. Evans, M., et al.: A Horizon Study for Cosmic Explorer: Science, Observatories, and Community (2021) [arXiv:2109.09882](https://arxiv.org/abs/2109.09882) [astro-ph.IM]
299. Punturo, M., et al.: The Einstein telescope: a third-generation gravitational wave observatory. *Class. Quant. Gravit.* **27**, 194002 (2010). <https://doi.org/10.1088/0264-9381/27/19/194002>
300. Maggiore, M., et al.: Science case for the Einstein telescope. *JCAP* **03**, 050 (2020). <https://doi.org/10.1088/1475-7516/2020/03/050>. [arXiv:1912.02622](https://arxiv.org/abs/1912.02622) [astro-ph.CO]
301. Amaro-Seoane, P., et al.: Laser Interferometer Space Antenna. *arXiv e-prints* (2017) [arXiv:1702.00786](https://arxiv.org/abs/1702.00786) [astro-ph.IM]
302. Ruan, W.-H., Guo, Z.-K., Cai, R.-G., Zhang, Y.-Z.: Taiji program: gravitational-wave sources. *Int. J. Mod. Phys. A* **35**(17), 2050075 (2020). <https://doi.org/10.1142/S0217751X2050075X>. [arXiv:1807.09495](https://arxiv.org/abs/1807.09495) [gr-qc]
303. Wu, Y.-L., Luo, Z.-R., Wang, J.-Y., et al.: China's first step towards probing the expanding universe and the nature of gravity using a space borne gravitational wave antenna. *Commun. Phys.* **4**, 34 (2021). <https://doi.org/10.1038/s42005-021-00529-z>
304. Luo, J., et al.: The first round result from the TianQin-1 satellite. *Class. Quant. Gravit.* **37**(18), 185013 (2020). <https://doi.org/10.1088/1361-6382/aba66a>. [arXiv:2008.09534](https://arxiv.org/abs/2008.09534) [physics.ins-det]
305. Mei, J., et al.: The TianQin project: current progress on science and technology. *PTEP* **2021**(5), 05–107 (2021). <https://doi.org/10.1093/ptep/ptaa114>. [arXiv:2008.10332](https://arxiv.org/abs/2008.10332) [gr-qc]
306. Gowling, C., Hindmarsh, M.: Observational prospects for phase transitions at LISA: fisher matrix analysis. *JCAP* **10**, 039 (2021). <https://doi.org/10.1088/1475-7516/2021/10/039>. [arXiv:2106.05984](https://arxiv.org/abs/2106.05984) [astro-ph.CO]
307. Vachaspati, T., Vilenkin, A.: Gravitational radiation from cosmic strings. *Phys. Rev. D* **31**, 3052 (1985). <https://doi.org/10.1103/PhysRevD.31.3052>
308. Blanco-Pillado, J.J., Olum, K.D.: Stochastic gravitational wave background from smoothed cosmic string loops. *Phys. Rev. D* **96**(10), 104046 (2017). <https://doi.org/10.1103/PhysRevD.96.104046>. [arXiv:1709.02693](https://arxiv.org/abs/1709.02693) [astro-ph.CO]
309. Blanco-Pillado, J.J., Olum, K.D., Siemens, X.: New limits on cosmic strings from gravitational wave observation. *Phys. Lett. B* **778**, 392–396 (2018). <https://doi.org/10.1016/j.physletb.2018.01.050>. [arXiv:1709.02434](https://arxiv.org/abs/1709.02434) [astro-ph.CO]
310. Ringeval, C., Suyama, T.: Stochastic gravitational waves from cosmic string loops in scaling. *JCAP* **12**, 027 (2017). <https://doi.org/10.1088/1475-7516/2017/12/027>. [arXiv:1709.03845](https://arxiv.org/abs/1709.03845) [astro-ph.CO]
311. Vilenkin, A.: Gravitational radiation from cosmic strings. *Phys. Lett. B* **107**, 47–50 (1981). [https://doi.org/10.1016/0370-2693\(81\)91144-8](https://doi.org/10.1016/0370-2693(81)91144-8)
312. Hogan, C.J., Rees, M.J.: Gravitational interactions of cosmic strings. *Nature* **311**, 109–113 (1984). <https://doi.org/10.1038/311109a0>
313. Siemens, X., Mandic, V., Creighton, J.: Gravitational wave stochastic background from cosmic (super)strings. *Phys. Rev. Lett.* **98**, 111101 (2007). <https://doi.org/10.1103/PhysRevLett.98.111101>. [arXiv:astro-ph/0610920](https://arxiv.org/abs/astro-ph/0610920)
314. DePies, M.R., Hogan, C.J.: Stochastic gravitational wave background from light cosmic strings. *Phys. Rev. D* **75**, 125006 (2007). <https://doi.org/10.1103/PhysRevD.75.125006>. [arXiv:astro-ph/0702335](https://arxiv.org/abs/astro-ph/0702335)
315. Olmez, S., Mandic, V., Siemens, X.: Gravitational-wave stochastic background from kinks and cusps on cosmic strings. *Phys. Rev. D* **81**, 104028 (2010). <https://doi.org/10.1103/PhysRevD.81.104028>. [arXiv:1004.0890](https://arxiv.org/abs/1004.0890) [astro-ph.CO]
316. Vachaspati, T., Pogosian, L., Steer, D.: Cosmic Strings. *Scholarpedia* **10**(2), 31682 (2015). <https://doi.org/10.4249/scholarpedia.31682>. [arXiv:1506.04039](https://arxiv.org/abs/1506.04039) [astro-ph.CO]
317. Harigaya, K., Kawasaki, M.: QCD axion dark matter from long-lived domain walls during matter domination. *Phys. Lett. B* **782**, 1–5 (2018). <https://doi.org/10.1016/j.physletb.2018.04.056>. [arXiv:1802.00579](https://arxiv.org/abs/1802.00579) [hep-ph]

318. Craig, N., Garcia Garcia, I., Koszegi, G., McCune, A.: P not PQ. *JHEP* **09**, 130 (2021). [https://doi.org/10.1007/JHEP09\(2021\)130](https://doi.org/10.1007/JHEP09(2021)130). arXiv:2012.13416 [hep-ph]
319. Borah, D., Mishra, S.: Spontaneous R-parity breaking, left-right symmetry and consistent cosmology with transitory domain walls. *Phys. Rev. D* **84**, 055008 (2011). <https://doi.org/10.1103/PhysRevD.84.055008>. arXiv:1105.5006 [hep-ph]
320. Ouahid, M.A., Loualidi, M.A., Laamara, R.A., Saidi, E.H.: Neutrino phenomenology in the flavored NMSSM without domain wall problems. *Phys. Rev. D* **102**(11), 115023 (2020). <https://doi.org/10.1103/PhysRevD.102.115023>. arXiv:1810.10753 [hep-ph]
321. Kibble, T.W.B., Lazarides, G., Shafi, Q.: Strings in SO(10). *Phys. Lett. B* **113**, 237–239 (1982). [https://doi.org/10.1016/0370-2693\(82\)90829-2](https://doi.org/10.1016/0370-2693(82)90829-2)
322. Kibble, T.W.B., Lazarides, G., Shafi, Q.: Walls Bounded by Strings. *Phys. Rev. D* **26**, 435 (1982). <https://doi.org/10.1103/PhysRevD.26.435>
323. Chang, C.-F., Cui, Y.: Stochastic gravitational wave background from global cosmic strings. *Phys. Dark Univ.* **29**, 100604 (2020). <https://doi.org/10.1016/j.dark.2020.100604>. arXiv:1910.04781 [hep-ph]
324. Copeland, E.J., Myers, R.C., Polchinski, J.: Cosmic f- and d-strings. *JHEP* **0406**, 013 (2004)
325. Sakellariadou, M.: Cosmic strings and cosmic superstrings. *Nucl. Phys. B Proc. Suppl.* **192–193**, 68–90 (2009). <https://doi.org/10.1016/j.nuclphysbps.2009.07.046>. arXiv:0902.0569 [hep-th]
326. Dror, J.A., Hirayama, T., Kohri, K., Murayama, H., White, G.: Testing the seesaw mechanism and leptogenesis with gravitational waves. *Phys. Rev. Lett.* **124**(4), 041804 (2020). <https://doi.org/10.1103/PhysRevLett.124.041804>. arXiv:1908.03227 [hep-ph]
327. Damour, T., Vilenkin, A.: Gravitational radiation from cosmic (super)strings: bursts, stochastic background, and observational windows. *Phys. Rev. D* **71**, 063510 (2005)
328. Martins, C.J.A.P., Shellard, E.P.S.: Quantitative string evolution. *Phys. Rev. D* **54**, 2535–2556 (1996). <https://doi.org/10.1103/PhysRevD.54.2535>. arXiv:hep-ph/9602271
329. Martins, C.J.A.P., Shellard, E.P.S.: Extending the velocity dependent one scale string evolution model. *Phys. Rev. D* **65**, 043514 (2002). <https://doi.org/10.1103/PhysRevD.65.043514>. arXiv:hep-ph/0003298
330. Blanco-Pillado, J.J., Olum, K.D., Shlaer, B.: The number of cosmic string loops. *Phys. Rev. D* **89**(2), 023512 (2014). <https://doi.org/10.1103/PhysRevD.89.023512>. arXiv:1309.6637 [astro-ph.CO]
331. Blanco-Pillado, J.J., Olum, K.D., Shlaer, B.: Large parallel cosmic string simulations: new results on loop production. *Phys. Rev. D* **83**, 083514 (2011). <https://doi.org/10.1103/PhysRevD.83.083514>. arXiv:1101.5173 [astro-ph.CO]
332. Ringeval, C., Sakellariadou, M., Bouchet, F.: Cosmological evolution of cosmic string loops. *JCAP* **02**, 023 (2007). <https://doi.org/10.1088/1475-7516/2007/02/023>. arXiv:astro-ph/0511646
333. Lorenz, L., Ringeval, C., Sakellariadou, M.: Cosmic string loop distribution on all length scales and at any redshift. *JCAP* **10**, 003 (2010). <https://doi.org/10.1088/1475-7516/2010/10/003>. arXiv:1006.0931 [astro-ph.CO]
334. Auclair, P., Ringeval, C., Sakellariadou, M., Steer, D.: Cosmic string loop production functions. *JCAP* **06**, 015 (2019). <https://doi.org/10.1088/1475-7516/2019/06/015>. arXiv:1903.06685 [astro-ph.CO]
335. Cui, Y., Lewicki, M., Morrissey, D.E., Wells, J.D.: Cosmic archaeology with gravitational waves from cosmic strings. *Phys. Rev. D* **97**(12), 123505 (2018). <https://doi.org/10.1103/PhysRevD.97.123505>. arXiv:1711.03104 [hep-ph]
336. Cui, Y., Lewicki, M., Morrissey, D.E., Wells, J.D.: Probing the pre-BBN universe with gravitational waves from cosmic strings. *JHEP* **01**, 081 (2019). [https://doi.org/10.1007/JHEP01\(2019\)081](https://doi.org/10.1007/JHEP01(2019)081). arXiv:1808.08968 [hep-ph]
337. Gouttenoire, Y., Servant, G., Simakachorn, P.: Beyond the standard models with cosmic strings. *JCAP* **07**, 032 (2020). <https://doi.org/10.1088/1475-7516/2020/07/032>. arXiv:1912.02569 [hep-ph]
338. Vincent, G.R., Hindmarsh, M., Sakellariadou, M.: Correlations in cosmic string networks. *Phys. Rev. D* **55**, 573–581 (1997). <https://doi.org/10.1103/PhysRevD.55.573>. arXiv:astro-ph/9606137D
339. Hindmarsh, M.: Signals of inflationary models with cosmic strings. *Prog. Theor. Phys. Suppl.* **190**, 197–228 (2011). <https://doi.org/10.1143/PTPS.190.197>. arXiv:1106.0391 [astro-ph.CO]
340. Matsunami, D., Pogosian, L., Saurabh, A., Vachaspati, T.: Decay of cosmic string loops due to particle radiation. *Phys. Rev. Lett.* **122**(20), 201301 (2019). <https://doi.org/10.1103/PhysRevLett.122.201301>. arXiv:1903.05102 [hep-ph]
341. Saurabh, A., Vachaspati, T., Pogosian, L.: Decay of cosmic global string loops. *Phys. Rev. D* **101**(8), 083522 (2020). <https://doi.org/10.1103/PhysRevD.101.083522>. arXiv:2001.01030 [hep-ph]

342. Hindmarsh, M., Lizarraga, J., Urrio, A., Urrestilla, J.: Loop decay in Abelian-Higgs string networks. *Phys. Rev. D* **104**(4), 043519 (2021). <https://doi.org/10.1103/PhysRevD.104.043519>. arXiv:2103.16248 [astro-ph.CO]
343. Auclair, P., Steer, D.A., Vachaspati, T.: Particle emission and gravitational radiation from cosmic strings: observational constraints. *Phys. Rev. D* **101**(8), 083511 (2020). <https://doi.org/10.1103/PhysRevD.101.083511>. arXiv:1911.12066 [hep-ph]
344. Martins, C.J.A.P.: Scaling properties of cosmological axion strings. *Phys. Lett. B* **788**, 147–151 (2019). <https://doi.org/10.1016/j.physletb.2018.11.031>. arXiv:1811.12678 [astro-ph.CO]
345. Gorghetto, M., Hardy, E., Villadoro, G.: Axions from strings: the attractive solution. *JHEP* **07**, 151 (2018). [https://doi.org/10.1007/JHEP07\(2018\)151](https://doi.org/10.1007/JHEP07(2018)151). arXiv:1806.04677 [hep-ph]
346. Buschmann, M., Foster, J.W., Safdi, B.R.: Early-Universe Simulations of the Cosmological Axion (2019) arXiv:1906.00967 [astro-ph.CO]
347. Figueroa, D.G., Hindmarsh, M., Lizarraga, J., Urrestilla, J.: Irreducible background of gravitational waves from a cosmic defect network: update and comparison of numerical techniques. *Phys. Rev. D* **102**(10), 103516 (2020). <https://doi.org/10.1103/PhysRevD.102.103516>. arXiv:2007.03337 [astro-ph.CO]
348. Gorghetto, M., Hardy, E., Nicolaescu, H.: Observing Invisible Axions with Gravitational Waves (2021) arXiv:2101.11007 [hep-ph]
349. Chang, C.-F., Cui, Y.: Gravitational Waves from Global Cosmic Strings and Cosmic Archaeology (2021) arXiv:2106.09746 [hep-ph]
350. Sakellariadou, M.: A Note on the evolution of cosmic string/superstring networks. *JCAP* **04**, 003 (2005). <https://doi.org/10.1088/1475-7516/2005/04/003>. arXiv:hep-th/0410234
351. Avgoustidis, A., Shellard, E.P.S.: Cosmic string evolution in higher dimensions. *Phys. Rev. D* **71**, 123513 (2005). <https://doi.org/10.1103/PhysRevD.71.123513>
352. Hindmarsh, M., Saffin, P.M.: Scaling in a  $SU(2)/\mathbb{Z}_3$  model of cosmic superstring networks. *JHEP* **08**, 066 (2006). <https://doi.org/10.1088/1126-6708/2006/08/066>. arXiv:hep-th/0605014
353. Urrestilla, J., Vilenkin, A.: Evolution of cosmic superstring networks: A Numerical simulation. *JHEP* **02**, 037 (2008). <https://doi.org/10.1088/1126-6708/2008/02/037>. arXiv:0712.1146 [hep-th]
354. Rajantie, A., Sakellariadou, M., Stoica, H.: Numerical experiments with p F- and q D-strings: the formation of (p, q) bound states. *JCAP* **11**, 021 (2007). <https://doi.org/10.1088/1475-7516/2007/11/021>. arXiv:0706.3662 [hep-th]
355. Sakellariadou, M., Stoica, H.: Dynamics of F/D networks: the role of bound states. *JCAP* **08**, 038 (2008). <https://doi.org/10.1088/1475-7516/2008/08/038>. arXiv:0806.3219 [hep-th]
356. Copeland, E.J., Kibble, T.W.B., Steer, D.A.: Collisions of strings with Y junctions. *Phys. Rev. Lett.* **97**, 021602 (2006). <https://doi.org/10.1103/PhysRevLett.97.021602>. arXiv:hep-th/0601153
357. Copeland, E.J., Kibble, T.W.B., Steer, D.A.: Constraints on string networks with junctions. *Phys. Rev. D* **75**, 065024 (2007). <https://doi.org/10.1103/PhysRevD.75.065024>
358. Copeland, E.J., Firouzjahi, H., Kibble, T.W.B., Steer, D.A.: Collision of cosmic superstrings. *Phys. Rev. D* **77**, 063521 (2008). <https://doi.org/10.1103/PhysRevD.77.063521>
359. Avgoustidis, A., Pourtsidou, A., Sakellariadou, M.: Zipping and unzipping in string networks: dynamics of Y-junctions. *Phys. Rev. D* **91**(2), 025022 (2015). <https://doi.org/10.1103/PhysRevD.91.025022>. arXiv:1411.7959 [hep-th]
360. Hogan, C.J.: Gravitational waves from cosmic superstrings. In: American Astronomical Society Meeting Abstracts. American Astronomical Society Meeting Abstracts, vol. 209, pp. 74–13 (2006)
361. Abbott, B.P., et al.: Constraints on cosmic strings using data from the first Advanced LIGO observing run. *Phys. Rev. D* **97**(10), 102002 (2018). <https://doi.org/10.1103/PhysRevD.97.102002>. arXiv:1712.01168 [gr-qc]
362. Boyle, L.A., Steinhardt, P.J.: Probing the early universe with inflationary gravitational waves. *Phys. Rev. D* **77**, 063504 (2008). <https://doi.org/10.1103/PhysRevD.77.063504>. arXiv:astro-ph/0512014
363. Boyle, L.A., Buonanno, A.: Relating gravitational wave constraints from primordial nucleosynthesis, pulsar timing, laser interferometers, and the CMB: Implications for the early Universe. *Phys. Rev. D* **78**, 043531 (2008). <https://doi.org/10.1103/PhysRevD.78.043531>. arXiv:0708.2279 [astro-ph]
364. Moroi, T., Randall, L.: Wino cold dark matter from anomaly mediated SUSY breaking. *Nucl. Phys. B* **570**, 455–472 (2000). [https://doi.org/10.1016/S0550-3213\(99\)00748-8](https://doi.org/10.1016/S0550-3213(99)00748-8). arXiv:hep-ph/9906527
365. Nelson, A.E., Xiao, H.: Axion cosmology with early matter domination. *Phys. Rev. D* **98**(6), 063516 (2018). <https://doi.org/10.1103/PhysRevD.98.063516>. arXiv:1807.07176 [astro-ph.CO]



366. Salati, P.: Quintessence and the relic density of neutralinos. *Phys. Lett. B* **571**, 121–131 (2003). <https://doi.org/10.1016/j.physletb.2003.07.073>. arXiv:astro-ph/0207396
367. Chung, D.J.H., Everett, L.L., Matchev, K.T.: Inflationary cosmology connecting dark energy and dark matter. *Phys. Rev. D* **76**, 103530 (2007). <https://doi.org/10.1103/PhysRevD.76.103530>. arXiv:0704.3285 [hep-ph]
368. Poulin, V., Smith, T.L., Grin, D., Karwal, T., Kamionkowski, M.: Cosmological implications of ultralight axionlike fields. *Phys. Rev. D* **98**(8), 083525 (2018). <https://doi.org/10.1103/PhysRevD.98.083525>. arXiv:1806.10608 [astro-ph.CO]
369. Cui, Y., Lewicki, M., Morrissey, D.E.: Gravitational wave bursts as harbingers of cosmic strings diluted by inflation. *Phys. Rev. Lett.* **125**(21), 211302 (2020). <https://doi.org/10.1103/PhysRevLett.125.211302>. arXiv:1912.08832 [hep-ph]
370. Blasi, S., Brdar, V., Schmitz, K.: Has NANOGrav found first evidence for cosmic strings? *Phys. Rev. Lett.* **126**(4), 041305 (2021). <https://doi.org/10.1103/PhysRevLett.126.041305>. arXiv:2009.06607 [astro-ph.CO]
371. Buchmuller, W., Domcke, V., Schmitz, K.: Stochastic gravitational-wave background from metastable cosmic strings. *JCAP* **12**(12), 006 (2021). <https://doi.org/10.1088/1475-7516/2021/12/006>. arXiv:2107.04578 [hep-ph]
372. Elor, G., et al.: New Ideas in Baryogenesis: A Snowmass White Paper. arXiv e-prints (2022) arXiv:2203.05010 [hep-ph]
373. King, S.F., Pascoli, S., Turner, J., Zhou, Y.-L.: Gravitational waves and proton decay: complementary windows into grand unified theories. *Phys. Rev. Lett.* **126**(2), 021802 (2021). <https://doi.org/10.1103/PhysRevLett.126.021802>. arXiv:2005.13549 [hep-ph]
374. Chun, E.J., Velasco-Sevilla, L.: Tracking Down the Route to the SM with Inflation and Gravitational Waves (2021) arXiv:2112.14483 [hep-ph]
375. Ramberg, N., Visinelli, L.: QCD axion and gravitational waves in light of NANOGrav results. *Phys. Rev. D* **103**(6), 063031 (2021). <https://doi.org/10.1103/PhysRevD.103.063031>. arXiv:2012.06882 [astro-ph.CO]
376. Gelmini, G.B., Simpson, A., Vitagliano, E.: Gravitational waves from axionlike particle cosmic string-wall networks. *Phys. Rev. D* **104**(6), 061301 (2021). <https://doi.org/10.1103/PhysRevD.104.L061301>. arXiv:2103.07625 [hep-ph]
377. Ellis, J., Lewicki, M.: Cosmic string interpretation of NANOGrav pulsar timing data. *Phys. Rev. Lett.* **126**(4), 041304 (2021). <https://doi.org/10.1103/PhysRevLett.126.041304>. arXiv:2009.06555 [astro-ph.CO]
378. Blanco-Pillado, J.J., Olum, K.D., Wachter, J.M.: Comparison of cosmic string and superstring models to NANOGrav 12.5-year results. *Phys. Rev. D* **103**(10), 103512 (2021). <https://doi.org/10.1103/PhysRevD.103.103512>. arXiv:2102.08194 [astro-ph.CO]
379. Yagi, K., Seto, N.: Detector configuration of DECIGO/BBO and identification of cosmological neutron-star binaries. *Phys. Rev. D* **83**, 044011 (2011). <https://doi.org/10.1103/PhysRevD.83.044011>. arXiv:1101.3940 [astro-ph.CO]
380. El-Neaj, Y.A., et al.: AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quant. Technol.* **7**, 6 (2020). <https://doi.org/10.1140/epjqt/s40507-020-0080-0>. arXiv:1908.00802 [gr-qc]
381. Hild, S., et al.: Sensitivity studies for third-generation gravitational wave observatories. *Class. Quant. Gravit.* **28**, 094013 (2011). <https://doi.org/10.1088/0264-9381/28/9/094013>. arXiv:1012.0908 [gr-qc]
382. Sesana, A., et al.: Unveiling the gravitational universe at  $\mu$ -Hz frequencies. *Exper. Astron.* **51**(3), 1333–1383 (2021). <https://doi.org/10.1007/s10686-021-09709-9>. arXiv:1908.11391 [astro-ph.IM]
383. Boehm, C., et al.: Theia: Faint objects in motion or the new astrometry frontier (2017) arXiv:1707.01348 [astro-ph.IM]
384. Datta, S., Ghosal, A., Samanta, R.: Baryogenesis from ultralight primordial black holes and strong gravitational waves from cosmic strings. *JCAP* **08**, 021 (2021). <https://doi.org/10.1088/1475-7516/2021/08/021>. arXiv:2012.14981 [hep-ph]
385. Chakraborty, J., Lazarides, G., Maji, R., Shafi, Q.: Primordial monopoles and strings, inflation, and gravity waves. *JHEP* **02**, 114 (2021). [https://doi.org/10.1007/JHEP02\(2021\)114](https://doi.org/10.1007/JHEP02(2021)114). arXiv:2011.01838 [hep-ph]



386. Samanta, R., Datta, S.: Gravitational wave complementarity and impact of NANOGrav data on gravitational leptogenesis. *JHEP* **05**, 211 (2021). [https://doi.org/10.1007/JHEP05\(2021\)211](https://doi.org/10.1007/JHEP05(2021)211). [arXiv:2009.13452](https://arxiv.org/abs/2009.13452) [hep-ph]
387. Hellings, R., Downs, G.: Upper limits on the isotropic gravitational radiation background from pulsar timing analysis. *Astrophys. J. Lett.* **265**, 39–42 (1983). <https://doi.org/10.1086/183954>
388. Antypas, D., et al.: New Horizons: Scalar and Vector Ultralight Dark Matter (2022) [arXiv:2203.14915](https://arxiv.org/abs/2203.14915) [hep-ex]
389. Carney, D., et al.: Snowmass2021 Cosmic Frontier White Paper: Ultraheavy particle dark matter (2022) [arXiv:2203.06508](https://arxiv.org/abs/2203.06508) [hep-ph]
390. Abbott, B.P., et al.: Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.* **116**(6), 061102 (2016). <https://doi.org/10.1103/PhysRevLett.116.061102>. [arXiv:1602.03837](https://arxiv.org/abs/1602.03837) [gr-qc]
391. Abbott, B.P., et al.: Binary black hole mergers in the first advanced LIGO observing run. *Phys. Rev. X* **6**(4), 041015 (2016). <https://doi.org/10.1103/PhysRevX.6.041015>. [arXiv:1606.04856](https://arxiv.org/abs/1606.04856) [gr-qc]. [Erratum: *Phys. Rev. X* **8**, 039903 (2018)]
392. Abbott, B.P., et al.: GW151226: observation of gravitational waves from a 22-solar-mass binary black hole coalescence. *Phys. Rev. Lett.* **116**(24), 241103 (2016). <https://doi.org/10.1103/PhysRevLett.116.241103>. [arXiv:1606.04855](https://arxiv.org/abs/1606.04855) [gr-qc]
393. Abbott, B.P., et al.: GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2. *Phys. Rev. Lett.* **118**(22), 221101 (2017). [arXiv:1706.01812](https://arxiv.org/abs/1706.01812) [gr-qc]. <https://doi.org/10.1103/PhysRevLett.118.221101>. [Erratum: *Phys. Rev. Lett.* **121**, 129901 (2018)]
394. Abbott, B.P., et al.: GW170814: a three-detector observation of gravitational waves from a binary black hole coalescence. *Phys. Rev. Lett.* **119**(14), 141101 (2017). <https://doi.org/10.1103/PhysRevLett.119.141101>. [arXiv:1709.09660](https://arxiv.org/abs/1709.09660) [gr-qc]
395. Abbott, B.P., et al.: GW170608: observation of a 19-solar-mass binary black hole coalescence. *Astrophys. J.* **851**(2), 35 (2017). <https://doi.org/10.3847/2041-8213/aa9f0c>. [arXiv:1711.05578](https://arxiv.org/abs/1711.05578) [astro-ph.HE]
396. Abbott, B.P., et al.: GWTC-1: a gravitational-wave transient catalog of compact binary mergers observed by ligo and virgo during the first and second observing runs. *Phys. Rev. X* **9**(3), 031040 (2019). <https://doi.org/10.1103/PhysRevX.9.031040>. [arXiv:1811.12907](https://arxiv.org/abs/1811.12907) [astro-ph.HE]
397. Abbott, R., et al.: GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses (2020) [arXiv:2004.08342](https://arxiv.org/abs/2004.08342) [astro-ph.HE]
398. Abbott, B.P., et al.: GW190425: observation of a compact binary coalescence with total mass  $\sim 3.4M_{\odot}$ . *Astrophys. J. Lett.* **892**, 3 (2020). <https://doi.org/10.3847/2041-8213/ab75f5>. [arXiv:2001.01761](https://arxiv.org/abs/2001.01761) [astro-ph.HE]
399. Abbott, R., et al.: GW190814: gravitational waves from the coalescence of a 2.3 solar mass black hole with a 26 solar mass compact object. *Astrophys. J.* **896**(2), 44 (2020). <https://doi.org/10.3847/2041-8213/ab960f>. [arXiv:2006.12611](https://arxiv.org/abs/2006.12611) [astro-ph.HE]
400. Bird, S., Cholis, I., Muñoz, J.B., Ali-Haïmoud, Y., Kamionkowski, M., Kovetz, E.D., Raccanelli, A., Riess, A.G.: Did LIGO detect dark matter? *Phys. Rev. Lett.* **116**(20), 201301 (2016). <https://doi.org/10.1103/PhysRevLett.116.201301>. [arXiv:1603.00464](https://arxiv.org/abs/1603.00464) [astro-ph.CO]
401. Clesse, S., García-Bellido, J.: The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO. *Phys. Dark Univ.* **15**, 142–147 (2017). <https://doi.org/10.1016/j.dark.2016.10.002>. [arXiv:1603.05234](https://arxiv.org/abs/1603.05234) [astro-ph.CO]
402. Sasaki, M., Suyama, T., Tanaka, T., Yokoyama, S.: Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914. *Phys. Rev. Lett.* **117**(6), 061101 (2016) [arXiv:1603.08338](https://arxiv.org/abs/1603.08338) [astro-ph.CO]. <https://doi.org/10.1103/PhysRevLett.121.059901>, <https://doi.org/10.1103/PhysRevLett.117.061101>. [erratum: *Phys. Rev. Lett.* **121**, no.5, 059901 (2018)]
403. Kashlinsky, A.: LIGO gravitational wave detection, primordial black holes, and the near-IR cosmic infrared background anisotropies. *Astrophys. J. Lett.* **823**(2), 25 (2016). <https://doi.org/10.3847/2041-8205/823/2/L25>. [arXiv:1605.04023](https://arxiv.org/abs/1605.04023) [astro-ph.CO]
404. Blinnikov, S., Dolgov, A., Porayko, N.K., Postnov, K.: Solving puzzles of GW150914 by primordial black holes. *JCAP* **11**, 036 (2016). <https://doi.org/10.1088/1475-7516/2016/11/036>. [arXiv:1611.00541](https://arxiv.org/abs/1611.00541) [astro-ph.HE]
405. Abbott, B.P., et al.: Exploring the sensitivity of next generation gravitational wave detectors. *Class. Quant. Gravit.* **34**(4), 044001 (2017). <https://doi.org/10.1088/1361-6382/aa51f4>. [arXiv:1607.08697](https://arxiv.org/abs/1607.08697) [astro-ph.IM]

406. Punturo, M., et al.: The third generation of gravitational wave observatories and their science reach. *Class. Quant. Gravit.* **27**, 084007 (2010). <https://doi.org/10.1088/0264-9381/27/8/084007>
407. Abbott, B.P., et al.: Search for Substellar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run. *Phys. Rev. Lett.* **121**(23), 231103 (2018). <https://doi.org/10.1103/PhysRevLett.121.231103>. [arXiv:1808.04771](https://arxiv.org/abs/1808.04771) [astro-ph.CO]
408. Abbott, B.P., et al.: Search for subsolar mass ultracompact binaries in advanced LIGO's second observing run. *Phys. Rev. Lett.* **123**(16), 161102 (2019). <https://doi.org/10.1103/PhysRevLett.123.161102>. [arXiv:1904.08976](https://arxiv.org/abs/1904.08976) [astro-ph.CO]
409. Abbott, R., et al.: Search for subsolar-mass binaries in the first half of Advanced LIGO and Virgo's third observing run (2021) [arXiv:2109.12197](https://arxiv.org/abs/2109.12197) [astro-ph.CO]
410. Nitz, A.H., Wang, Y.-F.: Search for gravitational waves from high-mass-ratio compact-binary mergers of stellar mass and subsolar mass black holes. *Phys. Rev. Lett.* **126**(2), 021103 (2021). <https://doi.org/10.1103/PhysRevLett.126.021103>. [arXiv:2007.03583](https://arxiv.org/abs/2007.03583) [astro-ph.HE]
411. Phukon, K.S., Baltus, G., Caudill, S., Clesse, S., Depasse, A., Fays, M., Fong, H., Kapadia, S.J., Magee, R., Tanasijczuk, A.J.: The hunt for sub-solar primordial black holes in low mass ratio binaries is open (2021) [arXiv:2105.11449](https://arxiv.org/abs/2105.11449) [astro-ph.CO]
412. Nitz, A.H., Wang, Y.-F.: Search for gravitational waves from the coalescence of subsolar-mass binaries in the first half of advanced LIGO and Virgo's third observing run. *Phys. Rev. Lett.* **127**(15), 151101 (2021). <https://doi.org/10.1103/PhysRevLett.127.151101>. [arXiv:2106.08979](https://arxiv.org/abs/2106.08979) [astro-ph.HE]
413. Nitz, A.H., Wang, Y.-F.: Broad search for gravitational waves from subsolar-mass binaries through LIGO and Virgo's third observing run (2022) [arXiv:2202.11024](https://arxiv.org/abs/2202.11024) [astro-ph.HE]
414. Unal, C., Kovetz, E.D., Patil, S.P.: Multi-messenger Probes of Massive Black Holes from Enhanced Primordial Fluctuations (2020) [arXiv:2008.11184](https://arxiv.org/abs/2008.11184) [astro-ph.CO]
415. Byrnes, C.T., Hindmarsh, M., Young, S., Hawkins, M.R.S.: Primordial black holes with an accurate QCD equation of state. *JCAP* **1808**(08), 041 (2018). <https://doi.org/10.1088/1475-7516/2018/08/041>. [arXiv:1801.06138](https://arxiv.org/abs/1801.06138) [astro-ph.CO]
416. Carr, B., Clesse, S., García-Bellido, J., Kuhnel, F.: Cosmic Conundra Explained by Thermal History and Primordial Black Holes (2019) [arXiv:1906.08217](https://arxiv.org/abs/1906.08217) [astro-ph.CO]
417. Clesse, S., Garcia-Bellido, J.: GW190425, GW190521 and GW190814: Three candidate mergers of primordial black holes from the QCD epoch (2020) [arXiv:2007.06481](https://arxiv.org/abs/2007.06481) [astro-ph.CO]
418. De Luca, V., Desjacques, V., Franciolini, G., Pani, P., Riotto, A.: GW190521 mass gap event and the primordial black hole scenario. *Phys. Rev. Lett.* **126**(5), 051101 (2021). <https://doi.org/10.1103/PhysRevLett.126.051101>. [arXiv:2009.01728](https://arxiv.org/abs/2009.01728) [astro-ph.CO]
419. Gerosa, D., Fishbach, M.: Hierarchical mergers of stellar-mass black holes and their gravitational-wave signatures. *Nature Astron.* **5**(8), 749–760 (2021). <https://doi.org/10.1038/s41550-021-01398-w>. [arXiv:2105.03439](https://arxiv.org/abs/2105.03439) [astro-ph.HE]
420. Farmer, R., Renzo, M., de Mink, S.E., Marchant, P., Justham, S.: Mind the gap: the location of the lower edge of the pair instability supernovae black hole mass gap (2019). <https://doi.org/10.3847/1538-4357/ab518b>. [arXiv:1910.12874](https://arxiv.org/abs/1910.12874) [astro-ph.SR]
421. Clesse, S., García-Bellido, J.: Massive primordial black holes from hybrid inflation as dark matter and the seeds of galaxies. *Phys. Rev. D* **92**(2), 023524 (2015). <https://doi.org/10.1103/PhysRevD.92.023524>. [arXiv:1501.07565](https://arxiv.org/abs/1501.07565) [astro-ph.CO]
422. Ding, Q.: Detectability of primordial black hole binaries at high redshift. *Phys. Rev. D* **104**(4), 043527 (2021). <https://doi.org/10.1103/PhysRevD.104.043527>. [arXiv:2011.13643](https://arxiv.org/abs/2011.13643) [astro-ph.CO]
423. Abbott, B.P., et al.: Binary black hole population properties inferred from the first and second observing runs of advanced LIGO and advanced virgo. *Astrophys. J. Lett.* **882**(2), 24 (2019). <https://doi.org/10.3847/2041-8213/ab3800>. [arXiv:1811.12940](https://arxiv.org/abs/1811.12940) [astro-ph.HE]
424. Kocsis, B., Suyama, T., Tanaka, T., Yokoyama, S.: Hidden universality in the merger rate distribution in the primordial black hole scenario. *Astrophys. J.* **854**(1), 41 (2018). <https://doi.org/10.3847/1538-4357/aaa7f4>. [arXiv:1709.09007](https://arxiv.org/abs/1709.09007) [astro-ph.CO]
425. Ali-Haïmoud, Y., Kovetz, E.D., Kamionkowski, M.: Merger rate of primordial black-hole binaries. *Phys. Rev. D* **96**(12), 123523 (2017). <https://doi.org/10.1103/PhysRevD.96.123523>. [arXiv:1709.06576](https://arxiv.org/abs/1709.06576) [astro-ph.CO]
426. Clesse, S., García-Bellido, J.: Seven hints for primordial black hole dark matter. *Phys. Dark Univ.* **22**, 137–146 (2018). <https://doi.org/10.1016/j.dark.2018.08.004>. [arXiv:1711.10458](https://arxiv.org/abs/1711.10458) [astro-ph.CO]

427. Fernandez, N., Profumo, S.: Unraveling the origin of black holes from effective spin measurements with LIGO-Virgo. *JCAP* **08**, 022 (2019). <https://doi.org/10.1088/1475-7516/2019/08/022>. [arXiv:1905.13019](https://arxiv.org/abs/1905.13019) [astro-ph.HE]
428. De Luca, V., Desjacques, V., Franciolini, G., Malhotra, A., Riotto, A.: The initial spin probability distribution of primordial black holes. *JCAP* **05**, 018 (2019). <https://doi.org/10.1088/1475-7516/2019/05/018>. [arXiv:1903.01179](https://arxiv.org/abs/1903.01179) [astro-ph.CO]
429. Gow, A.D., Byrnes, C.T., Hall, A., Peacock, J.A.: Primordial black hole merger rates: distributions for multiple LIGO observables. *JCAP* **2001**, 031 (2020). <https://doi.org/10.1088/1475-7516/2020/01/031>. [arXiv:1911.12685](https://arxiv.org/abs/1911.12685) [astro-ph.CO]
430. Hall, A., Gow, A.D., Byrnes, C.T.: Bayesian analysis of LIGO-Virgo mergers: primordial vs astrophysical black hole populations. *Phys. Rev. D* **102**, 123524 (2020). <https://doi.org/10.1103/PhysRevD.102.123524>. [arXiv:2008.13704](https://arxiv.org/abs/2008.13704) [astro-ph.CO]
431. Jedamzik, K.: Evidence for primordial black hole dark matter from LIGO/Virgo merger rates (2020) [arXiv:2007.03565](https://arxiv.org/abs/2007.03565) [astro-ph.CO]
432. Jedamzik, K.: Primordial Black Hole Dark Matter and the LIGO/Virgo observations (2020) [arXiv:2006.11172](https://arxiv.org/abs/2006.11172) [astro-ph.CO]
433. Bhagwat, S., De Luca, V., Franciolini, G., Pani, P., Riotto, A.: The Importance of Priors on LIGO-Virgo Parameter Estimation: the Case of Primordial Black Holes (2020) [arXiv:2008.12320](https://arxiv.org/abs/2008.12320) [astro-ph.CO]
434. De Luca, V., Franciolini, G., Pani, P., Riotto, A.: Primordial black holes confront LIGO/Virgo data: current situation. *JCAP* **06**, 044 (2020). <https://doi.org/10.1088/1475-7516/2020/06/044>. [arXiv:2005.05641](https://arxiv.org/abs/2005.05641) [astro-ph.CO]
435. De Luca, V., Franciolini, G., Pani, P., Riotto, A.: Constraints on primordial black holes: the importance of accretion. *Phys. Rev. D* **102**(4), 043505 (2020). <https://doi.org/10.1103/PhysRevD.102.043505>. [arXiv:2003.12589](https://arxiv.org/abs/2003.12589) [astro-ph.CO]
436. De Luca, V., Franciolini, G., Pani, P., Riotto, A.: The evolution of primordial black holes and their final observable spins. *JCAP* **04**, 052 (2020). <https://doi.org/10.1088/1475-7516/2020/04/052>. [arXiv:2003.02778](https://arxiv.org/abs/2003.02778) [astro-ph.CO]
437. Wong, K.W.K., Franciolini, G., De Luca, V., Baibhav, V., Berti, E., Pani, P., Riotto, A.: Constraining the primordial black hole scenario by Bayesian inference and machine learning: the GWTC-2 gravitational wave catalog. *Phys. Rev. D* **103**(2), 023026 (2021). <https://doi.org/10.1103/PhysRevD.103.023026>. [arXiv:2011.01865](https://arxiv.org/abs/2011.01865) [gr-qc]
438. García-Bellido, J., Nuño Siles, J.F., Ruiz Morales, E.: Bayesian analysis of the spin distribution of LIGO/Virgo black holes. *Phys. Dark Univ.* **31**, 100791 (2021). <https://doi.org/10.1016/j.dark.2021.100791>. [arXiv:2010.13811](https://arxiv.org/abs/2010.13811) [astro-ph.CO]
439. Dolgov, A., Postnov, K.: Why the mean mass of primordial black hole distribution is close to  $10M_{\odot}$ . *JCAP* **07**, 063 (2020). <https://doi.org/10.1088/1475-7516/2020/07/063>. [arXiv:2004.11669](https://arxiv.org/abs/2004.11669) [astro-ph.CO]
440. Dolgov, A.D., Kuranov, A.G., Mitichkin, N.A., Porey, S., Postnov, K.A., Sazhina, O.S., Simkin, I.V.: On mass distribution of coalescing black holes (2020) [arXiv:2005.00892](https://arxiv.org/abs/2005.00892) [astro-ph.CO]
441. Belotsky, K.M., Dmitriev, A.D., Esipova, E.A., Gani, V.A., Grobov, A.V., Khlopov, M.Y., Kirillov, A.A., Rubin, S.G., Svadkovsky, I.V.: Signatures of primordial black hole dark matter. *Mod. Phys. Lett. A* **29**(37), 1440005 (2014). <https://doi.org/10.1142/S0217732314400057>. [arXiv:1410.0203](https://arxiv.org/abs/1410.0203) [astro-ph.CO]
442. Mukherjee, S., Silk, J.: Can we distinguish astrophysical from primordial black holes via the stochastic gravitational wave background? *Mon. Not. R. Astron. Soc.* **506**(3), 3977–3985 (2021). <https://doi.org/10.1093/mnras/stab1932>. [arXiv:2105.11139](https://arxiv.org/abs/2105.11139) [gr-qc]
443. Mukherjee, S., Meinema, M.S.P., Silk, J.: Prospects of discovering subsolar primordial black holes using the stochastic gravitational wave background from third-generation detectors. *Mon. Not. R. Astron. Soc.* **510**(4), 6218–6224 (2022). <https://doi.org/10.1093/mnras/stab3756>. [arXiv:2107.02181](https://arxiv.org/abs/2107.02181) [astro-ph.CO]
444. Korol, V., Mandel, I., Miller, M.C., Church, R.P., Davies, M.B.: Merger rates in primordial black hole clusters without initial binaries. *Mon. Not. R. Astron. Soc.* **496**(1), 994–1000 (2020). <https://doi.org/10.1093/mnras/staa1644>. [arXiv:1911.03483](https://arxiv.org/abs/1911.03483) [astro-ph.HE]
445. Belotsky, K.M., Dokuchaev, V.I., Eroshenko, Y.N., Esipova, E.A., Khlopov, M.Y., Khromykh, L.A., Kirillov, A.A., Nikulin, V.V., Rubin, S.G., Svadkovsky, I.V.: Clusters of primordial black holes. *Eur. Phys. J. C* **79**(3), 246 (2019). <https://doi.org/10.1140/epjc/s10052-019-6741-4>. [arXiv:1807.06590](https://arxiv.org/abs/1807.06590) [astro-ph.CO]

446. Nakamura, T., Sasaki, M., Tanaka, T., Thorne, K.S.: Gravitational waves from coalescing black hole MACHO binaries. *Astrophys. J. Lett.* **487**, 139–142 (1997). <https://doi.org/10.1086/310886>. [arXiv:astro-ph/9708060](https://arxiv.org/abs/astro-ph/9708060)
447. Raidal, M., Vaskonen, V., Veermäe, H.: Gravitational waves from primordial black hole mergers. *JCAP* **09**, 037 (2017). <https://doi.org/10.1088/1475-7516/2017/09/037>. [arXiv:1707.01480](https://arxiv.org/abs/1707.01480) [astro-ph.CO]
448. Raidal, M., Spethmann, C., Vaskonen, V., Veermäe, H.: Formation and Evolution of Primordial Black Hole Binaries in the Early Universe (2018) [arXiv:1812.01930](https://arxiv.org/abs/1812.01930) [astro-ph.CO]
449. Young, S., Byrnes, C.T.: Initial clustering and the primordial black hole merger rate. *JCAP* **03**, 004 (2020). <https://doi.org/10.1088/1475-7516/2020/03/004>. [arXiv:1910.06077](https://arxiv.org/abs/1910.06077) [astro-ph.CO]
450. Mandic, V., Bird, S., Cholis, I.: Stochastic gravitational-wave background due to primordial binary black hole mergers. *Phys. Rev. Lett.* **117**(20), 201102 (2016). <https://doi.org/10.1103/PhysRevLett.117.201102>. [arXiv:1608.06699](https://arxiv.org/abs/1608.06699) [astro-ph.CO]
451. Clesse, S., García-Bellido, J.: Detecting the gravitational wave background from primordial black hole dark matter. *Phys. Dark Univ.* **18**, 105–114 (2017). <https://doi.org/10.1016/j.dark.2017.10.001>. [arXiv:1610.08479](https://arxiv.org/abs/1610.08479) [astro-ph.CO]
452. Wang, S., Terada, T., Kohri, K.: Prospective constraints on the primordial black hole abundance from the stochastic gravitational-wave backgrounds produced by coalescing events and curvature perturbations. *Phys. Rev. D* **99**(10), 103531 (2019). <https://doi.org/10.1103/PhysRevD.99.103531>. [arXiv:1903.05924](https://arxiv.org/abs/1903.05924) [astro-ph.CO]. [Erratum: *Phys. Rev. D* **101**, 069901 (2020)]
453. Bagui, E., Clesse, S.: A boosted gravitational-wave background for primordial black holes with broad mass distributions and thermal features (2021) [arXiv:2110.07487](https://arxiv.org/abs/2110.07487) [astro-ph.CO]
454. Braglia, M., García-Bellido, J., Kuroyanagi, S.: Testing Primordial Black Holes with multi-band observations of the stochastic gravitational wave background. *JCAP* **12**(12), 012 (2021). <https://doi.org/10.1088/1475-7516/2021/12/012>. [arXiv:2110.07488](https://arxiv.org/abs/2110.07488) [astro-ph.CO]
455. García-Bellido, J., Jaraba, S., Kuroyanagi, S.: The stochastic gravitational wave background from close hyperbolic encounters of primordial black holes in dense clusters (2021) [arXiv:2109.11376](https://arxiv.org/abs/2109.11376) [gr-qc]
456. Braglia, M., García-Bellido, J., Kuroyanagi, S.: Tracking the origin of black holes with the stochastic gravitational wave background popcorn signal (2022) [arXiv:2201.13414](https://arxiv.org/abs/2201.13414) [astro-ph.CO]
457. Arbey, A., Auffinger, J.: BlackHawk: A public code for calculating the Hawking evaporation spectra of any black hole distribution. *Eur. Phys. J. C* **79**(8), 693 (2019). <https://doi.org/10.1140/epjc/s10052-019-7161-1>. [arXiv:1905.04268](https://arxiv.org/abs/1905.04268) [gr-qc]
458. Dong, R., Kinney, W.H., Stojkovic, D.: Gravitational wave production by Hawking radiation from rotating primordial black holes. *JCAP* **10**, 034 (2016). <https://doi.org/10.1088/1475-7516/2016/10/034>. [arXiv:1511.05642](https://arxiv.org/abs/1511.05642) [astro-ph.CO]
459. Ananda, K.N., Clarkson, C., Wands, D.: The Cosmological gravitational wave background from primordial density perturbations. *Phys. Rev. D* **75**, 123518 (2007). <https://doi.org/10.1103/PhysRevD.75.123518>. [arXiv:gr-qc/0612013](https://arxiv.org/abs/gr-qc/0612013)
460. Baumann, D., Steinhardt, P.J., Takahashi, K., Ichiki, K.: Gravitational Wave Spectrum Induced by Primordial Scalar Perturbations. *Phys. Rev. D* **76**, 084019 (2007). <https://doi.org/10.1103/PhysRevD.76.084019>. [arXiv:hep-th/0703290](https://arxiv.org/abs/hep-th/0703290)
461. Inomata, K., Kawasaki, M., Mukaida, K., Tada, Y., Yanagida, T.T.: Inflationary primordial black holes for the LIGO gravitational wave events and pulsar timing array experiments. *Phys. Rev. D* **95**(12), 123510 (2017). <https://doi.org/10.1103/PhysRevD.95.123510>. [arXiv:1611.06130](https://arxiv.org/abs/1611.06130) [astro-ph.CO]
462. Nakama, T., Silk, J., Kamionkowski, M.: Stochastic gravitational waves associated with the formation of primordial black holes. *Phys. Rev. D* **95**(4), 043511 (2017). <https://doi.org/10.1103/PhysRevD.95.043511>. [arXiv:1612.06264](https://arxiv.org/abs/1612.06264) [astro-ph.CO]
463. Di, H., Gong, Y.: Primordial black holes and second order gravitational waves from ultra-slow-roll inflation. *JCAP* **07**, 007 (2018). <https://doi.org/10.1088/1475-7516/2018/07/007>. [arXiv:1707.09578](https://arxiv.org/abs/1707.09578) [astro-ph.CO]
464. Clesse, S., García-Bellido, J., Orani, S.: Detecting the Stochastic Gravitational Wave Background from Primordial Black Hole Formation (2018) [arXiv:1812.11011](https://arxiv.org/abs/1812.11011) [astro-ph.CO]
465. Bartolo, N., De Luca, V., Franciolini, G., Lewis, A., Peloso, M., Riotto, A.: Primordial black hole dark matter: LISA serendipity. *Phys. Rev. Lett.* **122**(21), 211301 (2019). <https://doi.org/10.1103/PhysRevLett.122.211301>. [arXiv:1810.12218](https://arxiv.org/abs/1810.12218) [astro-ph.CO]

466. Bartolo, N., De Luca, V., Franciolini, G., Peloso, M., Racco, D., Riotto, A.: Testing primordial black holes as dark matter with LISA. *Phys. Rev. D* **99**(10), 103521 (2019). <https://doi.org/10.1103/PhysRevD.99.103521>. arXiv:1810.12224 [astro-ph.CO]
467. Inomata, K., Nakama, T.: Gravitational waves induced by scalar perturbations as probes of the small-scale primordial spectrum. *Phys. Rev. D* **99**(4), 043511 (2019). <https://doi.org/10.1103/PhysRevD.99.043511>. arXiv:1812.00674 [astro-ph.CO]
468. Garcia-Bellido, J., Peloso, M., Unal, C.: Gravitational Wave signatures of inflationary models from Primordial Black Hole Dark Matter. *JCAP* **09**, 013 (2017). <https://doi.org/10.1088/1475-7516/2017/09/013>. arXiv:1707.02441 [astro-ph.CO]
469. Unal, C.: Imprints of primordial non-gaussianity on gravitational wave spectrum. *Phys. Rev. D* **99**(4), 041301 (2019). <https://doi.org/10.1103/PhysRevD.99.041301>. arXiv:1811.09151 [astro-ph.CO]
470. Romero-Rodriguez, A., Martinez, M., Pujolàs, O., Sakellariadou, M., Vaskonen, V.: Search for a scalar induced stochastic gravitational wave background in the third LIGO-Virgo observing run. *Phys. Rev. Lett.* **128**(5), 051301 (2022). <https://doi.org/10.1103/PhysRevLett.128.051301>. arXiv:2107.11660 [gr-qc]
471. Papanikolaou, T., Vennin, V., Langlois, D.: Gravitational waves from a universe filled with primordial black holes. *JCAP* **03**, 053 (2021). <https://doi.org/10.1088/1475-7516/2021/03/053>. arXiv:2010.11573 [astro-ph.CO]
472. Papanikolaou, T., Tzerefos, C., Basilakos, S., Saridakis, E.N.: Scalar induced gravitational waves from primordial black hole Poisson fluctuations in Starobinsky inflation (2021) arXiv:2112.15059 [astro-ph.CO]
473. Alba, V., Maldacena, J.: Primordial gravity wave background anisotropies. *JHEP* **03**, 115 (2016). [https://doi.org/10.1007/JHEP03\(2016\)115](https://doi.org/10.1007/JHEP03(2016)115). arXiv:1512.01531 [hep-th]
474. Contaldi, C.R.: Anisotropies of gravitational wave backgrounds: a line of sight approach. *Phys. Lett. B* **771**, 9–12 (2017). <https://doi.org/10.1016/j.physletb.2017.05.020>. arXiv:1609.08168 [astro-ph.CO]
475. Bartolo, N., Bertacca, D., Matarrese, S., Peloso, M., Ricciardone, A., Riotto, A., Tasinato, G.: Anisotropies and non-gaussianity of the cosmological gravitational wave background. *Phys. Rev. D* **100**(12), 121501 (2019). <https://doi.org/10.1103/PhysRevD.100.121501>. arXiv:1908.00527 [astro-ph.CO]
476. Bartolo, N., Bertacca, D., De Luca, V., Franciolini, G., Matarrese, S., Peloso, M., Ricciardone, A., Riotto, A., Tasinato, G.: Gravitational wave anisotropies from primordial black holes. *JCAP* **02**, 028 (2020). <https://doi.org/10.1088/1475-7516/2020/02/028>. arXiv:1909.12619 [astro-ph.CO]
477. Bartolo, N., Bertacca, D., Matarrese, S., Peloso, M., Ricciardone, A., Riotto, A., Tasinato, G.: Characterizing the cosmological gravitational wave background: anisotropies and non-gaussianity. *Phys. Rev. D* **102**(2), 023527 (2020). <https://doi.org/10.1103/PhysRevD.102.023527>. arXiv:1912.09433 [astro-ph.CO]
478. Domcke, V., Jinno, R., Rubira, H.: Deformation of the gravitational wave spectrum by density perturbations. *JCAP* **06**, 046 (2020). <https://doi.org/10.1088/1475-7516/2020/06/046>. arXiv:2002.11083 [astro-ph.CO]
479. Miller, A.L., Clesse, S., De Lillo, F., Bruno, G., Depasse, A., Tanasijczuk, A.: Probing planetary-mass primordial black holes with continuous gravitational waves. *Phys. Dark Univ.* **32**, 100836 (2021). <https://doi.org/10.1016/j.dark.2021.100836>. arXiv:2012.12983 [astro-ph.HE]
480. Guo, H.-K., Miller, A.: Searching for Mini Extreme Mass Ratio Inspirals with Gravitational-Wave Detectors (2022) arXiv:2205.10359 [astro-ph.IM]
481. Miller, A.L., Aggarwal, N., Clesse, S., De Lillo, F.: Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational-wave searches (2021) arXiv:2110.06188 [gr-qc]
482. Abbott, R., et al.: All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data (2022) arXiv:2201.00697 [gr-qc]
483. Garcia-Bellido, J., Nesseris, S.: Gravitational wave bursts from Primordial Black Hole hyperbolic encounters. *Phys. Dark Univ.* **18**, 123–126 (2017). <https://doi.org/10.1016/j.dark.2017.10.002>. arXiv:1706.02111 [astro-ph.CO]
484. García-Bellido, J., Nesseris, S.: Gravitational wave energy emission and detection rates of Primordial Black Hole hyperbolic encounters. *Phys. Dark Univ.* **21**, 61–69 (2018). <https://doi.org/10.1016/j.dark.2018.06.001>. arXiv:1711.09702 [astro-ph.HE]



485. Fuller, G.M., Kusenko, A., Takhistov, V.: Primordial black holes and  $r$ -process nucleosynthesis. *Phys. Rev. Lett.* **119**(6), 061101 (2017). <https://doi.org/10.1103/PhysRevLett.119.061101>. [arXiv:1704.01129](https://arxiv.org/abs/1704.01129) [astro-ph.HE]
486. Baker, M.J., Breitbach, M., Kopp, J., Mittnacht, L.: Primordial Black Holes from First-Order Cosmological Phase Transitions (2021) [arXiv:2105.07481](https://arxiv.org/abs/2105.07481) [astro-ph.CO]
487. Baker, M.J., Breitbach, M., Kopp, J., Mittnacht, L.: Detailed Calculation of Primordial Black Hole Formation During First-Order Cosmological Phase Transitions (2021) [arXiv:2110.00005](https://arxiv.org/abs/2110.00005) [astro-ph.CO]
488. Kawana, K., Xie, K.-P.: Primordial black holes from a cosmic phase transition: the collapse of Fermi-balls. *Phys. Lett. B* **824**, 136791 (2022). <https://doi.org/10.1016/j.physletb.2021.136791>. [arXiv:2106.00111](https://arxiv.org/abs/2106.00111) [astro-ph.CO]
489. Huang, P., Xie, K.-P.: Primordial black holes from an electroweak phase transition (2022) [arXiv:2201.07243](https://arxiv.org/abs/2201.07243) [hep-ph]
490. Marfatia, D., Tseng, P.-Y.: Correlated signals of first-order phase transitions and primordial black hole evaporation (2021) [arXiv:2112.14588](https://arxiv.org/abs/2112.14588) [hep-ph]
491. Hawking, S.W., Moss, I.G., Stewart, J.M.: Bubble collisions in the very early universe. *Phys. Rev. D* **26**, 2681 (1982). <https://doi.org/10.1103/PhysRevD.26.2681>
492. Jung, T.H., Okui, T.: Primordial black holes from bubble collisions during a first-order phase transition (2021) [arXiv:2110.04271](https://arxiv.org/abs/2110.04271) [hep-ph]
493. Liu, J., Bian, L., Cai, R.-G., Guo, Z.-K., Wang, S.-J.: Primordial black hole production during first-order phase transitions (2021) [arXiv:2106.05637](https://arxiv.org/abs/2106.05637) [astro-ph.CO]
494. Hashino, K., Kanemura, S., Takahashi, T.: Primordial black holes as a probe of strongly first-order electroweak phase transition (2021) [arXiv:2111.13099](https://arxiv.org/abs/2111.13099) [hep-ph]
495. Pierce, A., Riles, K., Zhao, Y.: Searching for dark photon dark matter with gravitational wave detectors. *Phys. Rev. Lett.* **121**(6), 061102 (2018). <https://doi.org/10.1103/PhysRevLett.121.061102>. [arXiv:1801.10161](https://arxiv.org/abs/1801.10161) [hep-ph]
496. Guo, H.-K., Riles, K., Yang, F.-W., Zhao, Y.: Searching for dark photon dark matter in LIGO O1 data. *Commun. Phys.* **2**, 155 (2019). <https://doi.org/10.1038/s42005-019-0255-0>. [arXiv:1905.04316](https://arxiv.org/abs/1905.04316) [hep-ph]
497. Abbott, R., et al.: Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run (2021) [arXiv:2105.13085](https://arxiv.org/abs/2105.13085) [astro-ph.CO]
498. Allen, B., Romano, J.D.: Detecting a stochastic background of gravitational radiation: Signal processing strategies and sensitivities. *Phys. Rev. D* **59**, 102001 (1999). <https://doi.org/10.1103/PhysRevD.59.102001>. [arXiv:gr-qc/9710117](https://arxiv.org/abs/gr-qc/9710117)
499. Miller, A.L., et al.: Probing new light gauge bosons with gravitational-wave interferometers using an adapted semicoherent method. *Phys. Rev. D* **103**(10), 103002 (2021). <https://doi.org/10.1103/PhysRevD.103.103002>. [arXiv:2010.01925](https://arxiv.org/abs/2010.01925) [astro-ph.IM]
500. Morisaki, S., Fujita, T., Michimura, Y., Nakatsuka, H., Obata, I.: Improved sensitivity of interferometric gravitational wave detectors to ultralight vector dark matter from the finite light-traveling time. *Phys. Rev. D* **103**(5), 051702 (2021). <https://doi.org/10.1103/PhysRevD.103.L051702>. [arXiv:2011.03589](https://arxiv.org/abs/2011.03589) [hep-ph]
501. Stadnik, Y., Flambaum, V.: Searching for dark matter and variation of fundamental constants with laser and maser interferometry. *Phys. Rev. Lett.* **114**, 161301 (2015)
502. Stadnik, Y., Flambaum, V.: Can dark matter induce cosmological evolution of the fundamental constants of nature? *Phys. Rev. Lett.* **115**, 201301 (2015)
503. Stadnik, Y., Flambaum, V.: Enhanced effects of variation of the fundamental constants in laser interferometers and application to dark-matter detection. *Phys. Rev. A* **93**, 063630 (2016)
504. Grote, H., Stadnik, Y.: Novel signatures of dark matter in laser-interferometric gravitational-wave detectors. *Physical Review Research* **1**(3), 033187 (2019)
505. Vermeulen, S.M., et al.: Direct limits for scalar field dark matter from a gravitational-wave detector (2021) [arXiv:2103.03783](https://arxiv.org/abs/2103.03783) [gr-qc]
506. Pierce, A., Zhang, Z., Zhao, Y., et al.: Dark photon dark matter produced by axion oscillations. *Phys. Rev. D* **99**(7), 075002 (2019)
507. Peccei, R.D., Quinn, H.R.: CP conservation in the presence of instantons. *Phys. Rev. Lett.* **38**, 1440–1443 (1977). <https://doi.org/10.1103/PhysRevLett.38.1440>
508. Preskill, J., Wise, M.B., Wilczek, F.: Cosmology of the invisible axion. *Phys. Lett. B* **120**, 127–132 (1983). [https://doi.org/10.1016/0370-2693\(83\)90637-8](https://doi.org/10.1016/0370-2693(83)90637-8)



509. Graham, P.W., Irastorza, I.G., Lamoreaux, S.K., Lindner, A., van Bibber, K.A.: Experimental searches for the axion and axion-like particles. *Ann. Rev. Nucl. Part. Sci.* **65**, 485–514 (2015). <https://doi.org/10.1146/annurev-nucl-102014-022120>. arXiv:1602.00039 [hep-ex]
510. Ayala, A., Domínguez, I., Giannotti, M., Mirizzi, A., Straniero, O.: Revisiting the bound on axion-photon coupling from Globular Clusters. *Phys. Rev. Lett.* **113**(19), 191302 (2014). <https://doi.org/10.1103/PhysRevLett.113.191302>. arXiv:1406.6053 [astro-ph.SR]
511. Ng, K.K.Y., Vitale, S., Hannuksela, O.A., Li, T.G.F.: Constraints on ultralight scalar bosons within black hole spin measurements from the ligo-virgo gwtc-2. *Phys. Rev. Lett.* **126**, 151102 (2021). <https://doi.org/10.1103/PhysRevLett.126.151102>
512. Gruzinov, A.: Black Hole Spindown by Light Bosons (2016) arXiv:1604.06422 [astro-ph.HE]
513. Davoudiasl, H., Denton, P.B.: Ultralight boson dark matter and event horizon telescope observations of M87\*. *Phys. Rev. Lett.* **123**(2), 021102 (2019). <https://doi.org/10.1103/PhysRevLett.123.021102>. arXiv:1904.09242 [astro-ph.CO]
514. Stott, M.J.: Ultralight Bosonic Field Mass Bounds from Astrophysical Black Hole Spin (2020) arXiv:2009.07206 [hep-ph]
515. Ng, K.K.Y., Vitale, S., Hannuksela, O.A., Li, T.G.F.: Constraints on ultralight scalar bosons within black hole spin measurements from the LIGO-Virgo GWTC-2. *Phys. Rev. Lett.* **126**(15), 151102 (2021). <https://doi.org/10.1103/PhysRevLett.126.151102>. arXiv:2011.06010 [gr-qc]
516. Baryakhtar, M., Galanis, M., Lasenby, R., Simon, O.: Black hole superradiance of self-interacting scalar fields. *Phys. Rev. D* **103**(9), 095019 (2021). <https://doi.org/10.1103/PhysRevD.103.095019>. arXiv:2011.11646 [hep-ph]
517. Chen, Y., Shu, J., Xue, X., Yuan, Q., Zhao, Y.: Probing axions with event horizon telescope polarimetric measurements. *Phys. Rev. Lett.* **124**, 061102 (2020). <https://doi.org/10.1103/PhysRevLett.124.061102>
518. Arvanitaki, A., Baryakhtar, M., Dimopoulos, S., Dubovsky, S., Lasenby, R.: Black hole mergers and the QCD axion at advanced LIGO. *Phys. Rev. D* **95**(4), 043001 (2017). <https://doi.org/10.1103/PhysRevD.95.043001>. arXiv:1604.03958 [hep-ph]
519. Zhu, S.J., Baryakhtar, M., Papa, M.A., Tsuna, D., Kawanaka, N., Eggenstein, H.-B.: Characterizing the continuous gravitational-wave signal from boson clouds around Galactic isolated black holes. *Phys. Rev. D* **102**(6), 063020 (2020). <https://doi.org/10.1103/PhysRevD.102.063020>. arXiv:2003.03359 [gr-qc]
520. Brito, R., Ghosh, S., Barausse, E., Berti, E., Cardoso, V., Dvorkin, I., Klein, A., Pani, P.: Stochastic and resolvable gravitational waves from ultralight bosons. *Phys. Rev. Lett.* **119**(13), 131101 (2017). <https://doi.org/10.1103/PhysRevLett.119.131101>. arXiv:1706.05097 [gr-qc]
521. Tsukada, L., Callister, T., Matas, A., Meyers, P.: First search for a stochastic gravitational-wave background from ultralight bosons. *Phys. Rev. D* **99**(10), 103015 (2019). <https://doi.org/10.1103/PhysRevD.99.103015>. arXiv:1812.09622 [astro-ph.HE]
522. Palomba, C., et al.: Direct constraints on ultra-light boson mass from searches for continuous gravitational waves. *Phys. Rev. Lett.* **123**, 171101 (2019). <https://doi.org/10.1103/PhysRevLett.123.171101>. arXiv:1909.08854 [astro-ph.HE]
523. Huang, J., Johnson, M.C., Sagunski, L., Sakellariadou, M., Zhang, J.: Prospects for axion searches with advanced ligo through binary mergers. *Phys. Rev. D* **99**, 063013 (2019). <https://doi.org/10.1103/PhysRevD.99.063013>
524. Zhang, J., Lyu, Z., Huang, J., Johnson, M.C., Sagunski, L., Sakellariadou, M., Yang, H.: First constraints on nuclear coupling of axionlike particles from the binary neutron star gravitational wave event GW170817. *Phys. Rev. Lett.* **127**(16), 161101 (2021). <https://doi.org/10.1103/PhysRevLett.127.161101>. arXiv:2105.13963 [hep-ph]
525. Kajantie, K., Laine, M., Rummukainen, K., Shaposhnikov, M.E.: Is there a hot electroweak phase transition at  $m_H \gtrsim m_W$  *Phys. Rev. Lett.* **77**, 2887–2890 (1996). <https://doi.org/10.1103/PhysRevLett.77.2887>. arXiv:hep-ph/9605288
526. Morrissey, D.E., Ramsey-Musolf, M.J.: Electroweak baryogenesis. *New J. Phys.* **14**, 125003 (2012). <https://doi.org/10.1088/1367-2630/14/12/125003>. arXiv:1206.2942 [hep-ph]
527. Barrow, J.L., et al.: Theories and Experiments for Testable Baryogenesis Mechanisms: A Snowmass White Paper (2022) arXiv:2203.07059 [hep-ph]
528. Craig, N., Englert, C., McCullough, M.: New probe of naturalness. *Phys. Rev. Lett.* **111**(12), 121803 (2013). <https://doi.org/10.1103/PhysRevLett.111.121803>. arXiv:1305.5251 [hep-ph]

529. Profumo, S., Ramsey-Musolf, M.J., Wainwright, C.L., Winslow, P.: Singlet-catalyzed electroweak phase transitions and precision Higgs boson studies. *Phys. Rev. D* **91**(3), 035018 (2015). <https://doi.org/10.1103/PhysRevD.91.035018>. arXiv:1407.5342 [hep-ph]
530. Barger, V., Langacker, P., McCaskey, M., Ramsey-Musolf, M.J., Shaughnessy, G.: LHC phenomenology of an extended standard model with a real scalar singlet. *Phys. Rev. D* **77**, 035005 (2008). <https://doi.org/10.1103/PhysRevD.77.035005>. arXiv:0706.4311 [hep-ph]
531. Espinosa, J.R., Konstandin, T., Riva, F.: Strong electroweak phase transitions in the standard model with a singlet. *Nucl. Phys. B* **854**, 592–630 (2012). <https://doi.org/10.1016/j.nuclphysb.2011.09.010>. arXiv:1107.5441 [hep-ph]
532. Chen, C.-Y., Kozaczuk, J., Lewis, I.M.: Non-resonant collider signatures of a singlet-driven electroweak phase transition. *JHEP* **08**, 096 (2017). [https://doi.org/10.1007/JHEP08\(2017\)096](https://doi.org/10.1007/JHEP08(2017)096). arXiv:1704.05844 [hep-ph]
533. Curtin, D., Meade, P., Yu, C.-T.: Testing electroweak baryogenesis with future colliders. *JHEP* **11**, 127 (2014). [https://doi.org/10.1007/JHEP11\(2014\)127](https://doi.org/10.1007/JHEP11(2014)127). arXiv:1409.0005 [hep-ph]
534. Kotwal, A.V., Ramsey-Musolf, M.J., No, J.M., Winslow, P.: Singlet-catalyzed electroweak phase transitions in the 100 TeV frontier. *Phys. Rev. D* **94**(3), 035022 (2016). <https://doi.org/10.1103/PhysRevD.94.035022>. arXiv:1605.06123 [hep-ph]
535. Huang, T., No, J.M., Pernié, L., Ramsey-Musolf, M., Safonov, A., Spannowsky, M., Winslow, P.: Resonant di-Higgs boson production in the  $b\bar{b}W$  channel: Probing the electroweak phase transition at the LHC. *Phys. Rev. D* **96**(3), 035007 (2017). <https://doi.org/10.1103/PhysRevD.96.035007>. arXiv:1701.04442 [hep-ph]
536. Li, H.-L., Ramsey-Musolf, M., Willocq, S.: Probing a scalar singlet-catalyzed electroweak phase transition with resonant di-Higgs boson production in the  $4b$  channel. *Phys. Rev. D* **100**(7), 075035 (2019). <https://doi.org/10.1103/PhysRevD.100.075035>. arXiv:1906.05289 [hep-ph]
537. No, J.M., Spannowsky, M.: Signs of heavy Higgs bosons at CLIC: An  $e^+e^-$  road to the electroweak phase transition. *Eur. Phys. J. C* **79**(6), 467 (2019). <https://doi.org/10.1140/epjc/s10052-019-6955-5>. arXiv:1807.04284 [hep-ph]
538. Buttazzo, D., Redigolo, D., Sala, F., Tesi, A.: Fusing vectors into scalars at high energy lepton colliders. *JHEP* **11**, 144 (2018). [https://doi.org/10.1007/JHEP11\(2018\)144](https://doi.org/10.1007/JHEP11(2018)144). arXiv:1807.04743 [hep-ph]
539. Liu, W., Xie, K.-P.: Probing electroweak phase transition with multi-TeV muon colliders and gravitational waves. *JHEP* **04**, 015 (2021). [https://doi.org/10.1007/JHEP04\(2021\)015](https://doi.org/10.1007/JHEP04(2021)015). arXiv:2101.10469 [hep-ph]
540. Carena, M., Krause, C., Liu, Z., Wang, Y.: New approach to electroweak symmetry non-restoration. *Phys. Rev. D* **104**(5), 055016 (2021). <https://doi.org/10.1103/PhysRevD.104.055016>. arXiv:2104.00638 [hep-ph]
541. Kozaczuk, J., Ramsey-Musolf, M.J., Shelton, J.: Exotic Higgs boson decays and the electroweak phase transition. *Phys. Rev. D* **101**(11), 115035 (2020). <https://doi.org/10.1103/PhysRevD.101.115035>. arXiv:1911.10210 [hep-ph]
542. Weir, D.J.: <https://www.ptplot.org/ptplot/>
543. Craig, N., Lou, H.K., McCullough, M., Thalappilil, A.: The higgs portal above threshold. *JHEP* **02**, 127 (2016). [https://doi.org/10.1007/JHEP02\(2016\)127](https://doi.org/10.1007/JHEP02(2016)127). arXiv:1412.0258 [hep-ph]
544. Chacko, Z., Cui, Y., Hong, S.: Exploring a Dark Sector Through the Higgs Portal at a Lepton Collider. *Phys. Lett. B* **732**, 75–80 (2014) arXiv:1311.3306 [hep-ph]. <https://doi.org/10.1016/j.physletb.2014.03.010>
545. Ruhdorfer, M., Salvioni, E., Weiler, A.: A Global View of the Off-Shell Higgs Portal. *SciPost Phys.* **8**, 027 (2020) arXiv:1910.04170 [hep-ph]. <https://doi.org/10.21468/SciPostPhys.8.2.027>
546. Garcia-Abenza, A., No, J.M.: Shining light into the Higgs portal with  $\gamma\gamma$  colliders. *Eur. Phys. J. C* **82**(2), 182 (2022) arXiv:2011.03551 [hep-ph]. <https://doi.org/10.1140/epjc/s10052-022-10089-3>
547. Dorsch, G.C., Huber, S.J., Mimasu, K., No, J.M.: Echoes of the Electroweak Phase Transition: Discovering a second Higgs doublet through  $A_0 \rightarrow ZH_0$ . *Phys. Rev. Lett.* **113**(21), 211802 (2014) arXiv:1405.5537 [hep-ph]. <https://doi.org/10.1103/PhysRevLett.113.211802>
548. Dorsch, G.C., Huber, S.J., Mimasu, K., No, J.M.: Hierarchical versus degenerate 2HDM: The LHC run 1 legacy at the onset of run 2. *Phys. Rev. D* **93**(11), 115033 (2016) arXiv:1601.04545 [hep-ph]. <https://doi.org/10.1103/PhysRevD.93.115033>
549. Cepeda, M., *et al.*: Report from Working Group 2: Higgs Physics at the HL-LHC and HE-LHC. CERN Yellow Rep. Monogr. 7, 221–584 (2019) arXiv:1902.00134 [hep-ph]. <https://doi.org/10.23731/CYRM-2019-007.221>

550. Chala, M., Ramos, M., Spannowsky, M.: Gravitational wave and collider probes of a triplet Higgs sector with a low cutoff. *Eur. Phys. J. C* **79**(2), 156 (2019) [arXiv:1812.01901](https://arxiv.org/abs/1812.01901) [hep-ph]. <https://doi.org/10.1140/epjc/s10052-019-6655-1>
551. Chiang, C.-W., Cottin, G., Du, Y., Fuyuto, K., Ramsey-Musolf, M.J.: Collider Probes of Real Triplet Scalar Dark Matter. *JHEP* **01**, 198 (2021) [arXiv:2003.07867](https://arxiv.org/abs/2003.07867) [hep-ph]. [https://doi.org/10.1007/JHEP01\(2021\)198](https://doi.org/10.1007/JHEP01(2021)198)
552. Bai, Y., Berger, J.: Lepton portal dark matter. *JHEP* **08**, 153 (2014). [https://doi.org/10.1007/JHEP08\(2014\)153](https://doi.org/10.1007/JHEP08(2014)153). [arXiv:1402.6696](https://arxiv.org/abs/1402.6696) [hep-ph]
553. Niemi, L., Schicho, P., Tenkanen, T.V.I.: Singlet-assisted electroweak phase transition at two loops. *Phys. Rev. D* **103**(11), 115035 (2021) [arXiv:2103.07467](https://arxiv.org/abs/2103.07467) [hep-ph]. <https://doi.org/10.1103/PhysRevD.103.115035>
554. Kainulainen, K., Keus, V., Niemi, L., Rummukainen, K., Tenkanen, T.V.I., Vaskonen, V.: On the validity of perturbative studies of the electroweak phase transition in the Two Higgs Doublet model. *JHEP* **06**, 075 (2019) [arXiv:1904.01329](https://arxiv.org/abs/1904.01329) [hep-ph]. [https://doi.org/10.1007/JHEP06\(2019\)075](https://doi.org/10.1007/JHEP06(2019)075)
555. Carena, M., Quiros, M., Wagner, C.E.M.: Opening the window for electroweak baryogenesis. *Phys. Lett. B* **380**, 81–91 (1996) [arXiv:hep-ph/9603420](https://arxiv.org/abs/hep-ph/9603420). [https://doi.org/10.1016/0370-2693\(96\)00475-3](https://doi.org/10.1016/0370-2693(96)00475-3)
556. Delepine, D., Gerard, J.M., Gonzalez Felipe, R., Weyers, J.: A Light stop and electroweak baryogenesis. *Phys. Lett. B* **386**, 183–188 (1996) [arXiv:hep-ph/9604440](https://arxiv.org/abs/hep-ph/9604440). [https://doi.org/10.1016/0370-2693\(96\)00921-5](https://doi.org/10.1016/0370-2693(96)00921-5)
557. Menon, A., Morrissey, D.E.: Higgs Boson Signatures of MSSM Electroweak Baryogenesis. *Phys. Rev. D* **79**, 115020 (2009) [arXiv:0903.3038](https://arxiv.org/abs/0903.3038) [hep-ph]. <https://doi.org/10.1103/PhysRevD.79.115020>
558. Cohen, T., Morrissey, D.E., Pierce, A.: Electroweak Baryogenesis and Higgs Signatures. *Phys. Rev. D* **86**, 013009 (2012) [arXiv:1203.2924](https://arxiv.org/abs/1203.2924) [hep-ph]. <https://doi.org/10.1103/PhysRevD.86.013009>
559. Curtin, D., Jaiswal, P., Meade, P.: Excluding Electroweak Baryogenesis in the MSSM. *JHEP* **08**, 005 (2012) [arXiv:1203.2932](https://arxiv.org/abs/1203.2932) [hep-ph]. [https://doi.org/10.1007/JHEP08\(2012\)005](https://doi.org/10.1007/JHEP08(2012)005)
560. Carena, M., Nardini, G., Quiros, M., Wagner, C.E.M.: MSSM Electroweak Baryogenesis and LHC Data. *JHEP* **02**, 001 (2013) [arXiv:1207.6330](https://arxiv.org/abs/1207.6330) [hep-ph]. [https://doi.org/10.1007/JHEP02\(2013\)001](https://doi.org/10.1007/JHEP02(2013)001)
561. Huang, W., Kang, Z., Shu, J., Wu, P., Yang, J.M.: New insights in the electroweak phase transition in the NMSSM. *Phys. Rev. D* **91**(2), 025006 (2015) [arXiv:1405.1152](https://arxiv.org/abs/1405.1152) [hep-ph]. <https://doi.org/10.1103/PhysRevD.91.025006>
562. Kozaczuk, J., Profumo, S., Haskins, L.S., Wainwright, C.L.: Cosmological Phase Transitions and their Properties in the NMSSM. *JHEP* **01**, 144 (2015) [arXiv:1407.4134](https://arxiv.org/abs/1407.4134) [hep-ph]. [https://doi.org/10.1007/JHEP01\(2015\)144](https://doi.org/10.1007/JHEP01(2015)144)
563. Huber, S.J., Konstandin, T., Nardini, G., Rues, I.: Detectable Gravitational Waves from Very Strong Phase Transitions in the General NMSSM. *JCAP* **03**, 036 (2016) [arXiv:1512.06357](https://arxiv.org/abs/1512.06357) [hep-ph]. <https://doi.org/10.1088/1475-7516/2016/03/036>
564. Nelson, A.E., Seiberg, N.: R symmetry breaking versus supersymmetry breaking. *Nucl. Phys. B* **416**, 46–62 (1994). [https://doi.org/10.1016/0550-3213\(94\)90577-0](https://doi.org/10.1016/0550-3213(94)90577-0). [arXiv:hep-ph/9309299](https://arxiv.org/abs/hep-ph/9309299)
565. Maggiore, M.: Gravitational wave experiments and early universe cosmology. *Phys. Rep.* **331**, 283 (2000)
566. Regimbau, R.: The astrophysical gravitational wave stochastic background. *Res. Astron. Astroph.* **11**, 1674 (2011)
567. Allen, B., Romano, J.D.: Detecting a stochastic background of gravitational radiation: Signal processing strategies and sensitivities. *Phys. Rev. D* **59**, 102001 (1999)
568. Romano, J.D., Cornish, N.J.: Detection methods for stochastic gravitational-wave backgrounds: a unified treatment. *Liv. Rev. Relativ.* **20**, 2 (2017)
569. Contaldi, C.: Anisotropies of gravitational wave backgrounds: A line of sight approach. *Phys. Lett. B* **771**, 9 (2017)
570. Jenkins, A.C., Sakellariadou, M.: Anisotropies in the stochastic gravitational-wave background: Formalism and the cosmic string case. *Phys. Rev. D* **98**, 063509 (2018)
571. Jenkins, A.C., M. Sakellariadou, M., Regimbau, T., Slezak, E.: Anisotropies in the astrophysical gravitational-wave background: Predictions for the detection of compact binaries by ligo and virgo. *Phys. Rev. D* **98**, 063501 (2018)
572. Jenkins, A.C., O’Shaughnessy, R., Sakellariadou, M., Wysocki, D.: Anisotropies in the astrophysical gravitational-wave background: The impact of black hole distributions. *Phys. Rev. Lett.* **122**, 111101 (2019)

573. Jenkins, A.C., Sakellariadou, M.: Shot noise in the astrophysical gravitational-wave background. *Phys. Rev. D* **100**, 063508 (2019)
574. Jenkins, A.C., Romano, J.D., Sakellariadou, M.: Estimating the angular power spectrum of the gravitational-wave background in the presence of shot noise. *Phys. Rev. D* **100**, 083501 (2019)
575. Bertacca, D., et al.: Projection effects on the observed angular spectrum of the astrophysical stochastic gravitational wave background. *Phys. Rev. D* **101**, 103513 (2020)
576. Cusin, G., Pitrou, C., Uzan, J.-P.: Anisotropy of the astrophysical gravitational wave background: Analytic expression of the angular power spectrum and correlation with cosmological observations. *Phys. Rev. Lett.* **96**, 103019 (2017)
577. Cusin, G., Pitrou, C., Uzan, J.-P.: The signal of the stochastic gravitational wave background and the angular correlation of its energy density. *Phys. Rev. D* **97**, 123527 (2018)
578. Cusin, G., Dvorkin, I., Pitrou, C., Uzan, J.-P.: First predictions of the angular power spectrum of the astrophysical gravitational wave background. *Phys. Rev. Lett.* **120**, 231101 (2018)
579. Cusin, G., Dvorkin, I., Pitrou, C., Uzan, J.-P.: Comment on the article “anisotropies in the astrophysical gravitational-wave background: The impact of black hole distributions” by a.c. jenkins et al. [[arXiv:1810.13435](https://arxiv.org/abs/1810.13435)]. [arXiv:1811.03582](https://arxiv.org/abs/1811.03582) (2018)
580. Cusin, G., Dvorkin, I., Pitrou, C., Uzan, J.-P.: Properties of the stochastic astrophysical gravitational wave background: astrophysical sources dependencies. *Phys. Rev. D* **100**, 063004 (2019)
581. Pitrou, C., Cusin, G., Uzan, J.-P.: A unified view of anisotropies in the astrophysical gravitational wave background. *Phys. Rev. D* **101**, 081301 (2020)
582. Alonso, D., Cusin, G., Ferreira, P.G., Pitrou, C.: Detecting the anisotropic astrophysical gravitational wave background in the presence of shot noise through cross-correlations. *Phys. Rev. D* **102**, 023002 (2020)
583. Cusin, G., Dvorkin, I., Pitrou, C., Uzan, J.-P.: Stochastic gravitational wave background anisotropies in the mhz band: astrophysical dependencies. *Mon. Not. R. Astron. Soc.* **493**, 1 (2019)
584. Cusin, G., Durrer, R., Ferreira, P.G.: Polarization of a stochastic gravitational wave background through diffusion by massive structures. *Phys. Rev. D* **99**(2), 023534 (2019) [arXiv:1807.10620](https://arxiv.org/abs/1807.10620) [astro-ph.CO]. <https://doi.org/10.1103/PhysRevD.99.023534>
585. Canas-Herrera, G., Contigiani, O., Vardanyan, V.: Cross-correlation of the astrophysical gravitational-wave background with galaxy clustering. *Phys. Rev. D* **102**, 043513 (2020)
586. Geller, M., Hook, A., Sundrum, R., Tsai, Y.: Primordial anisotropies in the gravitational wave background from cosmological phase transitions. *Phys. Rev. Lett.* **121**, 201303 (2018)
587. Bartolo, N., et al.: Anisotropies and non-gaussianity of the cosmological gravitational wave background. *Phys. Rev. D* **100**, 121501 (2019)
588. Bartolo, N., et al.: Characterizing the cosmological gravitational wave background: Anisotropies and non-gaussianity. *Phys. Rev. D* **102**, 023527 (2020)
589. Adshead, P., Afshordi, N., Dimastrogiovanni, E., Fasiello, M., Lim, E.A., Tasinato, G.: Multimessenger cosmology: Correlating cosmic microwave background and stochastic gravitational wave background measurements. *Phys. Rev. D* **103**(2), 023532 (2021) [arXiv:2004.06619](https://arxiv.org/abs/2004.06619) [astro-ph.CO]. <https://doi.org/10.1103/PhysRevD.103.023532>
590. Dall’Armi, L.V., Ricciardone, A., Bartolo, N., Bertacca, D., Matarrese, S.: The imprint of relativistic particles on the anisotropies of the stochastic gravitational-wave background. *Phys. Rev. D* **103**, 023522 (2021)
591. Bellomo, N., Bertacca, D., Jenkins, A.C., Matarrese, S., Raccanelli, A., Regimbau, T., Ricciardone, A., Sakellariadou, M.: CLASS\_GWB: robust modeling of the astrophysical gravitational wave background anisotropies (2021) [arXiv:2110.15059](https://arxiv.org/abs/2110.15059) [gr-qc]
592. Domcke, V., Jinno, R., Rubira, H.: Deformation of the gravitational wave spectrum by density perturbations. *JCAP* **06**, 046 (2020)
593. Ricciardone, A., et al.: Cross-correlating Astrophysical and Cosmological Gravitational Wave Backgrounds with the Cosmic Microwave Background. *Phys. Rev. Lett.* **127**, 271301 (2021)
594. Braglia, M., Kuroyanagi, S.: Probing pre-Recombination Physics by the Cross-Correlation of Stochastic Gravitational Waves and CMB Anisotropies. *Phys. Rev. D* **104**, 123547 (2021)
595. Mukherjee, S., Silk, J.: Time-dependence of the astrophysical stochastic gravitational wave background. *Mon. Not. R. Astron. Soc.* **491**, 4690 (2020)
596. Alonso, D., Cusin, G., Ferreira, P.G., Pitrou, C.: Detecting the anisotropic astrophysical gravitational wave background in the presence of shot noise through cross-correlations. *Phys. Rev. D* **102**(2), 023002 (2020) [arXiv:2002.02888](https://arxiv.org/abs/2002.02888) [astro-ph.CO]. <https://doi.org/10.1103/PhysRevD.102.023002>

597. Mukherjee, S., Silk, J.: Fundamental physics using the temporal gravitational wave background. *Phys. Rev. D* **104**, 063518 (2021). <https://doi.org/10.1103/PhysRevD.104.063518>
598. Grishchuk, L.P.: Amplification of gravitational waves in an isotropic universe. *Sov. Phys. JETP* **40**, 409 (1975)
599. Bar-Kana, R.: Limits on direct detection of gravitational waves. *Phys. Rev. D* **50**, 1157 (1994)
600. Starobinskii, A.A.: Spectrum of relict gravitational radiation and the early state of the universe. *JETP Lett.* **30**, 682 (1979)
601. Seto, N., Taruya, A.: Measuring a parity violation signature in the early universe via ground-based laser interferometers. *Phys. Rev. Lett.* **99**, 121101 (2007)
602. Easther, R., Lim, E.A.: Stochastic gravitational wave production after inflation. *JCAP* **0604**, 010 (2006)
603. Witten, E.: Cosmic separation of phases. *Phys. Rev. D* **30**, 272 (1984)
604. Hogan, C.J.: Gravitational radiation from cosmological phase transitions. *Mon. Not. R. Astron. Soc.* **218**, 629 (1986)
605. Turner, M.S., Wilczek, F.: Relic gravitational waves and extended inflation. *Phys. Rev. Lett.* **65**, 3080 (1990)
606. Kosowsky, A., Turner, M.S., Watkins, R.: Gravitational waves from first-order cosmological phase transitions. *Phys. Rev. Lett.* **69**, 2026 (1992)
607. Kamionkowski, M., et al.: Gravitational radiation from first-order phase transitions. *Phys. Rev. D* **49**, 2837 (1994)
608. Apreda, R., et al.: Gravitational waves from electroweak phase transitions. *Nucl. Phys. B* **631**, 342 (2002)
609. Caprini, C., et al.: Gravitational wave generation from bubble collisions in first-order phase transitions: an analytic approach. *Phys. Rev. D* **77**, 124015 (2008)
610. Binetruy, P., et al.: Cosmological backgrounds of gravitational waves and elisa/ngo: phase transitions, cosmic strings and other sources. *J. Cosm. Astrop. Phys.* **2012**, 027 (2012)
611. Caprini, C., et al.: Science with the space-based interferometer elisa. ii: Gravitational waves from cosmological phase transitions. *JCAP* **1604**, 001 (2016)
612. Fitz Axen, M., Banagiri, S., Matas, A., Caprini, C., V. Mandic, V.: Multi-wavelength observations of cosmological phase transitions using lisa and cosmic explorer. *Phys. Rev. D* **98**, 103508 (2018)
613. Caldwell, R.R., Allen, B.: Cosmological constraints on cosmic-string gravitational radiation. *Phys. Rev. D* **45**, 3447 (1992)
614. Damour, T., Vilenkin, A.: Gravitational wave bursts from cosmic strings. *Phys. Rev. Lett.* **85**, 3761 (2000)
615. X. Siemens, X., Mandic, V., Creighton, J.: Gravitational-wave stochastic background from cosmic strings. *Phys. Rev. Lett.* **98**, 111101 (2007)
616. Olmez, S., Mandic, V., Siemens, X.: Gravitational-wave stochastic background from kinks and cusps on cosmic strings. *Phys. Rev. D* **81**, 104028 (2010)
617. Siemens, X., et al.: Gravitational wave bursts from cosmic (super)strings: Quantitative analysis and constraints. *Phys. Rev. D* **73**, 105001 (2006)
618. Lorenz, L., et al.: Cosmic string loop distribution on all length scales and at any redshift. *JCAP* **1010**, 003 (2010)
619. Blanco-Pillado, J.J., et al.: Number of cosmic string loops. *Phys. Rev. D* **89**, 023512 (2014)
620. Abbott, B.P., et al.: Constraints on cosmic strings using data from the first advanced ligo observing run. *Phys. Rev. D* **97**, 102002 (2018)
621. Olmez, S., Mandic, V., Siemens, X.: Anisotropies in the gravitational-wave stochastic background. *J. Cosm. Astrop. Phys.* **07**, 009 (2012)
622. Raccanelli, A., Kovetz, E.D., Bird, S., Cholis, I., Muñoz, J.B.: Determining the progenitors of merging black-hole binaries. *Phys. Rev. D* **94**, 023516 (2016)
623. Raccanelli, A.: Gravitational wave astronomy with radio galaxy surveys. *Mon. Not. R. Astron. Soc.* **469**, 656 (2017)
624. Nishikawa, H., Kovetz, E.D., Kamionkowski, M., Silk, J.: Primordial-black-hole mergers in dark-matter spikes. *Phys. Rev. D* **99**, 043533 (2019)
625. Scelfo, G., Bellomo, N., Raccanelli, A., Matarrese, S., Verde, L.:  $G \times lss$ : chasing the progenitors of merging binary black holes. *JCAP* **2018**, 039 (2018)
626. Stiskalek, R., Veitch, J., Messenger, C.: Are stellar mass binary black hole mergers isotropically distributed? *Mon. Not. R. Astron. Soc.* **501**, 970 (2021)

627. Payne, E., Banagiri, S., Lasky, P., Thrane, E.: Searching for anisotropy in the distribution of binary black hole mergers. *Phys. Rev. D* **102**, 102004 (2020)
628. Bera, S., Rana, D., More, S., Bose, S.: Incompleteness be damned: Inference of  $h_0$  from bbh-galaxy cross-correlations. *Ap. J.* **902**, 79 (2020)
629. Callister, T., Fishbach, M., Holz, D.E., Farr, W.: Shouts and murmurs: Combining individual gravitational-wave sources with the stochastic background to measure the history of binary black hole mergers. *Ap. J. Lett.* **896**, 32 (2020)
630. Abbott, B.P., et al.: Directional limits on persistent gravitational waves from advanced ligo's first observing run. *Phys. Rev. Lett.* **118**, 121102 (2017)
631. Abbott, B.P., et al.: Directional limits on persistent gravitational waves using data from advanced ligo's first two observing runs. *Phys. Rev. D* **100**, 062001 (2019)
632. Adams, M.R., Cornish, N.J.: Detecting a stochastic gravitational wave background in the presence of a galactic foreground and instrument noise. *Phys. Rev. D* **89**, 022001 (2014)
633. Yang, K.Z., Mandic, V., Scarlata, C., Banagiri, S.: Searching for cross-correlation between stochastic gravitational wave background and galaxy number counts. *Mon. Not. R. Astron. Soc.* **500**, 1666 (2021)
634. Smith, R., Thrane, E.: Optimal search for an astrophysical gravitational-wave background. *Phys. Rev. X* **8**, 021019 (2018)
635. Banagiri, S., Mandic, V., Scarlata, C., Yang, K.Z.: Measuring angular n-point correlations of binary black-hole merger gravitational-wave events with hierarchical bayesian inference. *Phys. Rev. D* **102**, 063007 (2020)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Authors and Affiliations

Robert Caldwell<sup>1</sup> · Yanou Cui<sup>2</sup> · Huai-Ke Guo<sup>3</sup>  · Vuk Mandic<sup>4</sup> · Alberto Mariotti<sup>5</sup> · Jose Miguel No<sup>6</sup> · Michael J. Ramsey-Musolf<sup>7,8</sup> · Mairi Sakellariadou<sup>9</sup> · Kuver Sinha<sup>10</sup> · Lian-Tao Wang<sup>11</sup> · Graham White<sup>12</sup> · Yue Zhao<sup>3</sup> · Haipeng An<sup>13,14,15</sup> · Ligong Bian<sup>15,16</sup> · Chiara Caprini<sup>17,18</sup> · Sebastien Clesse<sup>19</sup> · James M. Cline<sup>20</sup> · Giulia Cusin<sup>17,21</sup> · Bartosz Fornal<sup>22</sup> · Ryusuke Jinno<sup>6</sup> · Benoit Laurent<sup>20</sup> · Noam Levi<sup>23</sup>  · Kun-Feng Lyu<sup>4</sup> · Mario Martinez<sup>24</sup>  · Andrew L. Miller<sup>25</sup>  · Diego Redigolo<sup>26</sup>  · Claudia Scarlata<sup>4</sup>  · Alexander Sevrin<sup>5</sup>  · Barmak Shams Es Haghi<sup>3</sup>  · Jing Shu<sup>27,28,29,30</sup>  · Xavier Siemens<sup>31</sup> · Danièle A. Steer<sup>32</sup>  · Raman Sundrum<sup>33</sup> · Carlos Tamarit<sup>34</sup>  · David J. Weir<sup>35</sup>  · Ke-Pan Xie<sup>36</sup>  · Feng-Wei Yang<sup>3</sup>  · Siyi Zhou<sup>37</sup> 

<sup>1</sup> Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, USA

<sup>2</sup> Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA

<sup>3</sup> Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA

<sup>4</sup> School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

<sup>5</sup> Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, and International Solvay Institutes, Pleinlaan 2, 1050 Brussels, Belgium

<sup>6</sup> Instituto de Física Teórica UAM/CSIC, C/ Nicolás Cabrera 13- 15, Campus de Cantoblanco, 28049 Madrid, Spain



- 7 Tsung Dao Lee Institute/Shanghai Jiao Tong University, Shanghai 200120, People's Republic of China
- 8 University of Massachusetts, Amherst, MA 01003, USA
- 9 Physics Department, King's College London, Strand, London WC2R 2LS, UK
- 10 Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
- 11 Department of Physics, University of Chicago, Chicago, IL 60637, USA
- 12 Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
- 13 Department of Physics, Tsinghua University, Beijing 100084, People's Republic of China
- 14 Center for High Energy Physics, Tsinghua University, Beijing 100084, People's Republic of China
- 15 Center for High Energy Physics, Peking University, Beijing 100871, People's Republic of China
- 16 Department of Physics and Chongqing Key Laboratory for Strongly Coupled Physics, Chongqing University, Chongqing 401331, People's Republic of China
- 17 Theoretical Physics Department, University of Geneva, 1211 Geneva, Switzerland
- 18 CERN, Theoretical Physics Department, 1 Esplanade des Particules, 1211 Genève 23, Switzerland
- 19 Service de Physique Théorique (CP225), University of Brussels (ULB), Boulevard du Triomphe, 1050 Brussels, Belgium
- 20 Department of Physics, McGill University, Montréal, QC H3A2T8, Canada
- 21 Sorbonne Université, CNRS, UMR 7095, Institut d'Astrophysique de Paris, 75014 Paris, France
- 22 Department of Chemistry and Physics, Barry University, Miami Shores, FL 33161, USA
- 23 Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel
- 24 Institut de Física d'Altes Energies, Barcelona Institute of Science and Technology and ICREA, 08193 Barcelona, Spain
- 25 Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium
- 26 INFN, Sezione di Firenze Via G. Sansone 1, 50019 Sesto Fiorentino, Italy
- 27 CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China
- 28 School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
- 29 School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, People's Republic of China
- 30 International Center for Theoretical Physics Asia-Pacific, Beijing, Hanzhou, People's Republic of China
- 31 Department of Physics, Oregon State University, Corvallis, OR 97331, USA
- 32 Laboratoire Astroparticule et Cosmologie, CNRS, Université Paris Cité, 75013 Paris, France
- 33 University of Maryland, College Park, MD 20742, USA
- 34 Physik-Department T70, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany
- 35 Department of Physics and Helsinki Institute of Physics, University of Helsinki, P.O. Box 64, 00014 Helsinki, Finland

<sup>36</sup> Department of Physics and Astronomy, University of Nebraska, Lincoln, NE 68588, USA

<sup>37</sup> Department of Physics, Kobe University, Kobe 657-8501, Japan