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To cite this article: K Saikawa 2020 *J. Phys.: Conf. Ser.* **1586** 012039

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Gravitational waves from cosmic domain walls: a mini-review

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Abstract. Domain walls are sheet-like topological defects produced when a discrete symmetry is spontaneously broken in the early universe. Although the existence of stable domain walls is disfavored by cosmological considerations, it is possible to consider unstable domain walls which disappear early enough not to lead cosmological disasters. In this contribution, we discuss the possibility that a significant amount of gravitational waves is produced by annihilation of such unstable domain walls in the early universe. After reviewing cosmological evolution of domain walls, we give an estimate of the expected gravitational wave signal based on the results of numerical simulations. In addition, we briefly review some well-motivated particle physics models that predict the formation of unstable domain walls. The detectability of predicted signals is also discussed in prospect of planned gravitational wave observatories.

1. Introduction

Since the recent direct observations, gravitational waves (GWs) are now getting more attention as an alternative way to probe the structure of our universe. Benefiting from substantial improvements in experimental sensitivities, we expect to obtain a lot of information about various astrophysical and cosmological phenomena from GW astronomy in the coming decades. In this context, it will become more important to investigate possible origins of GWs that can be relevant to present and future observations. In this contribution, we discuss domain walls as cosmological sources of GWs.

2. Domain walls

Domain walls are sheet-like topological defects that can be formed in the early universe when a discrete symmetry is spontaneously broken [1]. As a simple example, let us consider a theory of one real scalar field ϕ with a potential of the form

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2, \quad (1)$$

where v and λ are some real parameters. There is a discrete Z_2 symmetry given by the transformation $\phi \rightarrow -\phi$, which is spontaneously broken when the scalar field acquires a vacuum expectation value (VEV) $\langle\phi\rangle = \pm v$. Afterwards, two different domains (i.e. the region with $\langle\phi\rangle = v$ and that with $\langle\phi\rangle = -v$) are populated in the universe, but such regions must be finite because of the causality. This fact implies that there exist sheet-like regions around the



boundary between two different vacua, and in such regions the field energy density becomes higher than the surrounding domains. We call such field configurations *domain walls*. The properties of domain walls can be characterized by two quantities. One is their width δ , which is roughly given by the mass scale of the field which causes the spontaneous breaking of discrete symmetry ($\delta \sim m_\phi^{-1} \sim (\sqrt{\lambda}v)^{-1}$ in the above example), and the other is their tension σ , which corresponds to their surface energy density ($\sigma \sim \lambda^{1/2}v^3$ in the above example).

It is known that domain walls eventually enter into the so called scaling regime, where the system tends to evolve such that there are always $\mathcal{O}(1)$ walls within one Hubble radius [2]. In such a regime, the typical distance between two neighboring walls is given by the Hubble radius $\sim t$, which implies that the energy density of domain walls scales as $\rho_{\text{wall}} \sim \sigma/t$. Note that their energy density $\rho_{\text{wall}} \propto t^{-1}$ decays slower than that of cold matter $\rho_{\text{matter}} \propto a(t)^{-3}$ and radiations $\rho_{\text{radiation}} \propto a(t)^{-4}$, where $a(t)$ is the scale factor of the universe, and $a(t) \propto t^{1/2}$ in the radiation dominated universe. As a consequence, they eventually dominate over the energy density of the universe, conflicting with the standard cosmology [3].

One possible way to avoid the above mentioned domain wall problem is to assume that inflation happened after the spontaneous breaking of the discrete symmetry. In this case, domain walls become irrelevant for the late time cosmology, since their density is exponentially suppressed due to the inflationary expansion. On the other hand, it is also possible to avoid the domain wall problem even if inflation happened before the spontaneous breaking of the discrete symmetry, once we assume that domain walls are unstable and annihilated before they overclose the universe. In the following, we focus on the latter scenario.

Domain walls can be annihilated if we assume that the discrete symmetry is only approximate and there exists an energy bias that lifts the degenerate vacua [4, 5, 6]. Let us quantify this effect by introducing the parameter V_{bias} that corresponds to the difference of the potential energy between quasi-degenerate minima (figure 1). If V_{bias} is sufficiently large, it acts as a volume pressure $p_V \sim V_{\text{bias}}$ on the walls. The annihilation of domain walls occurs when this volume pressure becomes comparable to their tension $p_T \sim \sigma/R$, where R is the typical curvature radius of the walls. From the condition $p_T \sim p_V$ and the scaling relation $R \sim t$, we can estimate the time scale of the annihilation, $t_{\text{ann}} \sim \sigma/V_{\text{bias}}$. In the radiation dominated era, this time scale corresponds to the following temperature of the universe,

$$T_{\text{ann}} \sim 10 \text{ MeV} \left(\frac{\sigma}{1 \text{ TeV}^3} \right)^{-1/2} \left(\frac{V_{\text{bias}}}{1 \text{ MeV}^4} \right)^{1/2}. \quad (2)$$

Hence we can consider the scenario where domain walls are long-lived but annihilated before causing problems with cosmological observations according to the values of σ and V_{bias} .

3. Gravitational waves from domain walls

If domain walls lived for a sufficiently long time in the early universe, they can be regarded as possible cosmological sources of GWs [4, 7, 8]. Let us estimate typical GW signatures produced by such long-lived domain walls. The magnitude of GWs can be estimated by using the quadrupole formula $P \sim G\ddot{Q}_{ij}\ddot{Q}_{ij}$, where P is the power of the gravitational radiation, Q_{ij} is the quadrupole moment of the source, and G is the Newton's gravitational constant. For domain walls in the scaling regime, we have $Q_{ij} \sim M_{\text{wall}}t^2 \sim \sigma t^4$, where $M_{\text{wall}} \sim \sigma t^2$ is the typical mass energy of the walls. Hence the energy density of GWs can be estimated as $\rho_{\text{gw}} \sim Pt/t^3 \sim G\sigma^2$, which remains almost constant as long as domain walls are in the scaling regime.

In order to obtain a more quantitative estimate, the production of GWs from domain walls was studied by performing field theoretic lattice simulations in [9, 10, 11]. In these works, the cosmological evolution of domain walls was investigated by numerically solving the classical field equation for the scalar field with the potential (1) in the expanding universe. The spectrum of

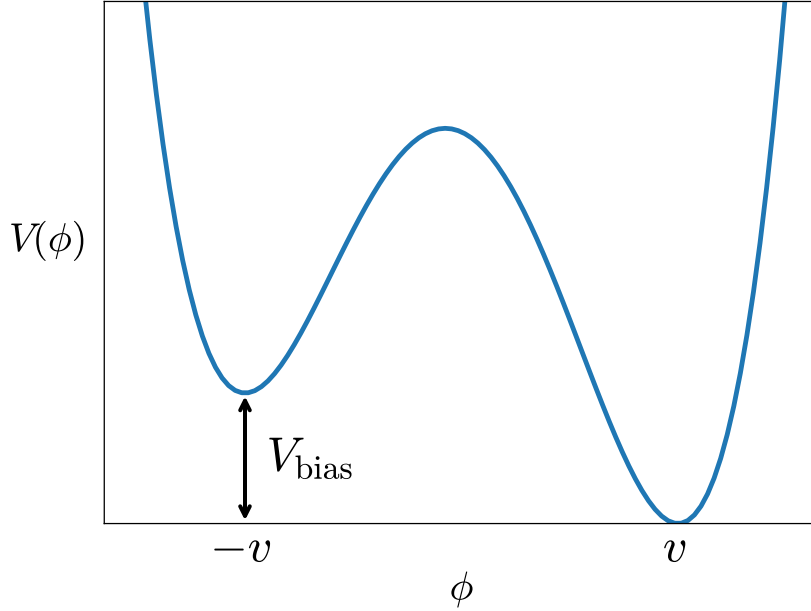


Figure 1. The scalar field potential with an energy bias, which leads to the formation of unstable domain walls.

GWs was estimated based on the data of the scalar field configurations obtained from the lattice simulations. The results of the simulations confirmed the behavior $\rho_{\text{gw}} \propto G\sigma^2$ obtained based on a naive estimate described above. It was also shown that the spectrum of GWs has a peak at the scale $\sim H$ corresponding to the Hubble radius, and that it decays as $\sim k^{-1}$ for higher wavenumbers.

The amplitude of GWs is conventionally parameterized by the quantity Ω_{gw} , which is the ratio of the energy density of GWs ρ_{gw} at the present time to the total energy density of the universe today. Assuming that the production of GWs is terminated at the temperature $T = T_{\text{ann}}$ and using the fact that the energy density of GWs is given by $\rho_{\text{gw}} \sim G\sigma^2$ at that time and diluted as $\rho_{\text{gw}} \propto a(t)^{-4}$ afterwards, we obtain

$$(\Omega_{\text{gw}} h^2)_{\text{peak}} \sim 3 \times 10^{-18} \left(\frac{g_{*s}(T_{\text{ann}})}{10} \right)^{-4/3} \left(\frac{\sigma}{1 \text{ TeV}^3} \right)^2 \left(\frac{T_{\text{ann}}}{10 \text{ MeV}^4} \right)^{-4}, \quad (3)$$

where the subscript “peak” refers to the amplitude at the peak frequency, $g_{*s}(T)$ is the effective degrees of freedom for the entropy density at temperature T , h is the reduced Hubble parameter, $h = H_0/100 \text{ km} \cdot \text{sec}^{-1} \text{ Mpc}^{-1}$. Furthermore, the peak frequency can be estimated as

$$f_{\text{peak}} \sim \left(\frac{a(T_{\text{ann}})}{a(t_0)} \right) H(t_{\text{ann}}) \sim 10^{-9} \text{ Hz} \left(\frac{g_{*p}(T_{\text{ann}})}{10} \right)^{1/2} \left(\frac{g_{*s}(T_{\text{ann}})}{10} \right)^{-1/3} \left(\frac{T_{\text{ann}}}{10 \text{ MeV}} \right), \quad (4)$$

where t_0 denotes the present time and $g_{*p}(T)$ is the effective degrees of freedom for the energy density at temperature T .

We see that the peak amplitude and frequency are determined by two parameters: One is the tension of domain walls σ , and the other is the temperature at their annihilation T_{ann} . Note

that T_{ann} is related to the magnitude of the energy bias in the potential [equation (2)]. Since the values of σ and T_{ann} depend on underlying particle physics models, we expect that the prediction for the GW signatures differs according to the details of the models. In the next section, we briefly discuss some particle physics models that lead to the formation of unstable domain walls and predict the production of a significant amount of GWs from them.

4. Particle physics models

One interesting possibility arises from the dynamics of the Standard Model (SM) Higgs field. In [12], it was pointed out that the SM Higgs potential may have quasi-degenerate minima based on the observation that the Higgs self coupling becomes negative at some high energy scale and that the contribution from some new physics at that scale can lift the Higgs potential. If the Higgs field acquires large quantum fluctuations during inflation, we expect that the Higgs field settles down to different minima in different patches of the universe, which leads to the formation of domain walls. It turns out that the values of relevant quantities such as σ and V_{bias} are sensitive to various parameters in the SM including the top quark mass, strong gauge coupling, and the Higgs boson mass, but it was shown that there exists a parameter region in which a significant amount of GWs can be produced from long-lived Higgs domain walls.

We also expect that the long-lived domain walls can be formed in the context of axion models. The QCD axion models based on the Peccei-Quinn (PQ) symmetry, which were proposed as a solution to the strong CP problem [13, 14], can lead to N_{DW} degenerate minima in the low energy effective potential, where N_{DW} is an integer determined by the QCD anomaly coefficient. In this framework, the formation of domain walls occurs around the epoch of the QCD phase transition. Their tension is estimated as $\sigma \approx 8m_a f_a^2 \approx 5 \times 10^9 \text{ GeV}^3 (f_a/10^{12} \text{ GeV})$, where m_a is the axion mass and f_a is its decay constant. It is known that domain walls become stable if $N_{\text{DW}} > 1$, and in order to avoid the cosmological domain wall problem one has to introduce an additional term in the effective potential that explicitly breaks the PQ symmetry [15]. The production of GWs from such unstable axionic domain walls was studied in [16], and it was shown that their amplitude is quite small, $(\Omega_{\text{gw}} h^2)_{\text{peak}} \lesssim 10^{-20}$, which is hard to observe even in future high-sensitivity GW experiments. On the other hand, it was pointed out that a large GW amplitude is predicted in some class of models with axion-like particles [17] or in the aligned axion models [18].

The third example is the next-to-minimal supersymmetric SM (NMSSM), which is an extension of the minimal supersymmetric SM (MSSM) with an additional singlet superfield that provides a solution to the so called μ -problem of the MSSM. The model possesses a discrete Z_3 symmetry, which is spontaneously broken when the scalar component of the singlet superfield acquires a VEV, and domain walls are formed at that time. The cosmological domain wall problem can be avoided by introducing a small bias term V_{bias} , which is generated by imposing various additional symmetries that allows a small but non-vanishing V_{bias} [19] or making the Z_3 symmetry anomalous for some hidden strong gauge interactions [20]. The GW signatures from the NMSSM domain walls were analyzed in [21], and it was shown that a significant amount of GWs can be produced if the annihilation of domain walls happened slightly before the epoch of the Big Bang nucleosynthesis and the singlet-Higgs couplings are sufficiently small.

5. Implications for present and future observations

According to the parameters of underlying particle physics models, the GW signatures are predicted in various frequency ranges. According to equation (4), the peak frequency is determined by the temperature at the annihilation of domain walls T_{ann} . Furthermore, equation (3) implies that a large amplitude of GWs is predicted if the tension of domain walls σ is sufficiently large and their lifetime is sufficiently long. In figure 2, we compare these predictions to sensitivities of ongoing and planned GW experiments. The frequency ranges of

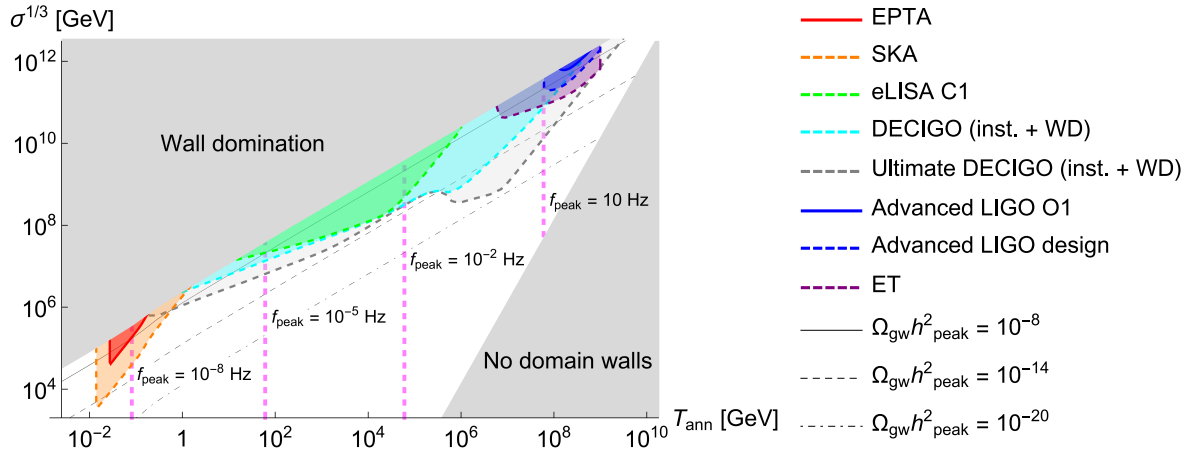


Figure 2. Predicted GW signatures from domain walls and sensitivities of ongoing and planned GW experiments in the parameter space of T_{ann} and $\sigma^{1/3}$ [28]. The gray region with “Wall domination” corresponds to the parameter space where domain walls overclose the universe, and that with “No domain walls” corresponds to the parameter space where the energy bias V_{bias} is so large that the large scale domain walls cannot be formed.

$f \sim \mathcal{O}(1-10)$ Hz are probed by ground-based interferometers such as Advanced LIGO [22], and the planned detector ET [23] is expected to achieve further improvement in sensitivity. The intermediate frequency ranges will be searched by space-borne interferometers such as LISA [24] and DECIGO [25]. Much lower frequency ranges $f \sim \mathcal{O}(10^{-9}-10^{-8})$ Hz can be probed based on the Pulsar Timing Array such as the ongoing project EPTA [26] and the future project SKA [27]. From figure 2, we see that future GW experiments can cover a wider parameter space and they could potentially observe the predicted GW signatures.

6. Conclusions

The formation of domain walls is a solid prediction of particle physics models with a spontaneously broken discrete symmetry. In order to avoid the cosmological domain wall problem, they must be unstable and annihilated at sufficiently early times. In such a scenario, we expect that they have left some imprints on the spectrum of GWs. We have seen that there are various well-motivated particle physics models that predict the production of a significant amount of GWs from long-lived domain walls. Such signatures of GWs can potentially be observed in forthcoming GW experiments, which will allow us to gain some information about fundamental theories with discrete symmetries.

Acknowledgments

The author acknowledges partial support by the Deutsche Forschungsgemeinschaft through Grant No. EXC 153 (Excellence Cluster “Universe”) and Grant No. SFB 1258 (Collaborative Research Center “Neutrinos, Dark Matter, Messengers”) as well as by the European Union through Grant No. H2020-MSCA-ITN-2015/674896 (Innovative Training Network “Elusives”).

References

- [1] Kibble T W B 1976 *J. Phys. A* **9** 1387
- [2] Press W H, Ryden B S and Spergel D N 1989 *Astrophys. J.* **347** 590
- [3] Zeldovich Y B, Kobzarev I Y and Okun L B 1974 *Zh. Eksp. Teor. Fiz.* **67** 3
- [4] Vilenkin A 1981 *Phys. Rev. D* **23** 852

- [5] Gelmini G B, Gleiser M and Kolb E W 1989 *Phys. Rev. D* **39** 1558
- [6] Larsson S E, Sarkar S and White P L 1997 *Phys. Rev. D* **55** 5129 (*Preprint* hep-ph/9608319)
- [7] Preskill J, Trivedi S P, Wilczek F and Wise M B 1991 *Nucl. Phys. B* **363** 207
- [8] Gleiser M and Roberts R 1998 *Phys. Rev. Lett.* **81** 5497 (*Preprint* astro-ph/9807260)
- [9] Hiramatsu T, Kawasaki M and Saikawa K 2010 *J. Cosmol. Astropart. Phys.* JCAP05(2010)032 (*Preprint* 1002.1555)
- [10] Kawasaki M and Saikawa K 2011 *J. Cosmol. Astropart. Phys.* JCAP09(2011)008 (*Preprint* 1102.5628)
- [11] Hiramatsu T, Kawasaki M and Saikawa K 2014 *J. Cosmol. Astropart. Phys.* JCAP02(2014)031 (*Preprint* 1309.5001)
- [12] Kitajima N and Takahashi F 2015 *Phys. Lett. B* **745** 112 (*Preprint* 1502.03725)
- [13] Peccei R D and Quinn H R 1977 *Phys. Rev. Lett.* **38** 1440
- [14] Peccei R D and Quinn H R 1977 *Phys. Rev. D* **16** 1791
- [15] Sikivie P 1982 *Phys. Rev. Lett.* **48** 1156
- [16] Hiramatsu T, Kawasaki M, Saikawa K and Sekiguchi T 2013 *J. Cosmol. Astropart. Phys.* JCAP01(2013)001 (*Preprint* 1207.3166)
- [17] Daido R, Kitajima N and Takahashi F 2015 *J. Cosmol. Astropart. Phys.* JCAP07(2015)046 (*Preprint* 1504.07917)
- [18] Higaki T, Jeong K S, Kitajima N, Sekiguchi T and Takahashi F 2016 *J. High Energy Phys.* JHEP08(2016)044 (*Preprint* 1606.05552)
- [19] Panagiotakopoulos C and Tamvakis K 1999 *Phys. Lett. B* **446** 224 (*Preprint* hep-ph/9809475)
- [20] Hamaguchi K, Nakayama K and Yokozaki N 2012 *Phys. Lett. B* **708** 100 (*Preprint* 1107.4760)
- [21] Kadota K, Kawasaki M and Saikawa K 2015 *J. Cosmol. Astropart. Phys.* JCAP10(2015)041 (*Preprint* 1503.06998)
- [22] Aasi J *et al.* [LIGO Scientific Collaboration] 2015 *Class. Quant. Grav.* **32** 074001 (*Preprint* 1411.4547)
- [23] Punturo M *et al.* 2010 *Class. Quant. Grav.* **27** 194002
- [24] Audley H *et al.* [LISA Collaboration] 2017 *Preprint* 1702.00786
- [25] Kawamura S *et al.* 2006 *Class. Quant. Grav.* **23** S125
- [26] Kramer M and Champion D J 2013 *Class. Quant. Grav.* **30** 224009
- [27] Janssen G *et al.* 2015 *PoS AASKA* **14** 037 (*Preprint* 1501.00127)
- [28] Saikawa K 2017 *Universe* **3** 40 (*Preprint* 1703.02576)