# Gravitational waves from domain walls in the Standard Model



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# Gravitational waves from domain walls in the Standard Model

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**Abstract.** We study domain walls interpolating between the physical electroweak vacuum and the global minimum of the Standard Model scalar potential appearing at very high field strengths. Such domain walls could be created in the early Universe under the assumption of validity of the Standard Model up to very high energy scales. The creation of the network of domain walls which ends up in the electroweak vacuum percolating through the Universe is not as difficult to obtain as one may expect, although it requires certain tuning of initial conditions. Our numerical simulations confirm that such domain walls would swiftly decay. Moreover we have found that for the standard cosmology the energy density of gravitational waves emitted from domain walls is too small to be observed in present and planned detectors.

## 1. Introduction

After the discovery of the Higgs boson at the Large Hadron Collider [1, 2] all of the parameters of the Standard Model (SM) are known with accuracy high enough for the quantitative study of the RG improved effective SM potential. For the present experimental values the potential drops below the electroweak vacuum values at field strengths of the order of $10^{11}$ GeV and leads to a new minimum at superplanckian field strengths.

Early in the history of the Universe, when it was hotter and denser of when it rapidly expanded during during inflation [3, 4], the Higgs field fluctuations might have been large enough to overcome the potential barrier between the two minima. As a result a network of domain walls interpolating between patches of the Universe occupied by the Higgs field laying in different minima was created. Our main interest is evolution of this network. To remain independent from a specific model of the early Universe we investigate dependence of our results on initial conditions: a mean value of the field strength and an amplitude of fluctuations.

If minima of the potential are not degenerate, domain walls interpolating between these minima are unstable. We have found using numerical simulations based on Press, Ryden, Spergel (PRS) algorithm [5] that the conformal time needed for networks of SM domain walls to decay is relatively short and of the order of $10^{-9}\ \frac{\hbar}{\mathrm{GeV}}$.

Very short lifetime of the SM domain walls makes them consistent with the observational data protecting them from numerous problems which long-lived domain walls can cause. The effective equation of state of a network of cosmological domain walls predicts the negative pressure. The

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energy density of the network of stable domain walls decreases (with the expansion) slower then the energy density of both radiation and dust, so long lived domain walls tend to dominate the Universe. Moreover domain walls which pose a significant fraction of the energy density of the Universe at recombination would produce unacceptably large fluctuations of the Cosmic Microwave Background Radiation (CMBR).

During the process of the decay of a network of domain walls the energy of the field is transferred to other degrees of freedom, including production of gravitational waves (GWs). The recent observation of GWs at the LIGO and the Virgo experiments [6] promoted spectrum of GWs to one of the most promising observables which could in principle probe domain walls in the early Universe.

We estimate the spectrum of GWs produced during the decay of SM domain walls, in the case of the standard cosmology, using a direct calculation utilizing a lattice simulation. Our prediction for present energy density of produced GWs is orders of magnitude smaller than the sensitivity of present and planned detectors of GWs. However the present energy density could be greater if the evolution of the Universe before formation of domain walls was different then in the standard scenario.

## 2. RG improved SM effective potential

Previous studies of the evolution of domain walls focused on the dynamics driven by simple polynomial potentials. Even though the SM potential at the tree level is of this form, quantum corrections introduce significant modifications for large field strengths and generate a new minimum at superplanckian field strengths.

Our work is based on the general statement that the (space-time dependent) expectation value of the field strength $\Psi_{cl}(x)$ satisfies the following equation of motion (eom):

$$\frac{\delta}{\delta \Psi_{cl}(x)} \Gamma_{\text{eff}}[\Psi_{cl}] = 0, \tag{1}$$

where $\Gamma_{\text{eff}}$ is the 1PI effective action.

We have used the following approximation for the 1PI effective action of the SM $\Gamma_{\text{SM}}$ in our studies:

$$\Gamma_{\text{SM}}[\phi] \approx \int d^4x \sqrt{|\det g|} \left[ \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V_{\text{SM}}(\phi) \right], \tag{2}$$

where $\phi$ is a real scalar field which models the Higgs field in our simulations and $V_{\text{SM}}$ is the effective potential of the SM in zero temperature. The eom for the approximated effective action proposed in eq. (2) is of the form:

$$\frac{\partial^2 \phi}{\partial \eta^2} + \frac{2}{a} \left( \frac{da}{d\eta} \right) \frac{\partial \phi}{\partial \eta} - \Delta \phi + a^2 \frac{\partial V_{\text{eff}}}{\partial \phi} = 0, \tag{3}$$

assuming the Friedman-Robertson-Walker metric background:

$$g = dt^2 - a^2(t) \delta_{ij} dx^i dx^j = a^2(\eta) \left( d\eta^2 - \delta_{ij} dx^i dx^j \right), \tag{4}$$

where Latin indices correspond to spatial coordinates, $t$ is cosmic time and $\eta$ denotes conformal time (such that $d\eta = \frac{1}{a(t)} dt$). The contribution to the Friedman equations from the Higgs field energy-momentum tensor was neglected in our simulations.

Let us consider the following generalization of eq. (3)

$$\frac{\partial^2 \phi}{\partial \eta^2} + \alpha \left( \frac{d \log a}{d \log \eta} \right) \frac{1}{\eta} \frac{\partial \phi}{\partial \eta} - \Delta \phi + a^\beta \frac{\partial V}{\partial \phi} = 0, \tag{5}$$

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proposed in [5]. We used the Crank-Nicholson scheme for discretization of space-like derivatives and the "staggered leapfrog" for time derivatives which gives us the second order discretization scheme in both time and space. Eq. (5) with values $\alpha = 3$ and $\beta = 0$ combined with used discretization scheme are known as PRS algorithm [5]. This algorithm was widely used in the past for numerical simulations of the dynamics of domain walls for example in [7, 8].

As an approximation of $V_{\rm SM}$ we have used RG improved perturbative effective potential $\widetilde{V}_{\rm SM}$ presented in fig. 1. The loop level up to which we work when computing $\widetilde{V}_{\rm SM}$ numerically is two for effective quartic coupling $\lambda_{\rm eff}$ and three for RGEs. We have used expressions for RGEs, coupling constants and their values renormalised at the scale $\mu = m_{top}$ from [9].

The potential $\widetilde{V}_{\rm SM}$ resembles a mexican hat only at scales $\mathcal{O}(10^2$ GeV). At larger scales it is determined by the behaviour of $\lambda_{\rm eff}$. The potential reaches a maximum around the value $|h|_{\rm max} \sim 10^{10}$ GeV, $V_{\rm max} \sim 10^{34}$ GeV$^4$. Slope of the potential is much steeper for field values $|h| > |h|_{\rm max}$ than it is for $|h| < |h|_{\rm max}$, and potential quickly decreases below value $h_{EW}$ at the electroweak (EW) minimum for field strengths $|h| \gtrsim 10^{10}$GeV.

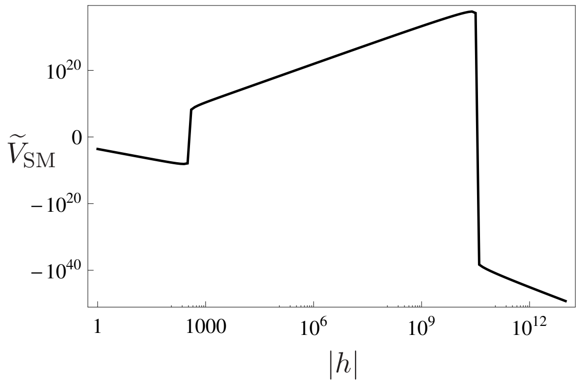


Figure 1: The RG improved effective SM potential of $\widetilde{V}_{\rm SM}$.

Assuming validity of the SM up to such high scales, one witnesses an intricate vacuum structure, which in principle allows for formation and non-trivial evolution of domain walls in the early Universe.

## 3. The width of domain walls

The estimation of the physical width of domain walls is critical for numerical simulations of their dynamics. The width must be at least a few times larger than the lattice spacing (i.e. the physical distance between neighboring points) used in the simulation in order to assure sufficient accuracy to model profiles of walls. On the other hand, statistical properties of the evolution of the network of domain walls will be reproduced poorly in simulations with too small lattice spacing, because only few walls (spreading over many lattice points) will fit into finite lattice. Simulations with the physical width of walls varying from 2 to 100 lattice spacing were used in the past [5, 10, 11, 12, 7, 13, 14, 15].

We estimated the width of domain walls in the SM using the approach based on the first integral of the eom (see [16] for derivation). Firstly we calculated the value $h_2$ of the Higgs field which gives the same value of the effective potential as the value $h_{\rm EW}$ and bigger than the local maximum. The planar wall solution of the eom in the Minkowski background is given in the implicit form:

$$X(\varphi_2) - X(\varphi_1) = \int_{\varphi_1}^{\varphi_2} \frac{d\varphi}{\sqrt{2\left(V_{\rm SM}(\varphi) - V_{\rm SM}(h_{\rm EW})\right)}}, \tag{6}$$

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and the wall's tension by the following integral formula:

$$\Sigma_{\rm SM}(\varphi_1, \varphi_2) := \int_{\varphi_1}^{\varphi_2} \frac{V_{\rm SM}(\varphi)d\varphi}{\sqrt{2\left(V_{\rm SM}\left(\varphi\right) - V_{\rm SM}(h_{\rm EW})\right)}}. \tag{7}$$

We have found values $\tilde{\varphi_1}$ and $\tilde{\varphi_2}$ such that $V_{\rm SM}\left(\tilde{\varphi_1}\right) = V_{\rm SM}\left(\tilde{\varphi_2}\right)$ and $\frac{\Sigma_{\rm SM}(\tilde{\varphi_1},\tilde{\varphi_2})}{\Sigma_{\rm SM}(h_{\rm EW},h_2)} \approx 97\%$, obtaining our estimation of the width of domain walls in the SM (using the convention $\hbar = 1 = c$, so the lengths and times are expressed in units of $\mathrm{GeV}^{-1}$):

$$w_{\rm SM} := X(\tilde{\varphi_2}) - X(\tilde{\varphi_1}) \approx 4 \times 10^{-9}\ \mathrm{GeV}^{-1}. \tag{8}$$

The potential energy density as a function of the distance in the direction perpendicular to the domain wall surface for the solution (6) is presented in fig. 2. The value $x = 0$ on the horizontal axis corresponds to $\varphi(0) = \tilde{\varphi_1}$.

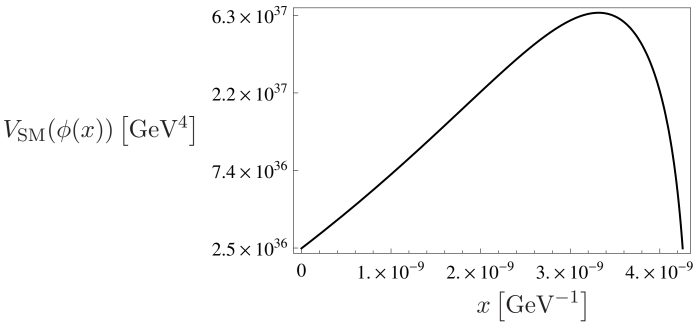



Figure 2: The potential energy density $V_{\rm SM}(\phi(x))$ of the planar SM domain wall as a function of the distance $x$ in the direction perpendicular to the wall surface.

We have chosen the physical lattice spacing $l$ to be equal to $10^{-10}$ GeV$^{-1}$, so the width of the walls is of the order of 40 $l$. We use consistently the units of $10^{10}$ GeV through the paper.

## 4. The Decay of domain walls

Cosmological domain walls are subject to many experimental constraints. The equation of state of the network of domain walls is generally predicted to $-2/3 < w_X < -1/3$, which is ruled out by the present observational data for a single component Dark Energy. Furthermore the energy density of a network of domain walls decreases slower then the energy density of both: the radiation and the dust, so long lived domain walls would dominate the Universe. Moreover domain walls present during the recombination would produce unacceptably large fluctuations of CMBR. Finally the final product of the decay of SM domain walls have to be the EW vacuum. For these reasons we concentrated on the determination of the time and the final state of the process of the decay of SM domain walls.

Our simulations were initialized with three initial values:

- initial conformal time $\eta_{start}$,
- initial mean value of the field strength $\theta$,
- initial standard deviation $\sigma$.

Initial conformal time $\eta_{start}$ is determined by the time at which domain walls are formed in the early Universe. However the initial time of the simulation must be earlier, in order to smooth out the initial numerical fluctuations by the field evolution. The range for initial conformal time in our simulations is from $10^{-4}\ l = 10^{-14}$ GeV$^{-1}$ to $10\ l = 10^{-9}$ GeV$^{-1}$.

Following [10], we assumed that an initial distribution of the field strength is given by the gaussian probability distribution:

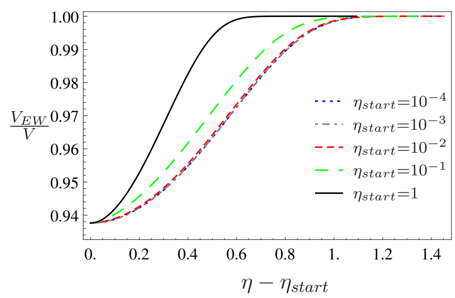
$$P(\phi) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\phi-\theta)^2}{2\sigma^2}}. \tag{9}$$

We studied the evolution of networks of domain walls initialized with different values of $\theta$ and $\sigma$ in order to accommodate variety of processes leading to the formation of the walls.

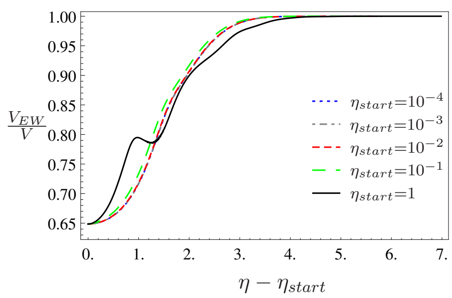
Initial conditions cannot be deduced from the dynamics of domain walls and must be derived from a model of the evolution of the early Universe. Our results can be thought as a constraint on the space of models of the early Universe.

### *4.1. Dependence on the initial time $\eta_{start}$*

We run simulations for different $\sigma = \mathcal{O}\left(10^{10}\ \text{GeV}\right)$ and $\theta = 0$ with five different initialization conformal times $\eta_{start}$. Even though observed decay times are of the same order for all considered initialization times, we observe a differences in the evolution of early formed (i.e. $\eta_{start} < l = 10^{-10}\ \text{GeV}^{-1}$) and late formed (i.e. $\eta_{start} > l$) domain walls. For initial conditions providing the configuration of the field where the electroweak vacuum strongly dominates, late domain walls decay faster then early ones. This issue is presented in fig. 3a in which we plot the evolution of the ratio of the number of lattice sites occupied by the field strength belonging to the basin of attraction of the electroweak minimum to the size of the lattice $\frac{V_{EW}}{V}$. For more moderate contribution of EW vacuum in initial conditions the decay time of late domain walls can be longer than for early ones. The example of this situation is illustrated in fig. 3b.




(a)




(b)

Figure 3: The time dependence of the fraction of lattice sites occupied by field on the electroweak side of the barrier $\frac{V_{EW}}{V}$ for small (a) and moderate (b) contribution of EW vacuum at initialization.

For nearly equal contribution of both vacua at initialization time late domain walls decay longer than early ones, as illustrated by the plot in fig. 4a. It is worth stressing that for simulations presented in fig. 4a $V_{EW}$ decreases initially, however finally the EW vacuum dominates the lattice. The decay of the domain walls leading to the final state without the EW vacuum is possible even for the initial configuration with slight dominance of the EW vacuum. These scenario is realized by the example shown in fig. 4b.

We observe decay times of networks of domain walls ranging from $0.7\ l = 7 \times 10^{-11}\ \text{GeV}^{-1}$ for initial conditions with the contribution of the high energy minimum of the order of a few percents, up to $1\ l = 1.3 \times 10^{-9}\ \text{GeV}^{-1}$ in the case of nearly equal contributions of both vacua at initialization. In all cases the decay time displays the weak dependence on the initialization time $\eta_{start}$.

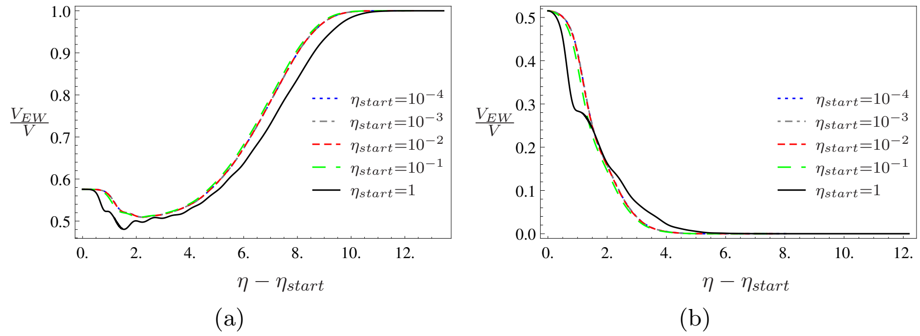



Figure 4: The time dependence of the fraction of lattice sites occupied by field on the electroweak side of the barrier $\frac{V_{EW}}{V}$ for nearly equal contributions of both vacua at initialization time.

*4.2. Dependence on mean value and variation of the field strength*

In [16] we considered cases when the sum of the mean field value $\theta$ and some fraction $\frac{1}{f}$ of the standard deviation $\sigma$ is equal to the position $v_{max}$ of the local maximum of the potential at the initialization time $\eta_{start}$. We restricted the initial standard deviation to $10^{-3}\theta \leq \sigma \leq \theta$.

For $f = 1$ simulations start with ratio $\frac{V_{EW}}{V}$ equal to 84 %. In this case the evolution of networks displays the weak dependence on the value of $\sigma$ and for all simulations the final state is the EW vacuum. Decay times in simulations with initialization times $10^{-4}\ l \leq \eta_{start} \leq 1\ l$ are all of the order of $2\ l = 2 \times 10^{-10}$ GeV$^{-1}$. The time dependence of $\frac{V_{EW}}{V}$ for the network of domain walls initialized at the time $\eta_{start} = 10^{-4}\ l$ is presented in fig. 5a. Late domain walls decay in the time of the order of $14\ l = 1.4 \times 10^{-9}$ GeV$^{-1}$. The time dependence of $\frac{V_{EW}}{V}$ for the network of domain walls initialized at the time $\eta_{start} = 10\ l$ is presented in fig. 5b.

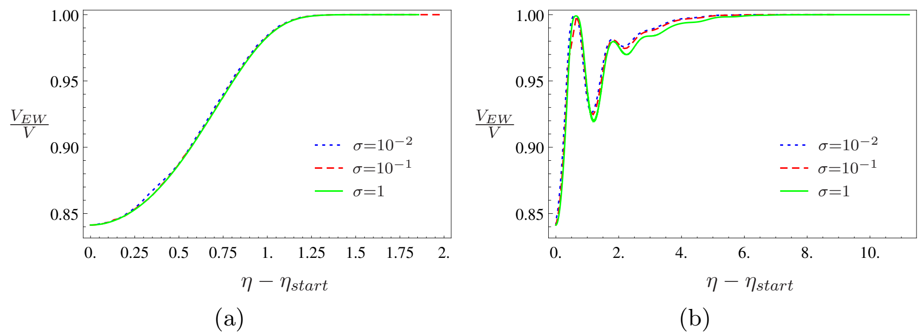
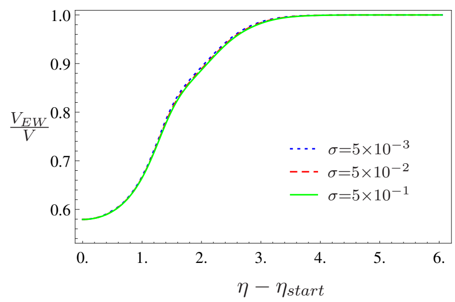
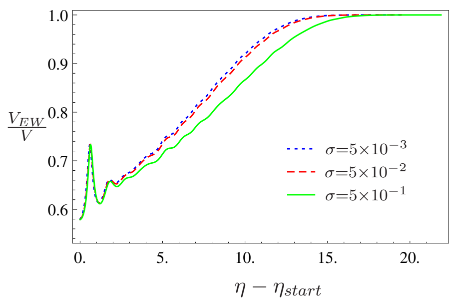



Figure 5: The time dependence of the fraction of lattice sites occupied by field on the electroweak side of the barrier $\frac{V_{EW}}{V}$ for different $\sigma$ for two initialization times: $\eta_{start} = 10^{-4}\ l$ (a) and $\eta_{start} = 10\ l$ (b).

For $f = 5$ simulations start with ratio $\frac{V_{EW}}{V}$ equal to 58 %. For $f = 5$ decay times for both early and late domain walls are longer then for $f = 1$. For early domain walls these times are of the order of $6\ l = 6 \times 10^{-10}$ GeV$^{-1}$ and for late domain walls are of the order of $20\ l = 2 \times 10^{-9}$ GeV$^{-1}$. The time dependence of $\frac{V_{EW}}{V}$ for networks of domain walls initialized at the time $\eta_{start} = 10^{-4}\ l$ is presented in fig. 6a and for ones initialized at the time $\eta_{start} = 10\ l$ is presented in fig. 6b.




(a)




(b)

Figure 6: Time dependence of the fraction of lattice sites occupied by field on the electroweak side of the barrier $\frac{V_{EW}}{V}$ for different $\sigma$ for two initialization times: $\eta_{start} = 10^{-4}\ l$ (a) and $\eta_{start} = 10\ l$ (b).

## 5. Computing the spectrum of gravitational waves

In our simulations we computed numerically spectrum of gravitational waves' energy density per unit logarithmic frequency interval at conformal time at which the decay of domain walls has ended $\eta_{dec}$. The algorithm which we used for calculation was proposed in [17] for calculation of the spectrum of primordial GWs and used in the case of domain walls in [15, 16].

During the evolution of the Universe gravitational waves produced by the network of domain walls were stretched by the expansion. The spectrum at the conformal time $\eta_{EQ}$ at which the energy densities of matter and radiation are equal can be computed, according to [17], as:

$$\frac{d\rho_{gw}}{d\log|k|}(\eta_{EQ}, k) = \frac{a(\eta_{dec})^4}{a(\eta_{EQ})^4}\frac{d\rho_{gw}}{d\log|k|}(\eta_{dec}, k). \tag{10}$$

The factor $\frac{a(\eta_{dec})^4}{a(\eta_{EQ})^4}$ is determined by the linear growth of the scale factor in the radiation domination epoch:

$$\frac{da}{d\eta} = a(\eta)^2 H(\eta) = const =: \dot{a}_{in}, \qquad a(\eta) = \dot{a}_{in}\eta + a_{in}, \tag{11}$$

where $H(\eta)$ is the value of the Hubble constant at the conformal time $\eta$ and $a_{in}$ is a constant which sets the value of the scale factor $a$ at the time when radiation starts to dominate the Universe. The value of the Hubble constant at the time of equality of matter and radiation energy densities can be calculated from present values of the Hubble constant $H_0$ and fractions of the critical density $\Omega_M$, $\Omega_R$ assuming simple scaling of energy densities:

$$H_{EQ}{}^2 = \frac{2H_0{}^2\Omega_M{}^4}{\Omega_R{}^3} = 2\times 10^{-55}\frac{\text{eV}^2}{\hbar^2}. \tag{12}$$

The value of the Hubble constant at conformal time after the decay of domain walls can be computed from parameters of the simulation:

$$H_{dec} = \frac{1}{a_{dec}\eta_{dec}}\left(1 - \frac{a_{in}}{a_{dec}}\right) = 10^{19}\left(1 - \frac{a_{in}}{a_{dec}}\right)\left(\frac{10^{-10}\ \hbar\text{GeV}^{-1}}{a_{dec}\eta_{dec}}\right)\frac{\text{eV}}{\hbar}. \tag{13}$$

The ratio $\frac{a_{in}}{a_{dec}}$ is relevant for the theories in which radiation domination epoch begins at very low energy scales. In most inflationary scenarios this value is negligible. Substituting (12) and

(13) we obtain:

$$\frac{a(\eta_{dec})}{a(\eta_{EQ})} = \sqrt{\frac{H_{EQ}}{H_{dec}}} = 7.1 \times 10^{-24} \left( \frac{10^{19} \frac{\mathrm{eV}}{\hbar}}{H_{dec}} \right)^{\frac{1}{2}}. \tag{14}$$

Furthermore assuming that the energy density of GWs scales in the matter domination epoch as $a^{-4}$ we can express the present spectrum as:

$$\frac{d\rho_{gw}}{d\log|k|}(\eta_0, k) = (1+z_{EQ})^{-4} \frac{a(\eta_{dec})^4}{a(\eta_{EQ})^4} \frac{d\rho_{gw}}{d\log|k|}(\eta_{dec}, k), \tag{15}$$

where $\eta_0$ is the present time and $z_{EQ}$ is the red-shift to the epoch of matter-radiation equality. The energy density of gravitational waves $\frac{d\rho_{gw}}{d\log|k|}(\eta)$ is usually presented as a fraction $\Omega_{gw}(\eta)$ of the critical density $\rho_{cr}(\eta) := {M_{Pl}}^2 H^2(\eta)$.

Finally we estimated the red-shift of the wave frequency to be equal to:

$$f_0 = \frac{a(\eta_{dec})}{a(\eta_0)} \frac{k}{2\pi} = 5.07 \times 10^6 \left( \frac{10^{19} \frac{\mathrm{eV}}{\hbar}}{H_{dec}} \right)^{\frac{1}{2}} \left( \frac{k}{10^{10} \frac{\mathrm{GeV}}{\hbar c}} \right) \mathrm{Hz}. \tag{16}$$

## 6. Spectrum of gravitational waves

Computing the spectrum of gravitational waves in lattice simulations encounters many complications. The modified eom (5) cannot be used in this calculation, because the modification of eom disturbs the dynamics of the short wavelength fluctuations. For the unmodified eom the width of the domain walls decreases as $\propto a^{-2}$, significantly restricting the dynamical range of simulations. As a result only late domain walls ($\eta_{start} = \mathcal{O}(10^{-9}\ \mathrm{GeV}^{-1})$) can be investigated in our simulations. Moreover as noticed in [15], used algorithm produces a spectrum that diverges as $k^3$ for random initialization of the field strength. Following [15] we introduced a cut-off scale in the Fourier transform of the initialization distribution of the order of the width of domain walls.

Fig. 7a presents the spectrum of GWs $\Omega_{gw}$ at the end of the simulation as a function of the frequency $f$ in units of Hz. $\Omega_{gw}$ was computed as an average over 5 simulations which were initialized with condition $\theta = v_{max} + \sigma$ for $\sigma = 10^8$ GeV and $\sigma = 10^9$ GeV at the initial conformal time $\eta_{start} = 10\ l$ with $a_{start} := a(\eta_{start}) = \frac{1}{5}$. Simulations ended at the conformal time equal to $\eta_{end} = 20\ l$ with $a_{end} := a(\eta_{end}) = 4$ with the width of domain walls at this time of the order of 10 $l$. We assumed that $a_{in} = 0$ and the value of Hubble constant at the end of simulations is equal to $\frac{1}{a_{end}\eta_{end}}$. The obtained spectrum is peaked at wave vectors of the order of $k_{peak} \sim 0.05\ l^{-1}$, corresponding to the frequency $f_{peak} \sim 3 \times 10^8$ GeV. In fig. 7b we plotted the spectrum of GWs at present time.

## 7. Summary

In this paper we investigated the possibility of formation of a network of SM domain walls in the early Universe. We concentrated on evolution and decay of such a network and left open the question of an underlying cosmological model which leads to initial conditions facilitating its creation. We modeled these processes using numerical simulations performed on the lattice using PRS algorithm. Main observables in our simulations were the conformal time at which the network of domain walls decays and the spectrum of emitted GWs.

We estimated the width of SM domain walls to be of the order of $4 \times 10^{-9}\ \frac{\hbar c}{\mathrm{GeV}}$. The width of domain walls in our simulations must be a few times bigger than the lattice spacing. We used lattice spacing equal to $l = 10^{-10}\ \frac{c\hbar}{\mathrm{GeV}}$ which results in units for (conformal) time $10^{-10}\ \frac{\hbar}{\mathrm{GeV}}$ and energy $10^{10}$ GeV.

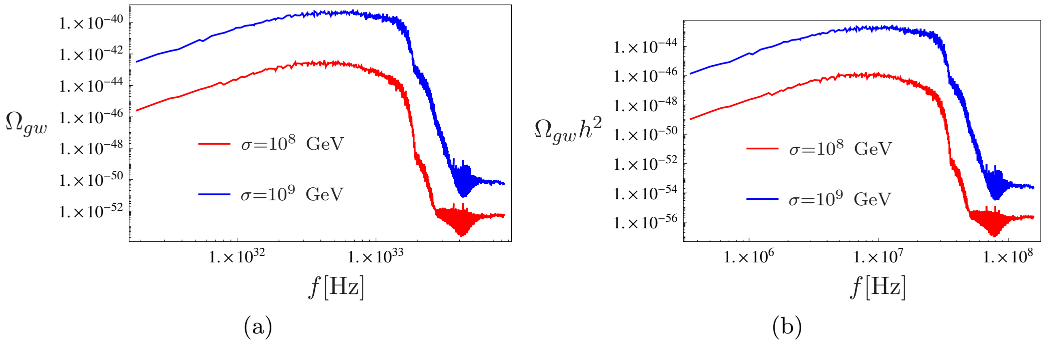



Figure 7: The spectrum of gravitational waves $\Omega_{gw}$ emitted from SM domain walls for $a_{in} = 0$ (standard cosmology) at the time of the decay (a) and at present time (b).

Our simulations show that domain walls, interpolating between minima of the effective potential of the SM, decay shortly after their formation. Decay times range from $8 \times 10^{-11}\ \hbar\text{GeV}^{-1}$ to $3 \times 10^{-9}\ \hbar\text{GeV}^{-1}$. Such short lifetimes exclude a scenario in which SM domain walls dominate the Universe leading to large distortion of the CMBR. An interesting conclusion from our studies is, that the creation of the network which ends up in the electroweak vacuum percolating through the Universe is not as difficult to obtain as one may think, although it requires certain tuning of initial conditions.

The second signature of the existence of the network of SM domain walls are gravitational waves emitted from decaying domain walls. Computed in our numerical simulations spectra of GWs (solid) are compared with predicted sensitivities (dashed) of future detectors: aLIGO [18], ET [19], LISA, LISA:TNG [20], DECIGO and BBO [21] in fig. 8.

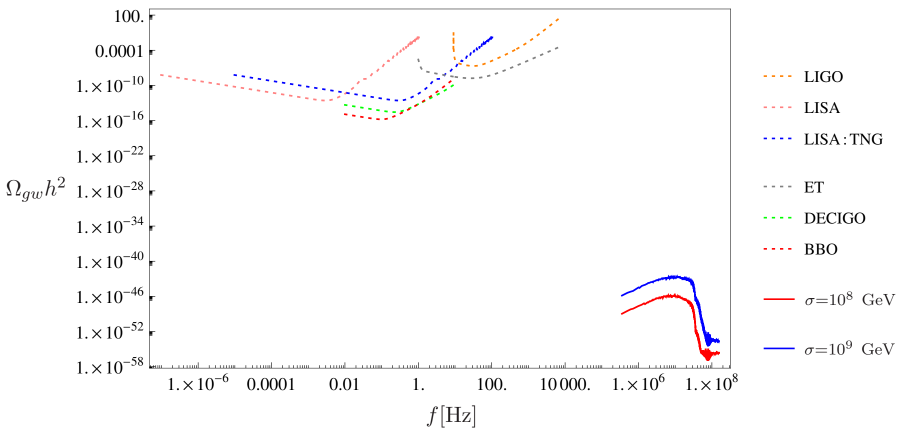



Figure 8: Predicted sensitivities (dashed) for future GWs detectors: aLIGO, ET, LISA, LISA:TNG, DECIGO and BBO compared with the spectrum of GWs (solid) calculated in lattice simulations for the initial values of $\sigma = 10^8,\ 10^9$ GeV and the standard cosmology.

Fig. 8 shows that the detection in upcoming years of GWs emitted by SM domain walls is excluded if one assume the standard cosmological evolution and validity of SM up to very high scales. However, both of these assumptions can be weakened. The present energy density of GWs produced by domain walls could be greater if the evolution of the Universe before the formation of domain walls was different then in the standard scenario. Models predicting very low scale of inflation [22] or including new components of energy density which shorten the radiation domination period [23, 24] would result in larger $\frac{a_{in}}{a_{dec}}$ (so lower $H_{dec}$). Moreover recent experimental bounds on the size of nonrenormalizable interactions of SM particles are very weak. The recent studies [25] have shown that the inclusion of the nonrenormalizable operators in the Lagrangian density modify the behaviour of the effective potential $V_{\text{eff}}$ at high scales and can even make EW vacuum stable. The scenario of nearly degenerate minima of Higgs potential due to inclusion of $|H|^6$ operator has been recently investigated in [26]. The authors of [26] argue that in this case the decay time of domain walls is longer, leading to the increased energy density of emitted GWs, even up to the sensitivity range of future interferometer detectors.

The future detection of GWs emitted from decaying Higgs domain walls, although not likely, would point toward non-standard cosmological scenarios and its significance for both particle physics and cosmology is hard to overestimate.

## Acknowledgments

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