Gravitational waves from cosmological domain walls in the Standard Model with nonrenormalizable operators

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Motivation

1. The quantitative study of the renormalisation group improved (RG improved) effective potential of the Standard Model (SM) has revealed existence of two families of minima.
2. It is possible that in the early Universe the Higgs field acquired fluctuations large enough to overcome the potential barrier and each of two vacua was randomly selected in each patch of the Universe.
3. The result of this process was a network of cosmological domain walls.
4. Evolution of these structures can be investigated in numerical simulations.

Considering nonrenormalizable operators

1. In our previous studies[1] we have studied Higgs domain walls neglecting all interactions beyond the Standard Model.
2. We observed that networks of Higgs domain walls were unstable and decayed shortly after their formation.
3. Short life-times of domain walls in this scenario suppress the energy density of emitted gravitational waves.
4. Recently we have investigated effects on Higgs domain walls of the hypothesis that yet unknown interactions with energy scale much smaller than the Planck scale exist in nature.
5. These new interactions might influence evolution of Higgs domain walls in the way that leads to reach phenomenology.[2]

[1] Tomasz Krajewski et al. "Domain walls and gravitational waves in the Standard Model". In: *JCAP* 1612.12 (2016), p. 036. DOI: 10.1088/1475-7516/2016/12/036. arXiv: 1608.05719 [astro-ph.CO].

[2] Naoya Kitajima and Fuminobu Takahashi. "Gravitational waves from Higgs domain walls". In: *Phys. Lett.* B745 (2015), pp. 112–117. DOI: 10.1016/j.physletb.2015.04.040. arXiv: 1502.03725 [hep-ph].

What are domain walls?

- Domain walls (DWs) are sheet-like topological defects.
- A potential with two (or more) local minima is necessary for the existence of DWs.
- Cosmological DWs could be produced in the early Universe during spontaneous symmetry breaking.
- DWs are formed at boundaries of regions (domains) where symmetry breaking field has different vacuum expectation values (VEVs).

Example

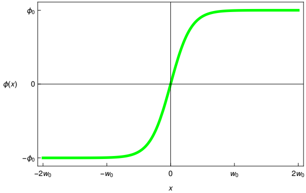
Let us consider the model given by the potential of the form:

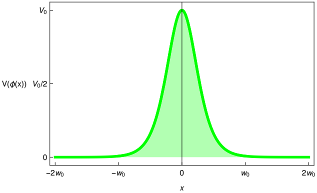
$$V(\phi) = V_0 \left(\left(\frac{\phi^2}{{\phi_0}^2} \right) - 1 \right).$$

The EOM has the time independent, planar solution

$$\phi(x) = \phi_0 \tanh \left(\frac{\pi x}{w_0} \right),$$

where $w_0 = \frac{\phi_0}{\sqrt{2V_0}}$ is the width of the domain wall.





The Effective Field Theory framework

According to the Effective Field Theory framework we parametrize the influence of New Physics by inclusion of the nonrenormalizable operator $|h|^6$ suppressed by the scale Λ to the Lagrangian density of the SM:

$$V_{\mathrm{SM}}^{\Lambda}(h) := V_{\mathrm{SM}}(h) + \frac{1}{6!}\frac{|h|^6}{\Lambda^2}.$$

This approximation is valid as far $|h| \ll \Lambda$.

- $|h|^6$ is the dimension 6 operator, so least suppressed irrelevant operator.
- $|h|^6$ contribute at tree level (not only via loop corrections) to the RG improved effective potential.

Considered range of Λ

We have considered values of the scale Λ ranging from the Planck scale $M_{Pl} = 2.43 \times 10^{18}\ \mathrm{GeV}$ to the scale $1.79 \times 10^{11}\ \mathrm{GeV}$.

- Effects of quantum gravity are traditionally connected with the Planck scale.
- Around scale $\Lambda \sim 1.88 \times 10^{11}\ \mathrm{GeV}$ the minima of the RG improved effective potential are degenerate.
- The scenario of nearly degenerate minima requires fine-tuning of the value of Λ.
- For $\Lambda = 1.79 \times 10^{11}\ \mathrm{GeV}$ the high field strength minimum is degraded to the saddle point.

Properties of the Higgs domain wall

The knowledge of the position of the local maximum v_{max} is needed in the lattice simulations.

- The value of v_{max} determines the significant range of parameters for the initialization of simulations.
- v_{max} is used in numerical simulations for detection of domain walls.

The estimation of the width w of domain walls is crucial for lattice simulations.

- w must be a few times larger than a lattice spacing to assure sufficient accuracy to model profiles of walls.
- Only few walls will fit into the finite lattice with too small spacing.

Position of the local maximum

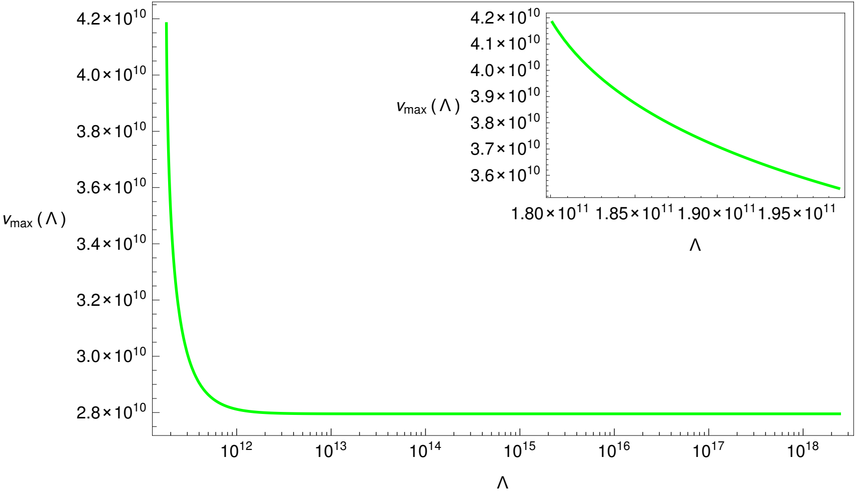


Figure: The position v_{max} of the local maximum separating two minima of the RG improved effective potential as a function of the scale of new physics Λ.

Width of Higgs domain walls

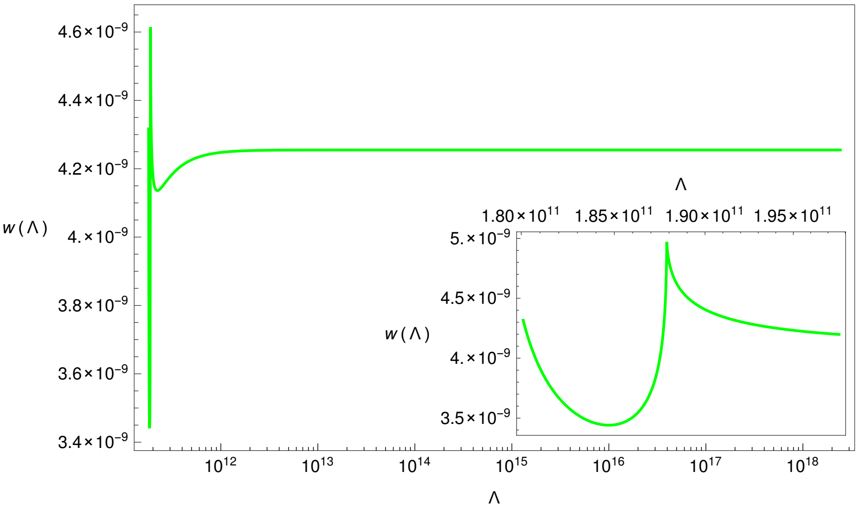
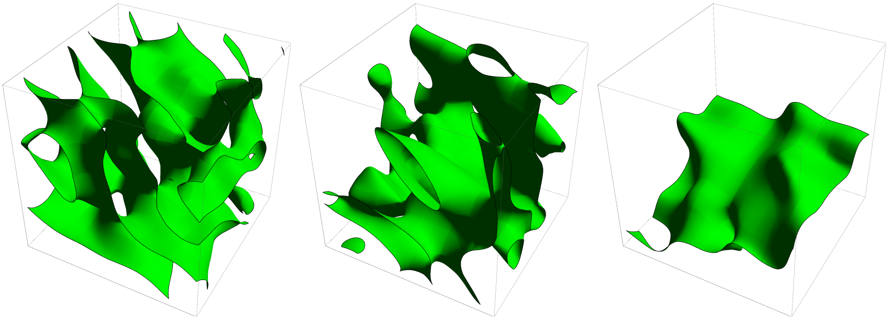


Figure: The width of domain walls w as a function of the scale of new physics Λ.

Networks of domain walls

- It is possible that in the early Universe, during the inflation for example, the Higgs field acquired fluctuations large enough to overcome the potential barrier between the two minima and each of two vacua was randomly selected in each patch of the Universe.
- This resulted in creation of the network of domain walls which interpolates between areas of the Universe occupied by the Higgs field laying in different minima at the end of inflation.
- Cosmological domain walls could form infinite networks.



(a) (b) (c)

Figure: The visualization of the network of SM domain walls obtained during a simulation at tree different times: (a)—$\eta = 1.7 \times 10^{-10}$ GeV^{-1}, (b)—$\eta = 4.0 \times 10^{-10}$ GeV^{-1} and (c)—$\eta = 5.5 \times 10^{-10}$ GeV^{-1}.

Initial conditions

Following general considerations[3] we assumed that the initial distribution of field strength is given by probability distribution:

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

For distributions produced during the inflation:

$$\sigma \sim \frac{\sqrt{N} H_I}{2\pi}.$$

We considered $\theta = 0$ and various values of σ.
Our simulations were initialized with three different conformal times η_{start}: $10^{-12}\ \mathrm{GeV}^{-1}$, $10^{-11}\ \mathrm{GeV}^{-1}$ and $10^{-10}\ \mathrm{GeV}^{-1}$.

[3] Z. Lalak et al. "Large scale structure from biased nonequilibrium phase transitions: Percolation theory picture". In: *Nucl. Phys.* B434 (1995), pp. 675–696. DOI: 10.1016/0550-3213(94)00557-U. arXiv: hep-ph/9404218 [hep-ph].

Dependence of the decay time on scale Λ for $\eta_{start} = 10^{-12}\ \mathrm{GeV}^{-1}$

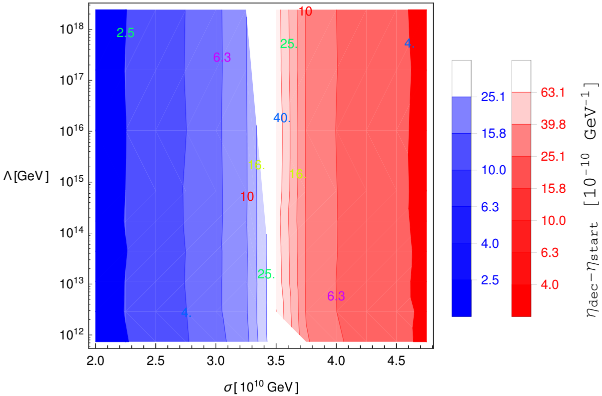
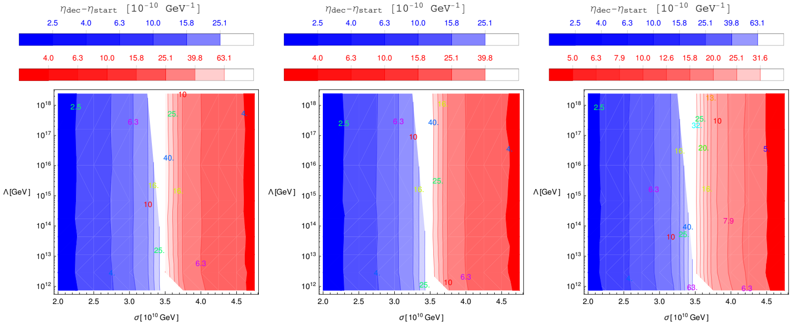


Figure: The dependence of the decay time of networks of Higgs domain walls as a function of the standard deviation σ and the suppression scale Λ for $\eta_{start} = 10^{-12}\mathrm{GeV}^{-1}$. Blue regions corresponds to networks decaying to the EWSB vacuum and red to networks decaying to the high field strength minimum.

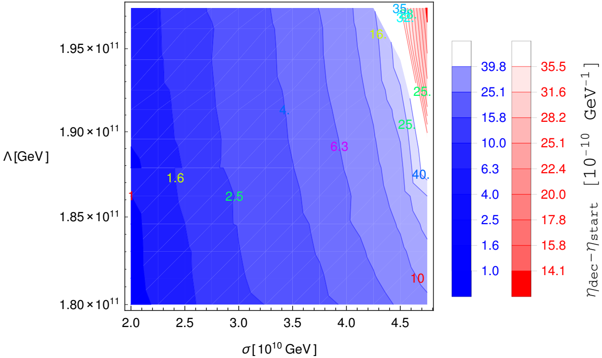
Dependence of the decay time on initialization time η_{start}



(a) (b) (c)

Figure: The dependence of the decay time of networks of Higgs domain walls as a function of the standard deviation σ and the suppression scale Λ for three different values of the conformal initialization time $\eta_{start} = 10^{-12}\mathrm{GeV}^{-1}$ (a), $\eta_{start} = 10^{-11}\mathrm{GeV}^{-1}$ (b) and $\eta_{start} = 10^{-10}\mathrm{GeV}^{-1}$ (c).

Dependence of the decay time for small values of Λ with $\eta_{start} = 10^{-10}\ \mathrm{GeV}^{-1}$



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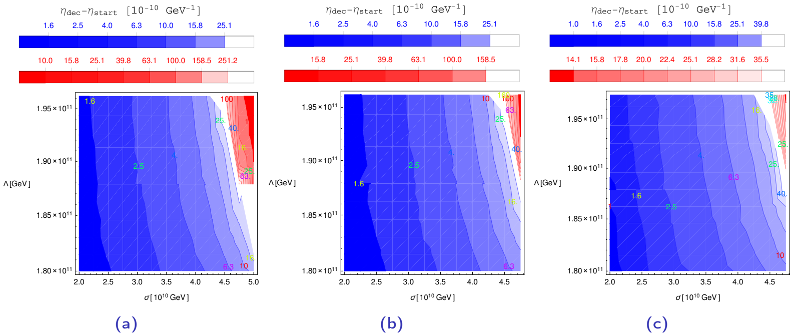
Dependence of the decay time for small values of Λ



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Position of the local maximum

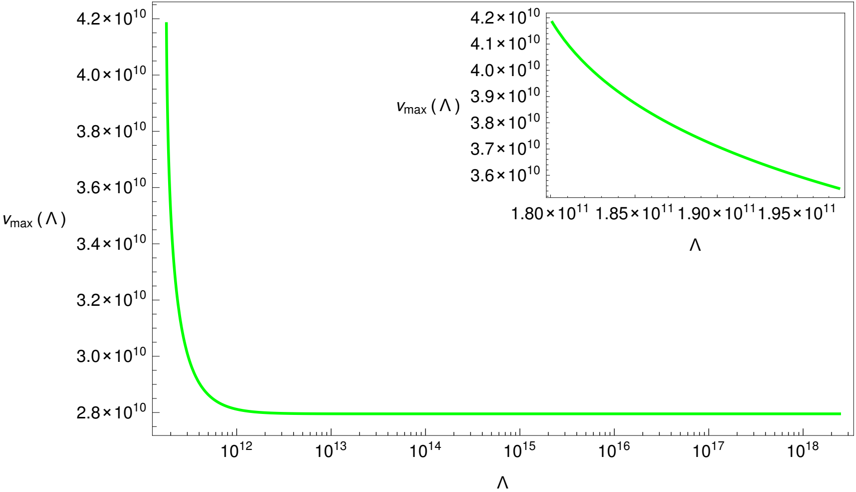
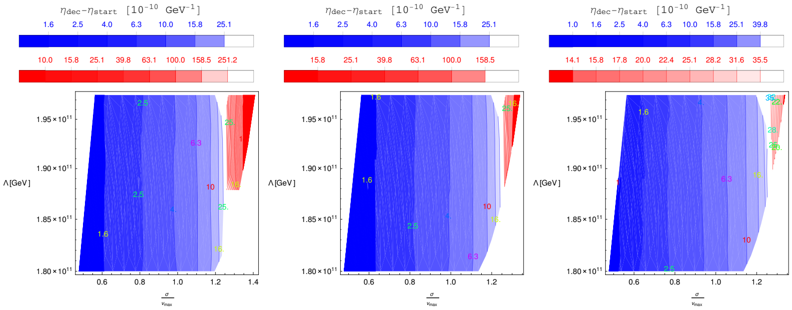


Figure: The position v_{max} of the local maximum separating two minima of the RG improved effective potential as a function of the scale of new physics Λ.

Dependence of the decay time on the fraction $\frac{\sigma}{v_{max}}$



(a) (b) (c)

Figure: The dependence of the decay time of networks of Higgs domain walls as a function of the fraction $\frac{\sigma}{v_{max}}$ and the suppression scale Λ for three different values of the conformal initialization time $\eta_{start} = 10^{-12}\mathrm{GeV}^{-1}$ (a), $\eta_{start} = 10^{-11}\mathrm{GeV}^{-1}$ (b) and $\eta_{start} = 10^{-10}\mathrm{GeV}^{-1}$ (c) and standard deviation $\sigma = 3.25 \times 10^{10}\mathrm{GeV}$ at initialization.

Redshifting the spectrum

Assuming that the energy density of GWs scales as a^{-4} we can write:

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

where η_0 is the present time and z_{EQ} is the red-shift to the epoch of matter-radiation equality. We estimated the redshift factor $\frac{a(\eta_{dec})}{a(\eta_{EQ})}$ as:

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

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

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

Spectrum of GWs after emission - preliminary results

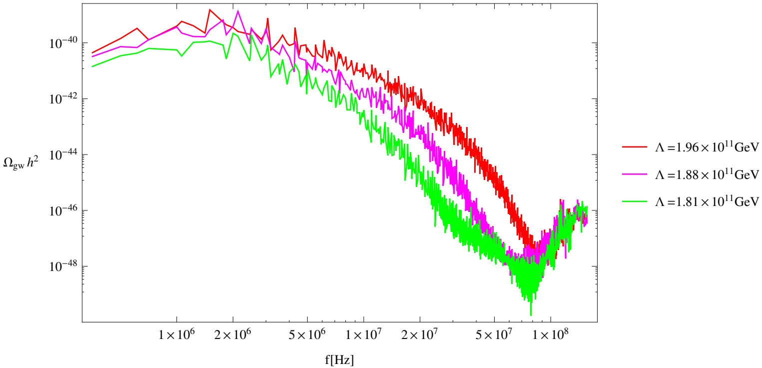


Figure: Spectrum of gravitational waves Ω_{gw} emitted from SM domain walls at the present time.

Present spectrum of GWs

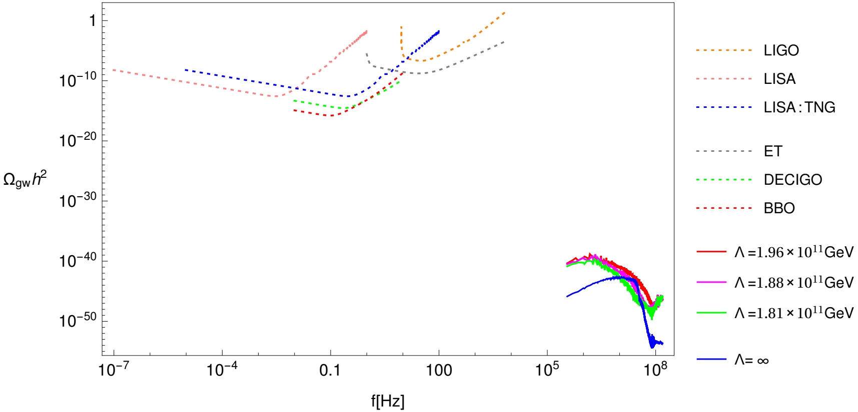


Figure: Predicted sensitivities (dashed) for future GWs detectors: aLIGO, ET, LISA, LISA:TNG, DECIGO and BBO compared with the spectrum of GWs (solid) calculated in lattice simulations for three values of suppression scale Λ.

Summary

1. Previous results are reproduced if the SM is valid up to the scale 10^{13} GeV.
2. Networks of domain walls initialized with $\sigma < 3.25 \times 10^{10}$ GeV decay to the EWSB vacuum.
3. For lower values of the scale Λ lifetimes of Higgs domain walls are still short and smaller than $10^{-8}\ \frac{\hbar}{\mathrm{GeV}}$.
4. Metastability of networks of Higgs domain walls with nearly degenerate minima is not realized for generic initial configurations.
5. Gravitational waves produced from generic initial configurations are too weak to be detected in the planned detectors.

Thank you for your attention.