Higgs domain walls in the Standard Model and its extensions

based on arXiv:1709.10100
in collaboration with Z. Lalak, M. Lewicki and P. Olszewski

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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.

Higgs domain walls

1. In our first attempt[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. In the next paper[2] 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.
4. Recently we have studied the influence of the thermal background on the dynamics of Higgs domain walls.

[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] Tomasz Krajewski et al. "Domain walls in the extensions of the Standard Model". In: (2017). arXiv: 1709.10100 [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).
- Cosmological domain walls form networks whose dynamics is non-linear.

Networks of cosmological domain walls could have twofold topologies: finite bubbles of one vacuum in a sea of the other or an infinite networks spreading through whole Universe.

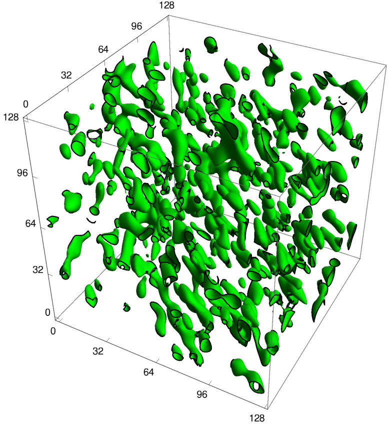

Figure : Network of domain walls formed by bubbles of finite volume.

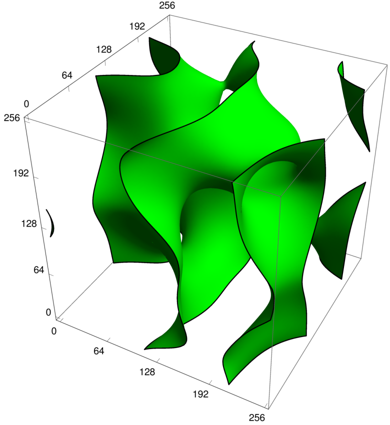

Figure : An example of the infinite network of domain walls.

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 $M_{\mathrm{Pl}} = 2.43 \times 10^{18}\ \mathrm{GeV}$ 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.

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 $\eta_{start} = 10^{-12}\ \mathrm{GeV}^{-1}$

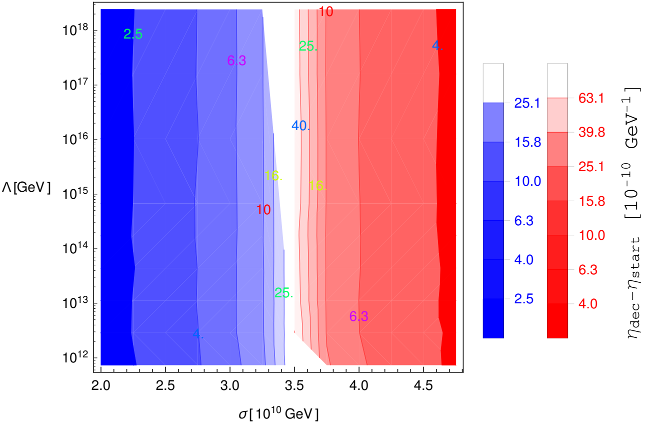

Figure : The dependence of the decay time of networks of Higgs domain walls as a function of the standard deviation σ and the suppression scale Λ for $\eta_{start} = 10^{-12}\,\mathrm{GeV}^{-1}$. Blue regions corresponds to networks decaying to the EWSB vacuum and red to networks decaying to the high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

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

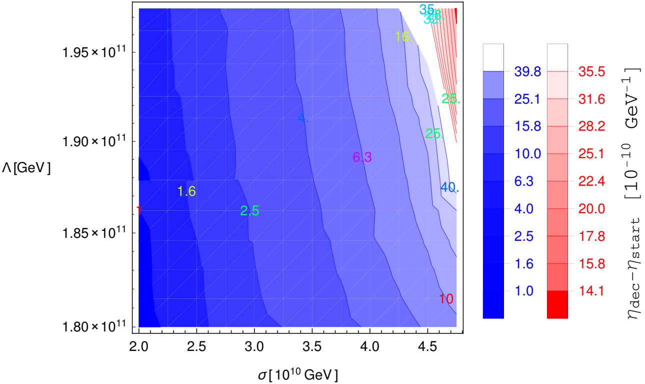

Figure : The dependence of the decay time of networks of Higgs domain walls as a function of the standard deviation σ and the suppression scale Λ for $\eta_{start} = 10^{-10}\,\mathrm{GeV}^{-1}$. Blue regions corresponds to networks decaying to the EWSB vacuum and red to networks decaying to the high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

Position of the local maximum

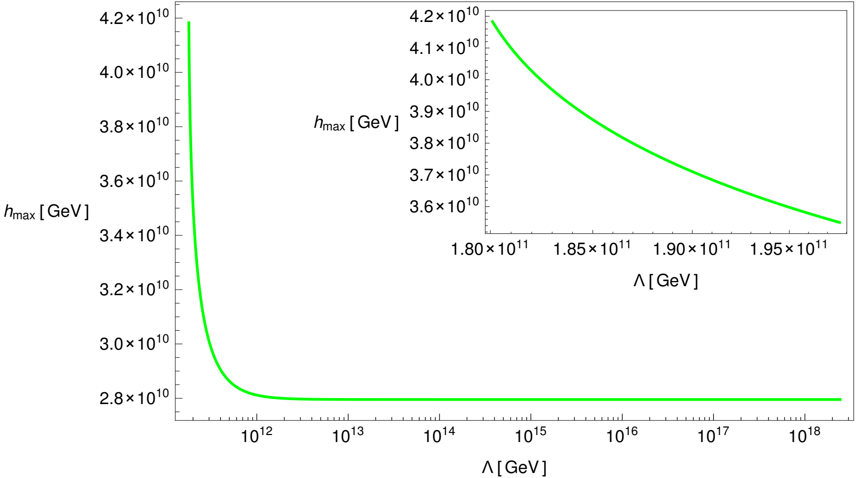

Figure : The position h_{max} of the local maximum separating two minima of the RG improved effective potential as a function of the scale of new physics Λ.

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

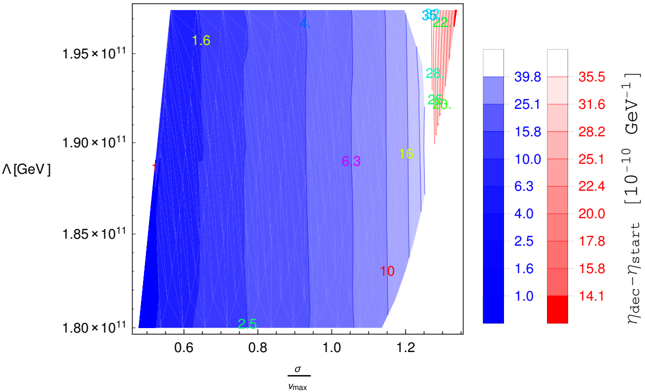

Figure : The dependence of the decay time of networks of Higgs domain walls as a function of the fraction $\frac{\sigma}{h_{max}}$ and the suppression scale Λ for $\eta_{start} = 10^{-10}\mathrm{GeV}^{-1}$ and standard deviation $\sigma = 3.25 \times 10^{10}\mathrm{GeV}$ at initialization.

Present spectrum of GWs

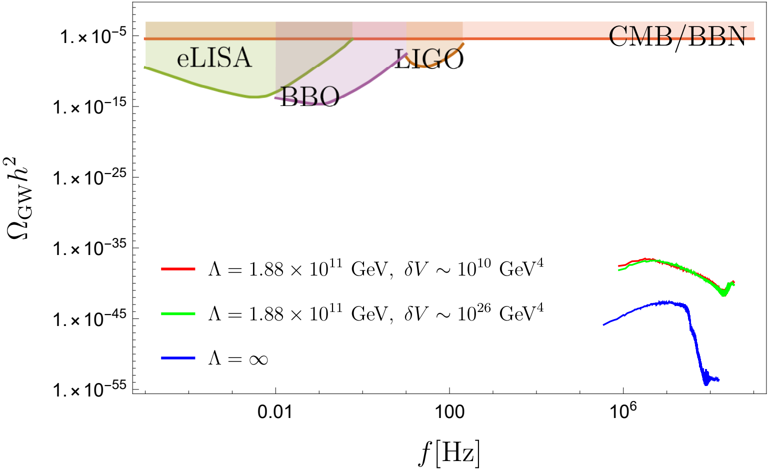

Figure : Predicted sensitivities (shaded regions) for future GWs detectors: aLIGO, LISA:TNG and BBO compared with the spectrum of GWs (solid) calculated in lattice simulations for two values of suppression scale Λ (red and green) and in the SM without nonrenormalizable operators (blue).

Higgs domain walls after reheating

- After reheating the early Universe was very hot and dense and it was better described that time by the thermal state with temperature T, than by the vacuum state.
- The dynamics of Higgs domain walls in the background of this thermal state could be different than in the vacuum state.
- The evolution of the domain walls in the cooling down Universe can be determined reliably only in lattice simulations.

Position of the local maximum

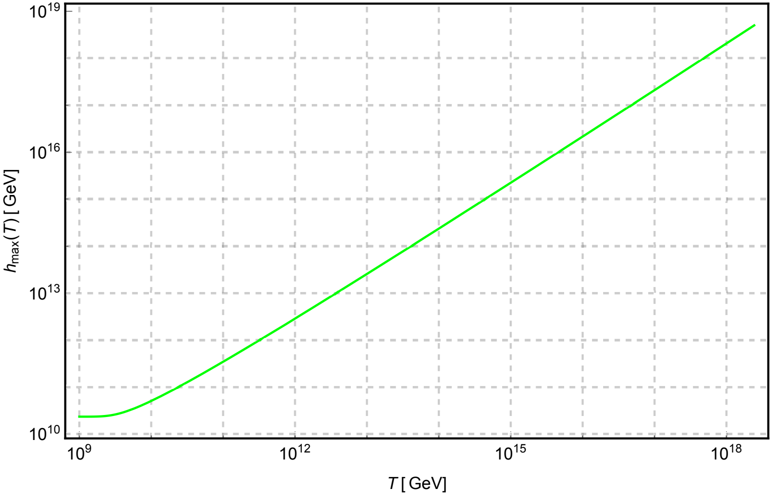

Figure : The position h_{max} of the local maximum separating two minima of the RG improved effective potential as a function of the temperature of thermal bath T.

Width of Higgs domain walls

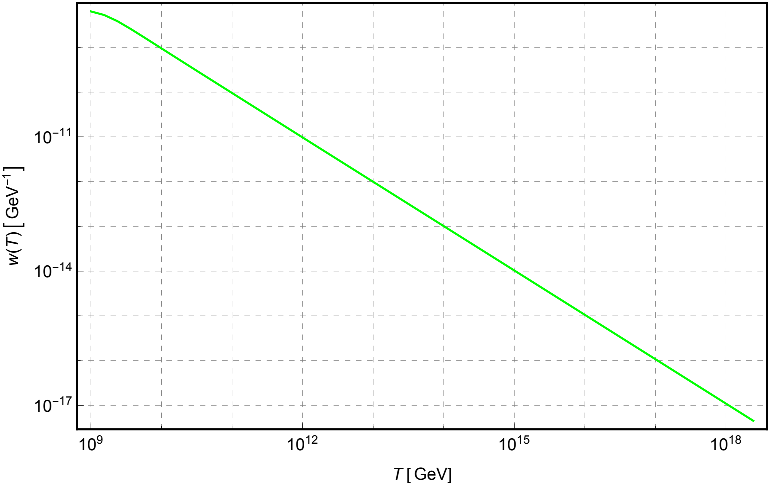

Figure : The width of domain walls w as a function of the temperature T.

Bounds on the standard deviation σ

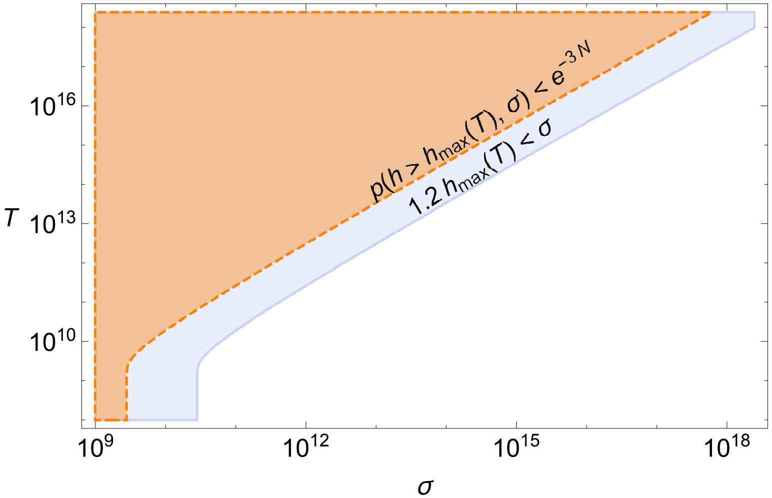

Figure : Maximal value of the standard deviation σ_I of initial distribution for given temperature T.

Bounds on the reheating temperature T_{RH}

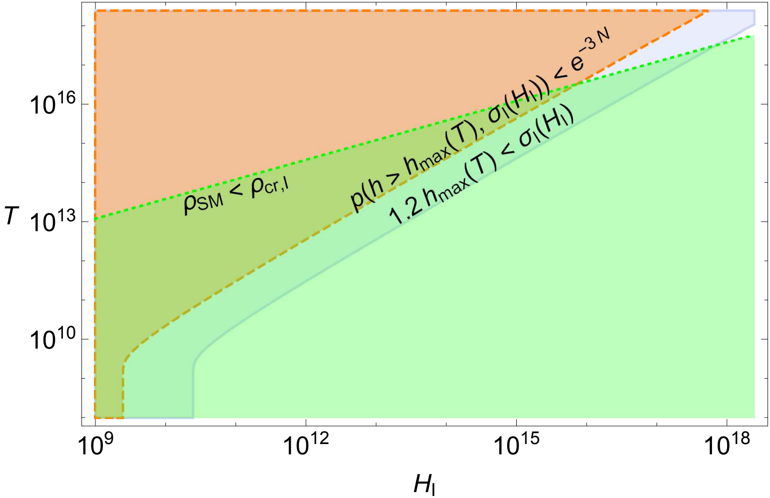

Figure : Maximal value of the reheating temperature from inflation with Hubble parameter value H_I.

Evolution in the thermal background

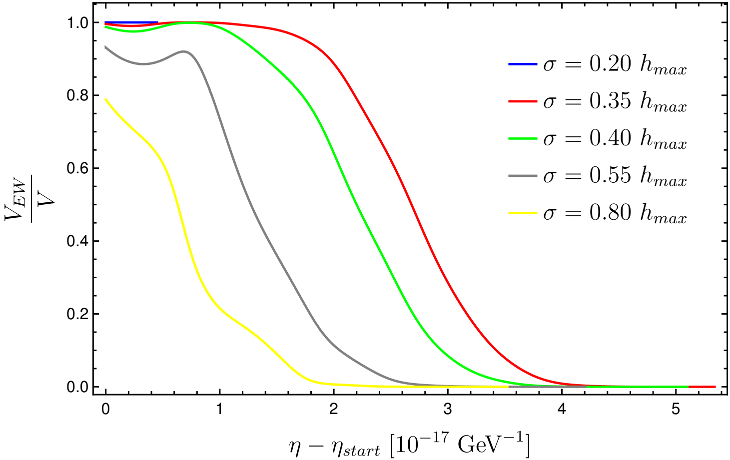

Figure : The fraction $\frac{V_{EW}}{V}$ as a function of conformal time η for values of standard deviation σ of initialization distribution.

Bounds from the evolution of Higgs domain walls

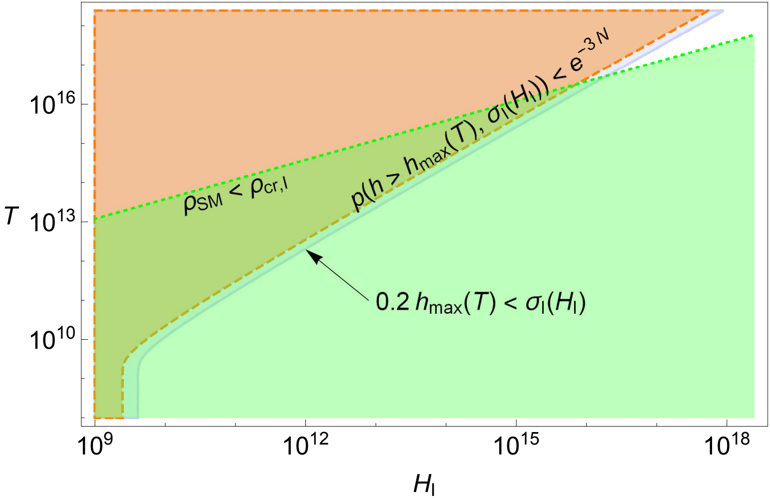

Figure : Bounds on inflationary models from the evolution of Higgs domain walls.

Summary

1. New Physics at scales higher than 10^{13} GeV does not influence Higgsa domain walls.
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} $\frac{\hbar}{\mathrm{GeV}}$ for generic inital configurations.
4. Thermal corrections to the effective potential stabilize the Higgs field by enlarging the basing of attraction of EWSB vacuum.
5. Higgs domain walls in the thermal background are highly unstable.
6. Gravitational waves produced from generic initial configurations are too weak to be detected in the planned detectors.

Thank you for your attention.