Higgs domain walls in the post-inflationary Universe

based on arXiv:1902.05560
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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.

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[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: *JCAP* 1805.05 (2018), p. 007. DOI: 10.1088/1475-7516/2018/05/007. arXiv: 1709.10100 [hep-ph].

The probability distribution of field's strengths

According to general considerations[3] the probability distribution of field's strengths of fluctuations produced during inflation is approximately gaussian:

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

with standard deviation of the order

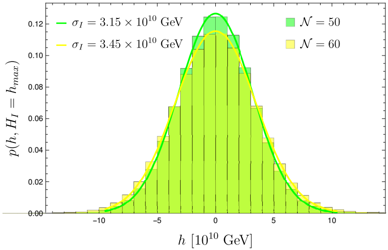
$$\sigma_I \sim \frac{\sqrt{N} H_I}{2\pi},$$

where H_I is value of the Hubble parameter and N is number of e-folds.

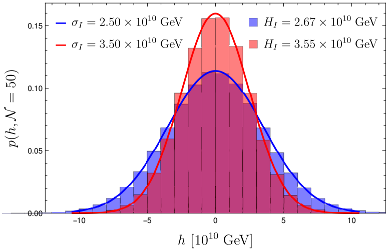
[3] Z. Lalak et al. "Large scale structure from biased nonequilibrium phase transitions: Percolation theory picture". In: *Nucl. Phys.* B434 (1995), pp. 675–696. DOI: 10.1016/0550-3213(94)00557-U. arXiv: hep-ph/9404218 [hep-ph].

Higgs field's fluctuations in the early Universe

Existence of the second minim of the effective potential of the SM may lead to catastrophic scenario[4] of formation of Hubble horizons with VEVs lying deep in the global minimum. Higgs field need to be stabilized during inflation (and reheating).



(a)



(b)

Figure: Distribution of the Higgs field strength values after inflation lasting $\mathcal{N} = 50$ or $\mathcal{N} = 60$ e-folds (a) and with various values Hubble parameter H_I (b).

[4] Jose R. Espinosa et al. "The cosmological Higgstory of the vacuum instability". In: *JHEP* 09 (2015), p. 174. DOI: 10.1007/JHEP09(2015)174. arXiv: 1505.04825 [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.

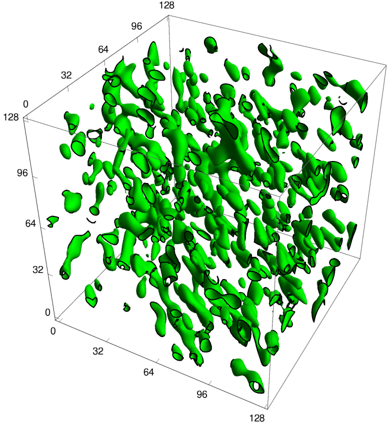


Figure: Network of domain walls formed by bubbles of finite volume.

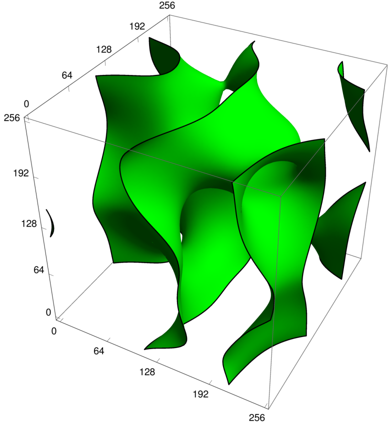


Figure: An example of the infinite network of domain walls.

The problem of cosmological domain walls

- Networks of domain walls have an effective equation of state $\rho = \omega p$ with $-2/3 < \omega < -1/3$ (with negative pressure), so long lived domain walls will dominate the Universe.
- Measurements of the CMB radiation exclude domain walls with the energy scale $> 1\ \mathrm{MeV}$ (Zel'dovich bound[5]) during the recombination.
- Measurements of the expansion of the Universe disfavour domain walls as a main component of the Dark Energy.
- SM domain walls are consistent with the present experimental data only if they decay fast enough.

[5] Ya. B. Zeldovich, I. Yu. Kobzarev, and L. B. Okun. "Cosmological Consequences of the Spontaneous Breakdown of Discrete Symmetry". In: *Zh. Eksp. Teor. Fiz.* 67 (1974). [Sov. Phys. JETP40,1(1974)], pp. 3–11.

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.

Properties of the Higgs domain wall

Higgs domain walls are configurations of the expectation value of the Higgs field which interpolates between minima of the effective scalar potential.
The knowledge of the position of the local maximum h_{max} is needed in the lattice simulations.

- The value of h_{max} determines the significant range of parameters for the initialization of simulations.
- h_{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

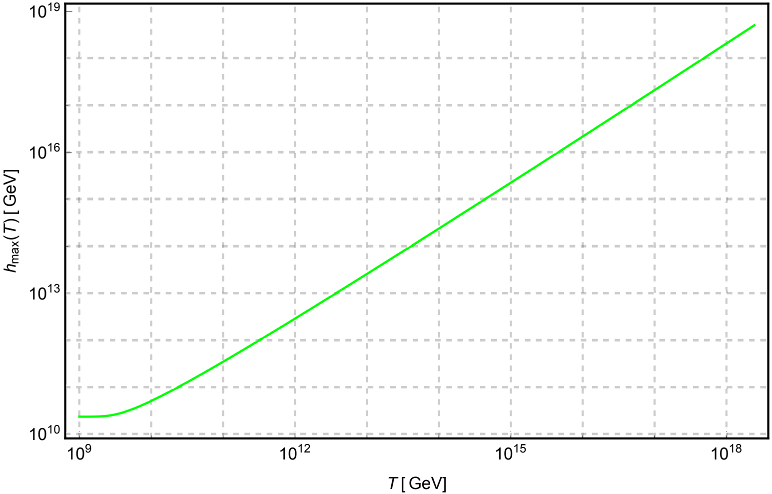


Figure: The position h_{max} of the local maximum separating two minima of the RG improved effective potential as a function of the temperature of thermal bath T.

Width of Higgs domain walls

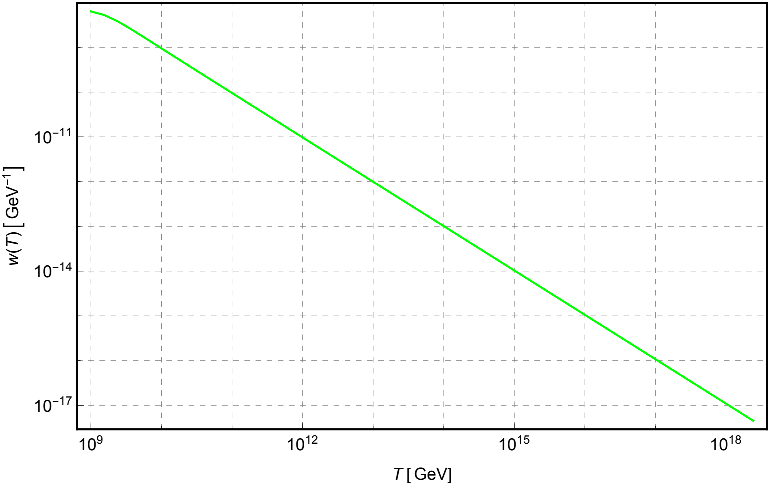


Figure: The width of domain walls w as a function of the temperature T.

Bounds on the standard deviation σ

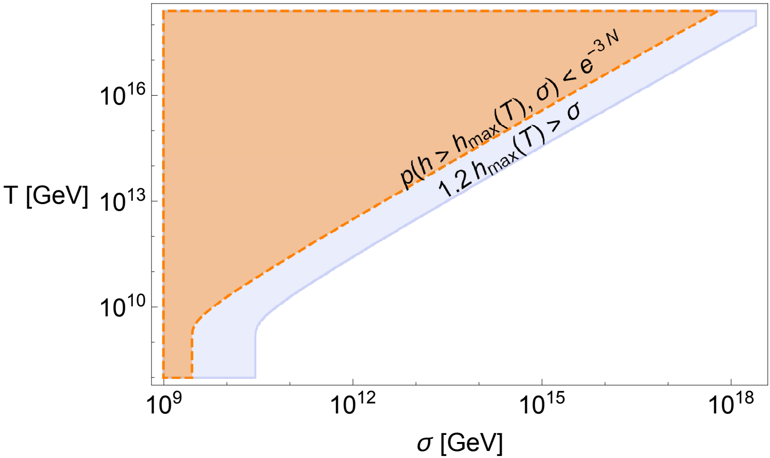


Figure: Maximal value of the standard deviation σ_I of initial distribution for given temperature T.

Bounds on the reheating temperature T_{RH}

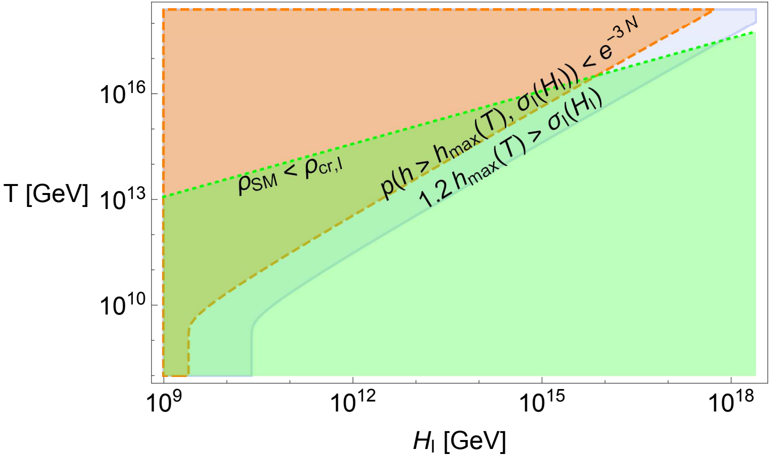


Figure: Maximal value of the reheating temperature from inflation with Hubble parameter value H_I.

Evolution in the thermal background

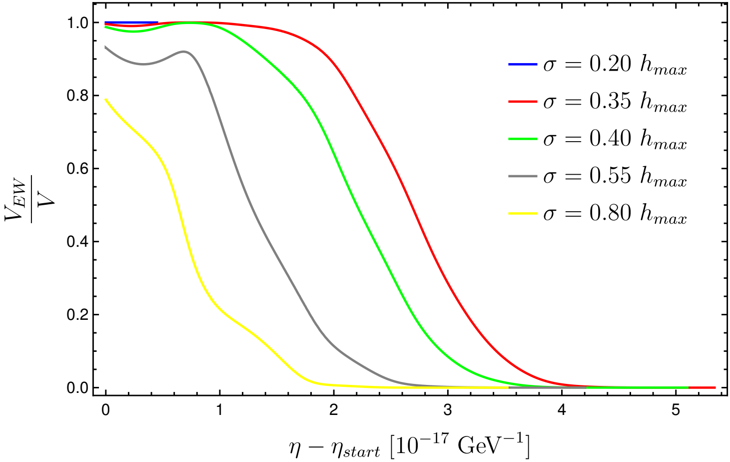


Figure: The fraction $\frac{V_{EW}}{V}$ as a function of conformal time η for values of standard deviation σ of initialization distribution.

Bounds from the evolution of Higgs domain walls

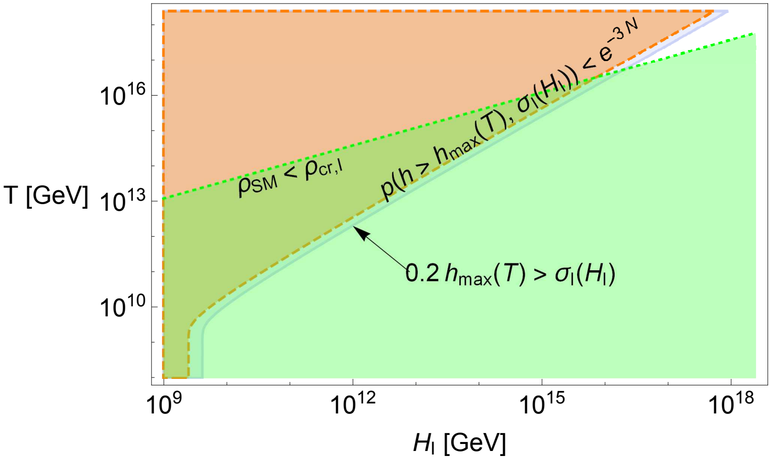


Figure: Bounds on inflationary models from the evolution of Higgs domain walls.

Summary

1. During inflation Higgs field's fluctuations proportional to the Hubble parameter were produced.
2. Domain walls which separate regions with different VEVs of the Higgs field could be formed in the early Universe.
3. Thermal corrections to the effective potential stabilize the Higgs field by enlarging the basing of attraction of EWSB vacuum.
4. Higgs domain walls in the thermal background are highly unstable.
5. Gravitational waves produced by decaying Higgs domain walls are too weak to be detected in the planned detectors.

Thank you for your attention.