The evolution of cosmological domain walls from Higgs effective potential

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What are domain walls?

Domain walls are sheet-like topological defects which can appear in case of existence of two (or more) local minima of a potential. They are formed during spontaneous symmetry breaking at boundaries of regions (domains) where symmetry breaking field has different vacuum expectation values (VEVs).

Does the SM allow for domain walls?

The quantitative study of the renormalisation group improved (RG improved) effective potential of Standard Model (SM) has revealed existence of the deeper family of minima at superplanckian values of Higgs field strengths. Domain walls can interpolate between these minima and (physically non-equivalent) electroweak minima.

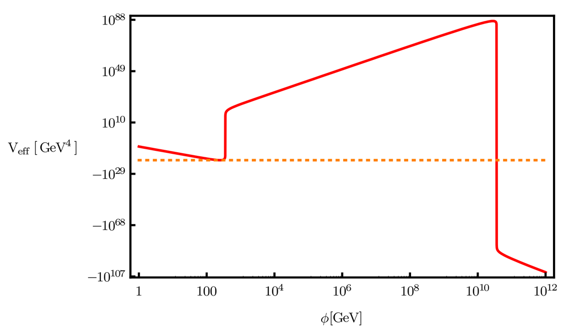

Fig. 1: The RG improved potential of the SM V_{eff} as a function of the VEV ϕ of the Higgs field.

The profile of the SM domain wall

The estimation of the width of domain walls is crucial for lattice simulations. The width must be a few times larger than a lattice spacing used in simulations in order to assure sufficient accuracy to model profiles of walls. On the other hand if we choose the lattice spacing too small only few walls will fit into the finite lattice.

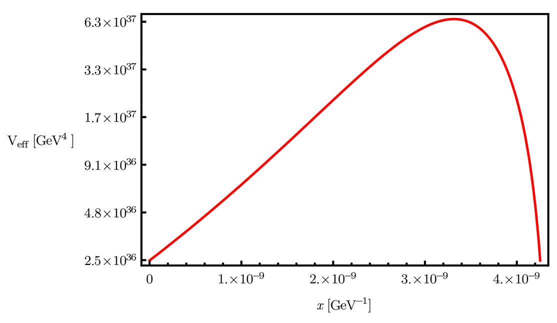

Fig. 2: Potential energy density $V_{eff}(\phi(x))$ of the planar domain wall as a function of the distance x in the direction perpendicular to the wall surface.

Networks of domain walls

It is possible that in the early Universe, the Higgs field acquired quantum fluctuations large enough to overcome the potential barrier between the two minima and either of two vacua is randomly selected in each patch of the Universe. This resulted in creation of the network of domain walls which interpolate between regions of the Universe occupied by the Higgs field laying in different minima. Cosmological domain walls could form infinite networks.

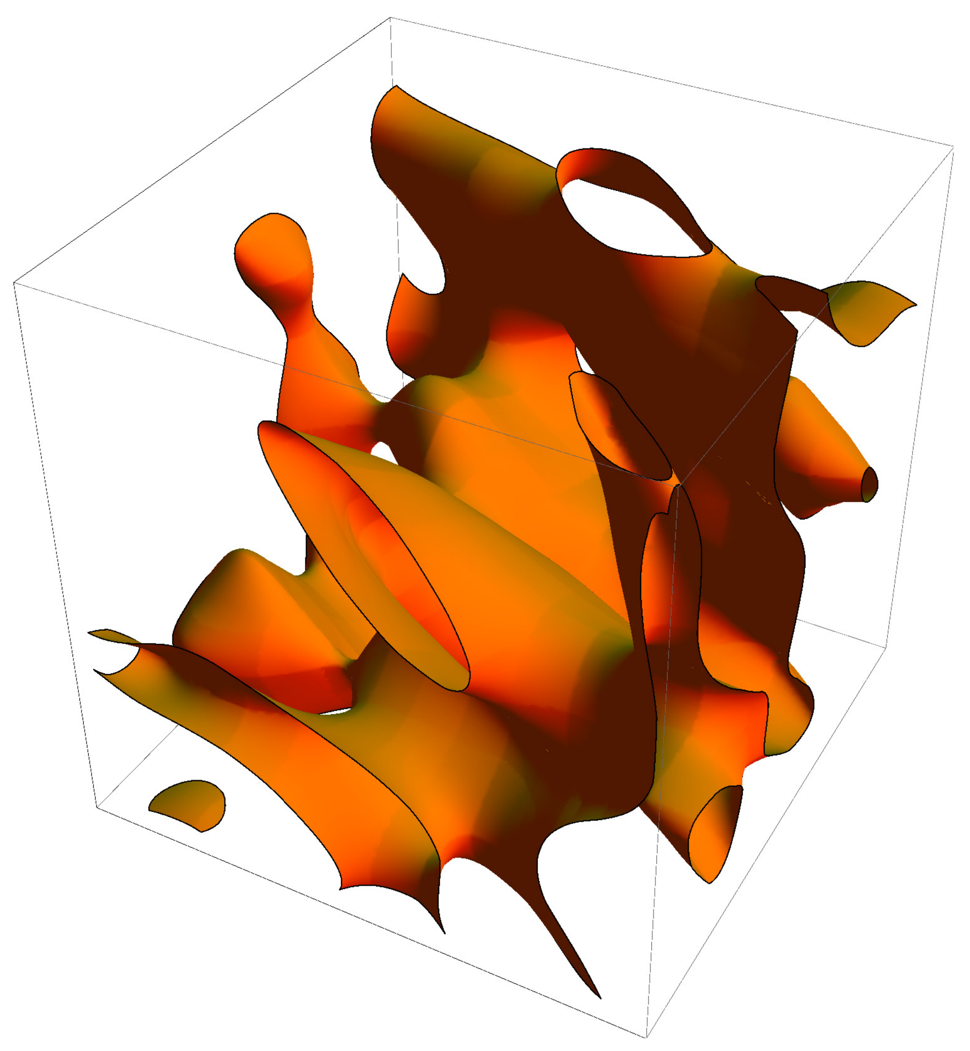

Fig. 3: The visualization of the network of SM domain walls obtained during a simulation.

The problem of cosmological domain walls

Networks of domain walls have an effective equation of state $\rho = wp$ with w determined generally to be $-2/3 < w < -1/3$, so with negative pressure. The energy density of networks of domain walls grows faster then the energy density of both: the radiation and the dust, so long lived domain walls will dominate the Universe. Measurements of the Cosmic Microwave Background radiation exclude existence of domain walls with the energy scale > 1 MeV (Zel'dovich bound [4]) during the recombination. Moreover present measurements of the expansion of the Universe disfavor domain walls as a main component of the Dark Energy. SM domain walls are consistent with the present experimental data only if they decay enough fast.

About our simulation

We modeled the Higgs field with a positive, real scalar field with a potential equal to the RG improved potential of the SM Higgs. We used the PRS algorithm [3] and optimization of a time step [2]. Our simulations were run on a lattice of the size 512^3. Following general considerations [1] we assumed an initial distribution of field strengths is given by the gaussian probability distribution (with a mean value θ and a standard deviation σ).

Dependence on the initialization conformal time

Observed decay times display weak dependence on the initialization conformal time η_{start}. For initial configurations where the electroweak vacuum strongly dominates, late domain walls decay faster then early ones. For more moderate contribution of the EW vacuum in initial conditions the decay time of late domain walls can be longer than for early ones. For nearly equal contributions of both vacua at the initialization, late domain walls decay longer leading to domination of the EW vacuum even if the fraction of lattice sites occupied by this vacuum decreases initially. The decay of domain walls ending in state without the EW vacuum is possible even for the initial configuration with a slight dominance of the EW vacuum.

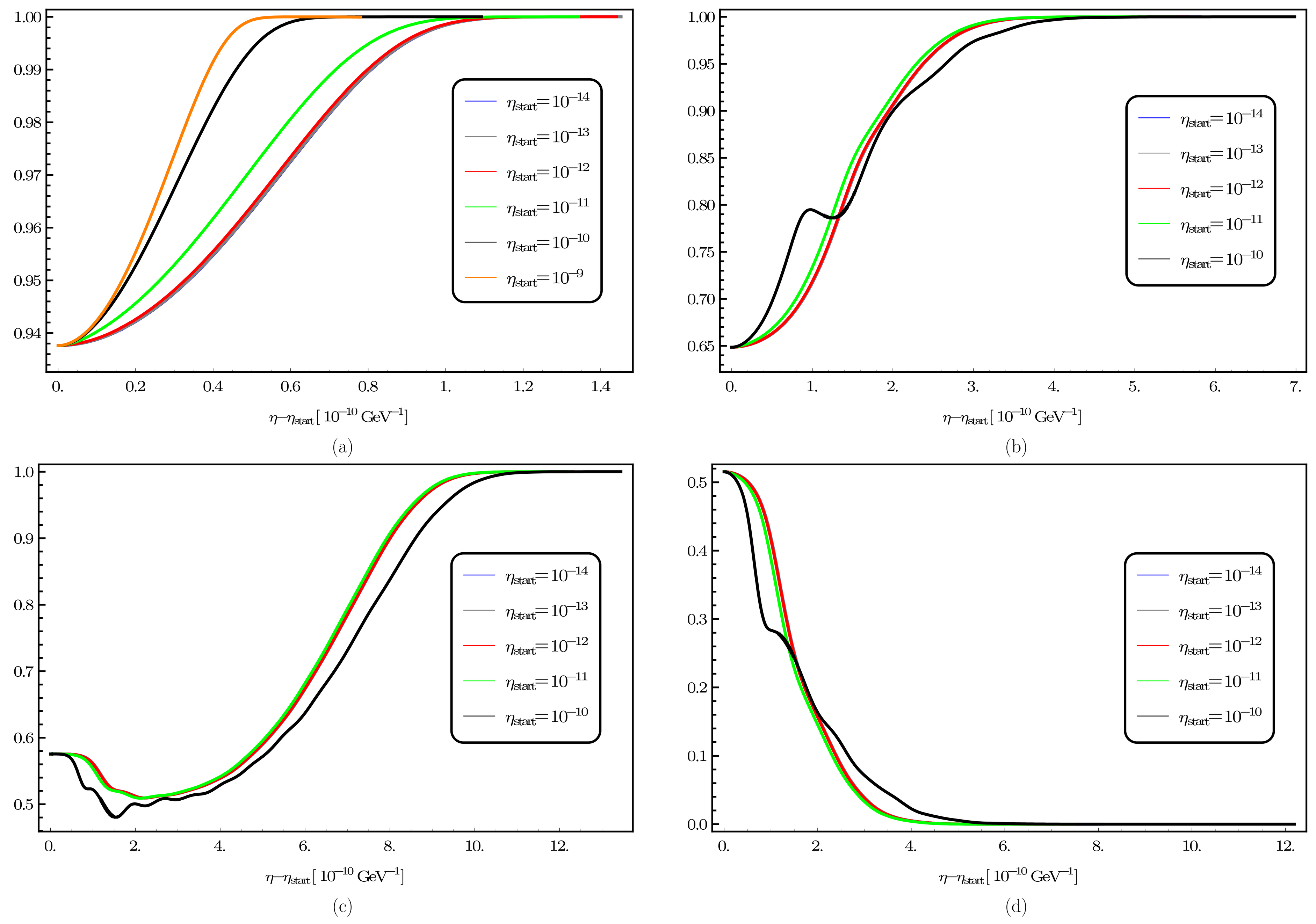

Fig. 4: The fraction of lattice volume occupied by field strengths belonging to the basin of attraction of the electroweak minimum for $\theta = 0$ and different σ: (a)—1.5×10^{10} GeV, (b)—3.0×10^{10} GeV, (c)—3.5×10^{10} GeV and (d)—4.0×10^{10} GeV.

Dependence on the standard deviation at initialization

We investigated the initial conditions satisfying $\theta + \sigma = v_{max}$, where v_{max} is position of the local maximum of the potential. In this case the evolution of networks displays the weak dependence on the value of the σ and for all simulations the final state is the EW vacuum. For late domain walls i.e. $\eta_{start} \geq 10^{-9}$ GeV^{-1} we observed the oscillations of surface area of the network. Moreover we considered possibility that $\theta = v_{max}$, when both vacua are equally populated. We found that in this case the only possible final state is the high field strength minimum. For $\theta = v_{max}$ the decay time strongly depends on the value of σ at the initialization.

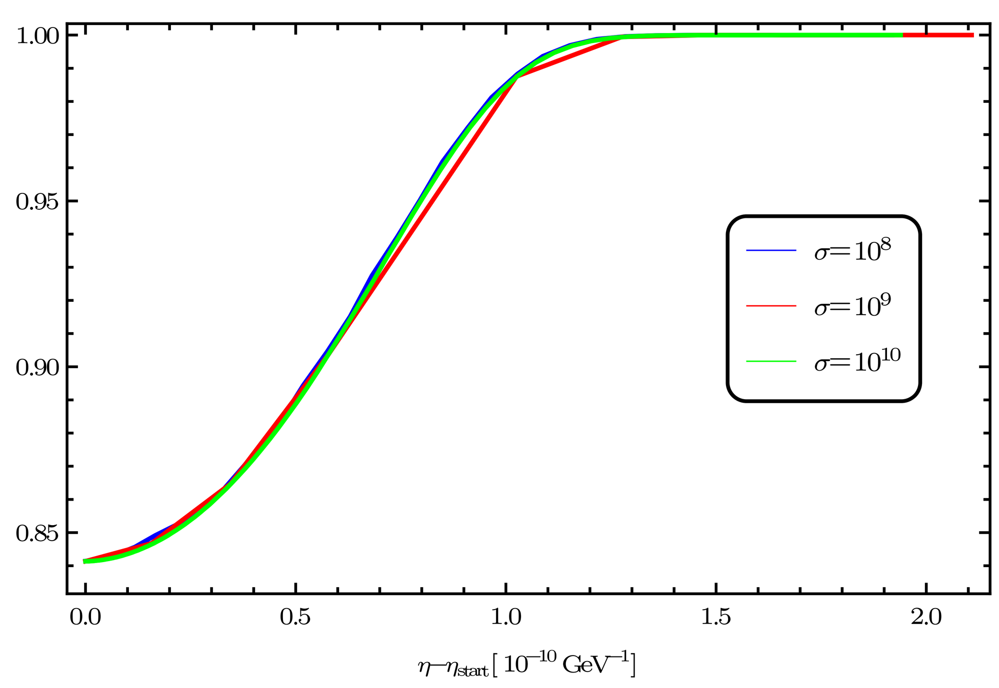

Fig. 5: The fraction of lattice volume occupied by field strengths belonging to the basin of attraction of the electroweak minimum for $\theta + \sigma = v_{max}$ and $\eta_{start} = 10^{-11}$ GeV^{-1}.

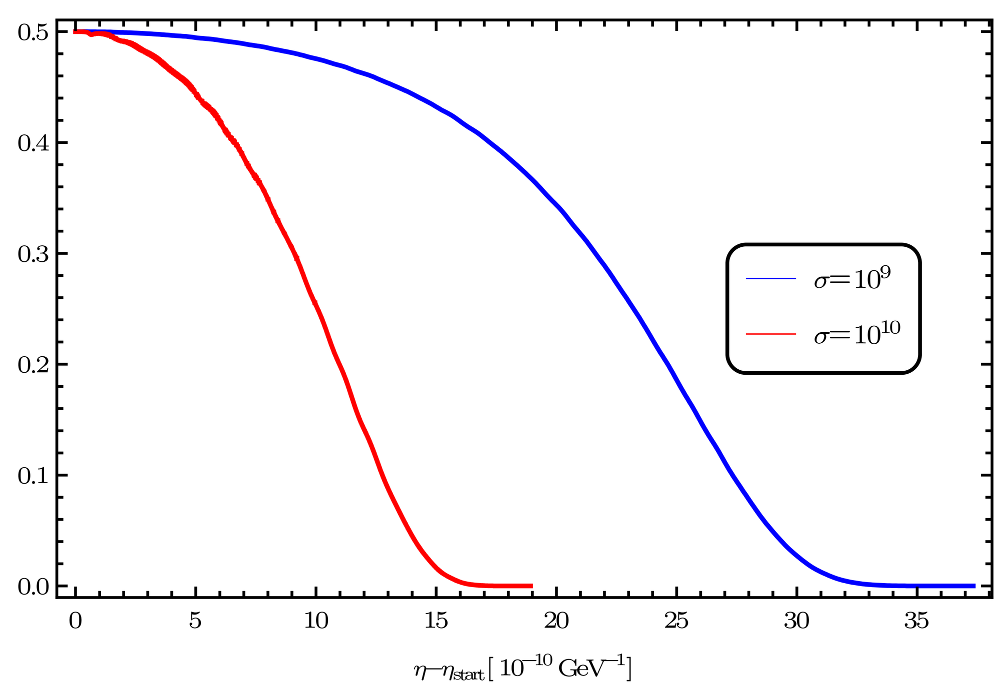

Fig. 6: The fraction of lattice volume occupied by field strengths belonging to the basin of attraction of the electroweak minimum for $\theta = v_{max}$ and $\eta_{start} = 10^{-7}$ GeV^{-1}.

Conclusions

- Domain walls which separate regions with different VEVs of the Higgs field could be formed in the early Universe.
- We observed networks of domain walls which evolution ends in the electroweak vacuum.
- The decay time of SM domain walls ranges from 8×10^{-11} GeV^{-1} to 4×10^{-9} GeV^{-1}.
- Models of the early Universe predicting the validity of SM up to high scales and Higgs field strengths of the order of the local maximum can lead to a unphysical final state.
- Decaying networks of domain walls can produce gravitational waves.

References:

[1] D. Coulson, Z. Lalak, and B. A. Ovrut, *Nonequilibrium phase transitions and domain walls*, in Particles, strings and cosmology. Proceedings, 19th Johns Hopkins Workshop and 5th PASCOS Interdisciplinary Symposium, Baltimore, USA, March 22-25, 1995, 1995, pp. 429–444.

[2] Z. Lalak, S. Lola, and P. Magnowski, *Dynamics of domain walls for split and runaway potentials*, Phys. Rev., D78 (2008), p. 085020.

[3] W. H. Press, B. S. Ryden, and D. N. Spergel, *Dynamical Evolution of Domain Walls in an Expanding Universe*, Astrophys. J., 347 (1989), pp. 590–604.

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