Domain Walls in the Early Universe and Generation of Matter and Antimatter Domains

S.I. Godnov
in collaboration with A.D. Dolgov, A.S. Rudenko, I.I. Tkachev

based on papaers
JCAP 1510 (2015) no.10, 027
JCAP 1610 (2016) no.10, 026

The $6^{\rm th}$ International Conference on New Frontiers in Physics
August 17 — 29, 2017 OAC, Crete, Greece

Outline

- The model
- Bounds on parameters
- Evolution of fields during inflation
- Generation of BAU
- Domain walls in expanding Universe

Model

Lagrangian:

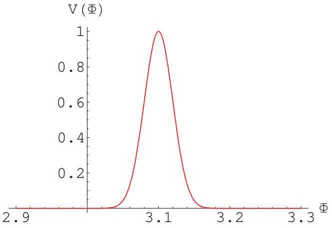
$$L = L_\Phi + L_\chi + L_{int},$$

where

$$\begin{aligned} L_\Phi &= \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2, \\ L_\chi &= \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m^2\chi^2 - \frac{1}{4}\lambda_\chi\chi^4, \\ L_{int} &= \mu^2\chi^2 V(\Phi). \end{aligned}$$

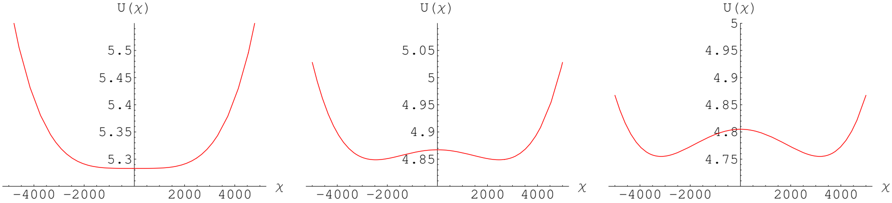
Potential shape:

$$V(\Phi) = \exp\left[-\frac{(\Phi-\Phi_0)^2}{2\Phi_1^2}\right],$$



Evolution of the potential

$$U(\Phi,\chi) = \left(\frac{1}{2}m^2 - \mu^2 V(\Phi)\right)\chi^2 + \frac{1}{4}\lambda_\chi \chi^4 + \frac{1}{2}M^2\Phi^2$$



$$\Phi = \Phi_0 + 2\Phi_1\sqrt{\ln\left(\sqrt{2}\mu/m\right)}$$
$$m^2/2 - \mu^2 V(\Phi) = 0$$

$$\Phi = \Phi_0 + \Phi_1$$

$$\Phi = \Phi_0$$

$\Phi_0 = 3.1\, m_{Pl}$, $\Phi_1 = 0.02\, m_{Pl}$, $\mu = 10^{-4} m_{Pl}$, and $m = 10^{-10} m_{Pl}$.
Field χ is measured in units of M, $U(\Phi,\chi)$ is in units $10^{-12}\, m_{Pl}^4$.

Equations of motion:

$$\ddot{\Phi} + 3H\dot{\Phi} + M^2\Phi + \mu^2\chi^2\frac{\Phi - \Phi_0}{\Phi_1^2}V(\Phi) = 0,$$
$$\ddot{\chi} + 3H\dot{\chi} + m^2\chi + \lambda_\chi\chi^3 - 2\mu^2\chi V(\Phi) = 0,$$

where $H = \dot{a}/a$ is the Hubble parameter, $a(t)$ is a scale factor, which enters the FLRW metric

$$ds^2 = dt^2 - a^2(t)\, d\mathbf{x}^2.$$

The Hubble parameter is defined by energy density ρ

$$H = \sqrt{\frac{8\pi\rho}{3m_{Pl}^2}} = \sqrt{\frac{8\pi}{3m_{Pl}^2}\left(\frac{\dot{\Phi}^2}{2} + \frac{M^2\Phi^2}{2} + \frac{\dot{\chi}^2}{2} + \frac{m^2\chi^2}{2} + \frac{\lambda_\chi\chi^4}{4} - \mu^2\chi^2V(\Phi)\right)},$$

where $m_{Pl} \approx 1.2 \cdot 10^{19}$ GeV is the Planck mass.

Bounds on model parameters

- We do not want to break common inflation scenario:
  $\Phi_{in} > 3.3 m_{Pl}$, $10^{-7} m_{Pl} < M < 10^{-6} m_{Pl}$.
- The size of a domain should be large enough (10 Mpc):
  $\Phi_0 \approx 3.1 m_{Pl}$
- χ should not noticeably affect the inflaton field:

$$M^2 \Phi_0^2 \gg \mu^2 \left. \chi^2 \right|_{\Phi=\Phi_0} \sim \frac{\mu^4}{\lambda_\chi},$$
$$\mu^4 \ll M^2 \Phi_0^2 \lambda_\chi.$$

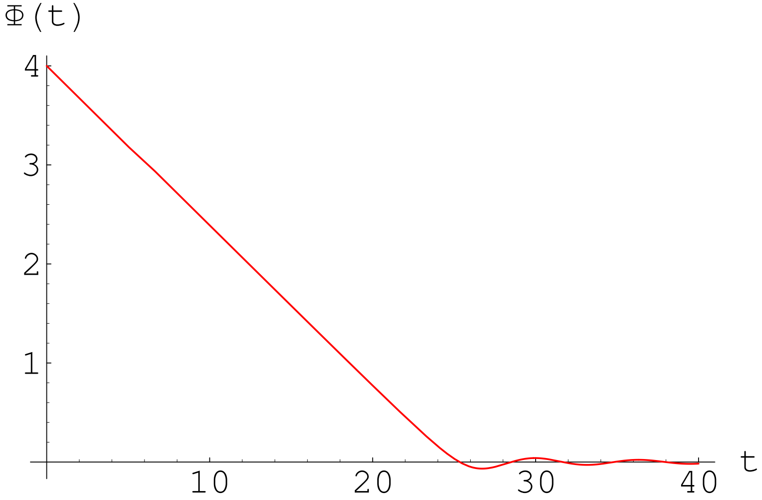
  For $M = 10^{-6} m_{Pl},\ \Phi_0 = 3.1\, m_{Pl}$ we obtain $\mu \ll 1.8 \cdot 10^{-3} m_{Pl} \sqrt[4]{\lambda_\chi}$.
- χ should be able to reach the minimum:
  $\chi \propto \exp(\mu t)$ for $\mu \gg H = \sqrt{4\pi/3}\, M/m_{Pl}\, \Phi \sim 6 \cdot 10^{-6} m_{Pl}$

$$\mu\tau = \mu \frac{8\sqrt{3\pi}\Phi_1}{M m_{Pl}} \gtrsim \ln \frac{\eta_{max}}{\chi_{in}} = \frac{1}{2} \ln \frac{2\mu^2}{\lambda_\chi \chi_{in}^2},$$
$$\mu \gtrsim \frac{M m_{Pl}}{16\sqrt{3\pi}\Phi_1} \ln \frac{2\mu^2}{\lambda_\chi \chi_{in}^2}.$$

- Field χ should slowly decrease with time after after vanishing of $V(\Phi)$:
  If $\lambda_\chi \chi^3$ dominates in equations of motion then $\chi = \sqrt{\frac{3H}{2\lambda_\chi}} \frac{1}{\sqrt{t-C}}$

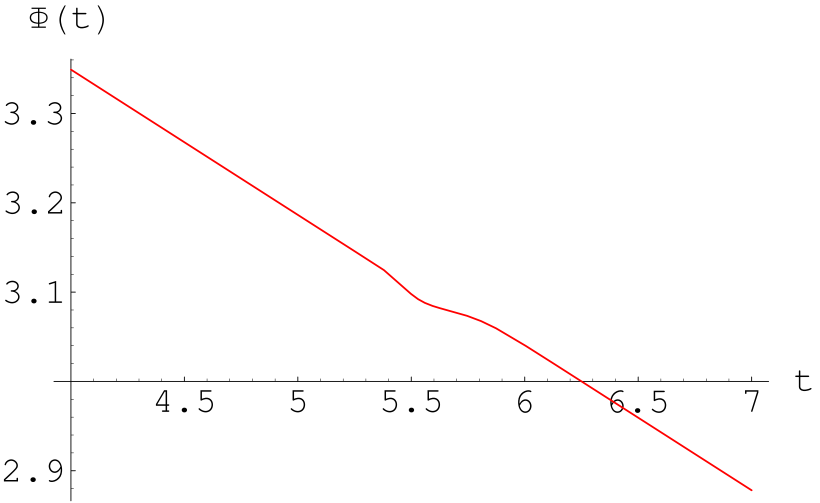
Inflaton field evolution

$\Phi_{in} = 4, \Phi_0 = 3.1, \Phi_1 = 0.02, M = 10^{-6}, \chi_{in} = 10^{-6}, m = 10^{-10}, \lambda_\chi = 2{\cdot}10^{-3}, \mu = 10^{-4}.$



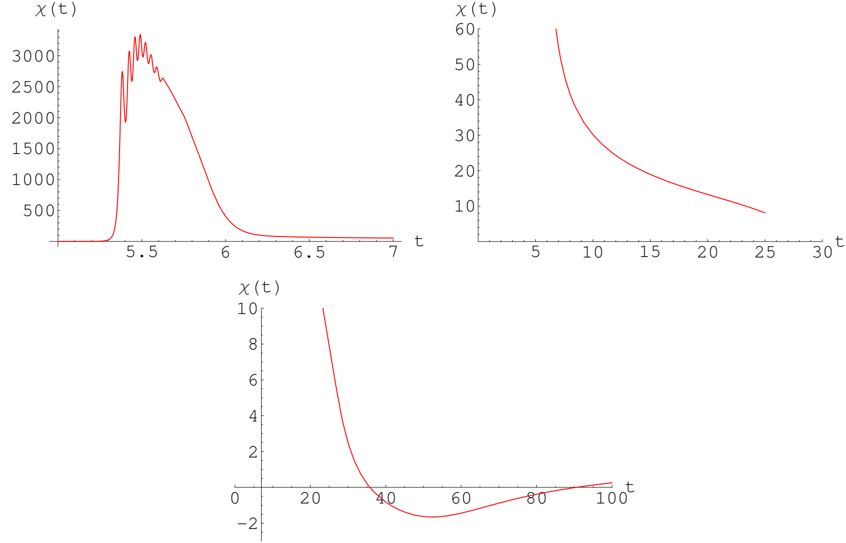
Inflaton field evolution

$\Phi_{in} = 4, \Phi_0 = 3.1, \Phi_1 = 0.02, M = 10^{-6}, \chi_{in} = 10^{-6}, m = 10^{-10}, \lambda_\chi = 2{\cdot}10^{-3}, \mu = 10^{-4}.$



Evolution of χ

$$\Phi_{in} = 4, \Phi_0 = 3.1, \Phi_1 = 0.02, M = 10^{-6}, \chi_{in} = 10^{-6}, m = 10^{-10}, \lambda_\chi = 2{\cdot}10^{-3}, \mu = 10^{-4}.$$



BAU generation

$$L_{free} = \bar{\psi}^k i\hat{\partial}\psi^k - m_{\psi kl}\bar{\psi}^k\psi^l = \bar{\psi}^k_R i\hat{\partial}\psi^k_R + \bar{\psi}^k_L i\hat{\partial}\psi^k_L - m_{\psi kl}(\bar{\psi}^k_R\psi^l_L + \bar{\psi}^k_L\psi^l_R).$$

$$L_{\chi\psi\psi} = g_{kl}\chi\bar{\psi}^k i\gamma_5\psi^l = g_{kl}\chi(\bar{\psi}^k_R i\gamma_5\psi^l_L + \bar{\psi}^k_L i\gamma_5\psi^l_R) = ig_{kl}\chi(\bar{\psi}^k_L\psi^l_R - \bar{\psi}^k_R\psi^l_L).$$

$$L_{free} + L_{\chi\psi\psi} = \bar{\psi}_R i\hat{\partial}\psi_R + \bar{\psi}_L i\hat{\partial}\psi_L - (\bar{\psi}_R M_\psi \psi_L + \bar{\psi}_L M^\dagger_\psi \psi_R),$$

where $M_\psi = m_\psi + ig\chi$.
With two unitary transformations, $\psi_R \to \psi'_R = U_R\psi_R$ and $\psi_L \to \psi'_L = U_L\psi_L$, it is always possible to diagonalize mass matrix:

$$L'_{free} = \bar{\psi}^a i\hat{\partial}\psi^a - m'_{\psi ab}\bar{\psi}^a\psi^b,$$

If there is an interaction with a vector boson X:

$$g_{Rkl}X_\mu\bar{\psi}^k_R\gamma^\mu\psi^l_R + g_{Lkl}X_\mu\bar{\psi}^k_L\gamma^\mu\psi^l_L \to g'_{Rab}X_\mu\bar{\psi}^a_R\gamma^\mu\psi^b_R + g'_{Lab}X_\mu\bar{\psi}^a_L\gamma^\mu\psi^b_L.$$

Asymmetry:

$$\Delta_B \sim \delta\frac{h}{g_X}\left(\frac{m_{th}}{m_{Pl}}\right)^{1/2} \Rightarrow \text{ for } h/g_X \sim 1,\; m_{th} \sim M \text{ we get } \delta \sim 10^{-7}$$

$$ds^2 = dt^2 - e^{2Ht}\left(dx^2 + dy^2 + dz^2\right).$$

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \, \partial_\nu \varphi - \frac{\lambda}{2}\left(\varphi^2 - \eta^2\right)^2.$$

$H = 0$, one-dimensional case ($\varphi = \varphi(z)$):

$$\frac{d^2\varphi}{dz^2} = 2\lambda\varphi\left(\varphi^2 - \eta^2\right).$$

Solution (wall at $z = 0$):

$$\varphi(z) = \eta \, \tanh \frac{z}{\delta_0},$$

where $\delta_0 = 1/(\sqrt{\lambda}\eta)$ is the width.

$H > 0$, stationary solutions (φ depends only on $za(t)$):

Basu, Vilenkin, Phys. Rev. D 50 (1994) 7150

$$\varphi = \eta \cdot f(u), \qquad \text{where} \quad u = Hze^{Ht}.$$

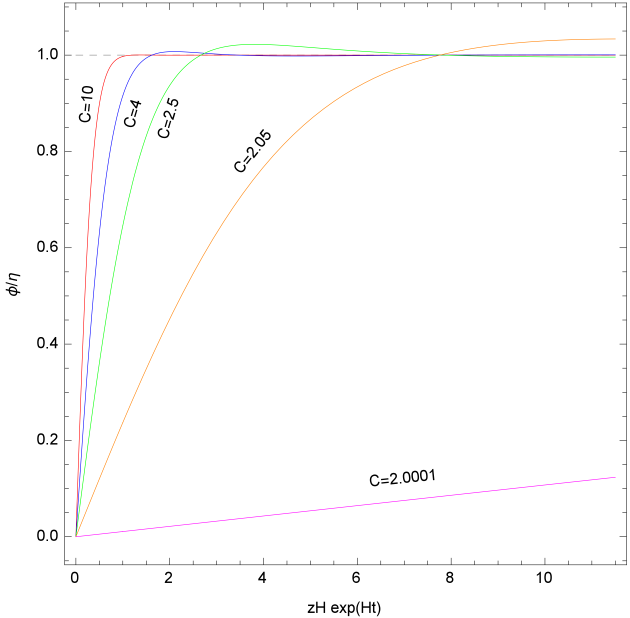
Equation of motion:

$$\left(1 - u^2\right) f'' - 4uf' = -2Cf\left(1 - f^2\right),$$

where $C = 1/(H\delta_0)^2 = \lambda\eta^2/H^2 > 0$.

Boundary conditions: $\quad f(0) = 0, \; f(\pm\infty) = \pm 1.$

Stationary solutions



$$\frac{\partial^2\varphi}{\partial t^2} + 3H\frac{\partial\varphi}{\partial t} - e^{-2Ht}\frac{\partial^2\varphi}{\partial z^2} = -2\lambda\varphi\left(\varphi^2 - \eta^2\right).$$

With the dimensionless variables $\tau = Ht$, $\zeta = Hz$, $f(\zeta,\tau) = \varphi(z,t)/\eta$:

$$\frac{\partial^2 f}{\partial\tau^2} + 3\frac{\partial f}{\partial\tau} - e^{-2\tau}\frac{\partial^2 f}{\partial\zeta^2} = 2Cf\left(1 - f^2\right),$$

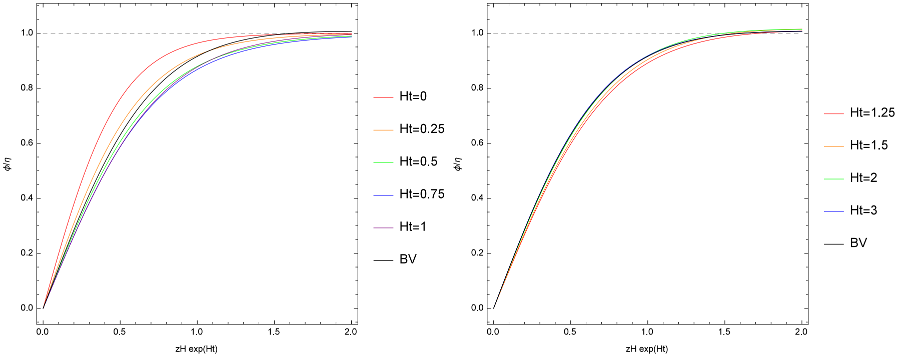
where $C = \lambda\eta^2/H^2 = 1/(H\delta_0)^2 > 0$.
Boundary conditions:

$$f(0,\tau) = 0, \qquad f(\pm\infty,\tau) = \pm 1,$$

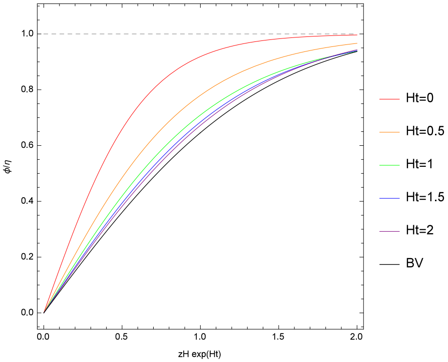
Starting conditions:

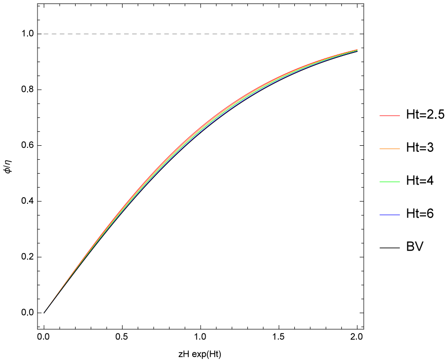
$$f(\zeta,0) = \tanh\frac{z}{\delta_0} = \tanh\sqrt{C}\zeta, \qquad \left.\frac{\partial f(\zeta,\tau)}{\partial\tau}\right|_{\tau=0} = 0.$$

$C = 4$

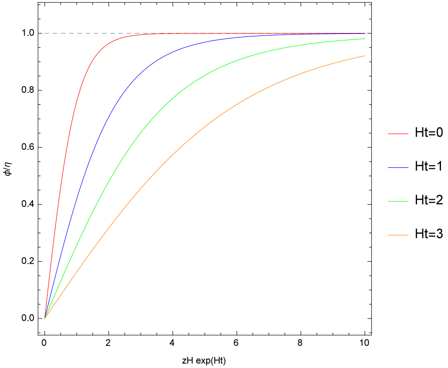

1.0
0.8
0.6
0.4
0.2
0.0
φ/η
0.0
0.5
1.0
1.5
2.0
zH exp(Ht)
Ht=0
Ht=0.25
Ht=0.5
Ht=0.75
Ht=1
BV
1.0
0.8
0.6
0.4
0.2
0.0
φ/η
0.0
0.5
1.0
1.5
2.0
zH exp(Ht)
Ht=1.25
Ht=1.5
Ht=2
Ht=3
BV

$C = 2.5$


1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
ϕ/η
zH exp(Ht)
Ht=0
Ht=0.5
Ht=1
Ht=1.5
Ht=2
BV

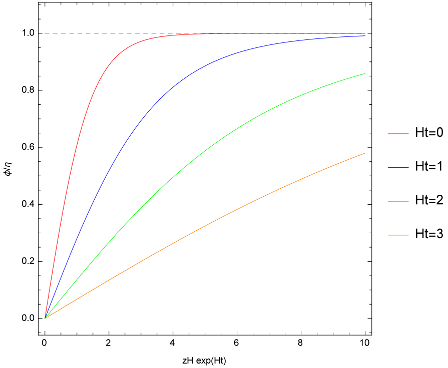

1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
ϕ/η
zH exp(Ht)
Ht=2.5
Ht=3
Ht=4
Ht=6
BV

$C < 2$



1.0
0.8
0.6
0.4
0.2
0.0
φ/η
0
2
4
6
8
10
zH exp(Ht)
Ht=0
Ht=1
Ht=2
Ht=3

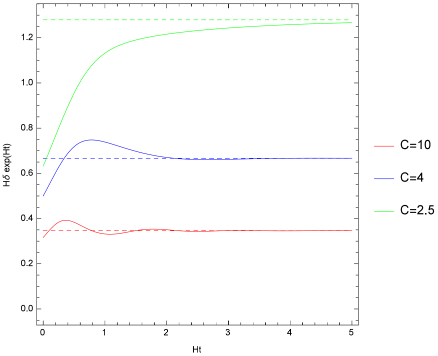
$C = 1$

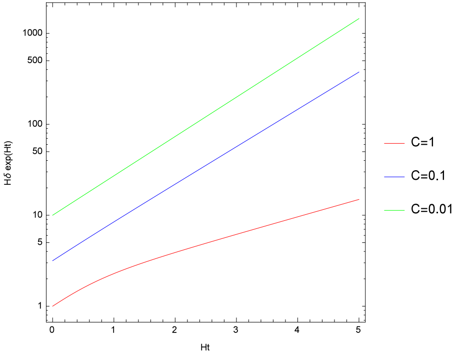


1.0
0.8
0.6
0.4
0.2
0.0
φ/η
0
2
4
6
8
10
zH exp(Ht)
Ht=0
Ht=1
Ht=2
Ht=3

$C = 0.5$

Wall width





Conclusions

- The scenario for generation of matter-antimatter domains (separated by cosmologically large distances) is suggested:
  - We found bounds on parameters at which this scenario can be realized.
  - The numerical simulation was performed to demonstrate that this scenario is possible.

- The evolution of a domain wall in the de Sitter space was studied:
  - In case $C = \lambda\eta^2/H^2 = 1/(H\delta_0)^2 > 2$ the solution tends to the stationary one.
  - In case $C = \lambda\eta^2/H^2 = 1/(H\delta_0)^2 < 2$ the solution is quickly expands. For $C \lesssim 0.1$ the growth of the width becomes almost exponential, i.e. the wall expands with the Universe.