

The mechanism of domain walls and strings formation in the early Universe

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Introduction

- ▶ Inflationary models with several fields could contain complicated potentials.
- ▶ These potentials may have several minima and saddle points (e.g. mexican hat, landscape, ...)
- ▶ Such conditions can lead to the formation of topologically non-trivial structures — solitons¹
- ▶ These non-trivial structures may lead to formation of Primordial Black Holes (PBH)²
- ▶ PBH can influence further evolution of the Universe

¹JCAP 04 (2018) 042

²JETP 92 (2001) 921

Numerical simulation

Lagrangian density of two real scalar fields:

$$\mathcal{L} = \frac{1}{2}g_{\mu\nu}(\partial^\mu\varphi\partial^\nu\varphi + \partial^\mu\chi\partial^\nu\chi) - \mathcal{V}(\varphi, \chi)$$

Equations of motion:

$$\begin{cases} \varphi_{tt} - 3H\varphi_t - \varphi_{xx} - \varphi_{yy} = -\frac{\partial\mathcal{V}}{\partial\varphi}, \\ \chi_{tt} - 3H\chi_t - \chi_{xx} - \chi_{yy} = -\frac{\partial\mathcal{V}}{\partial\chi}. \end{cases}$$

Numerical simulation

Boundary conditions:

$$-\infty \leq x \leq \infty, -\infty \leq y \leq \infty$$

$$\begin{cases} \varphi_x(\pm\infty, y, t) = 0, \\ \varphi_y(x, \pm\infty, t) = 0. \end{cases} \quad \begin{cases} \chi_x(\pm\infty, y, t) = 0, \\ \chi_y(x, \pm\infty, t) = 0. \end{cases}$$

Initial conditions:

$$\begin{cases} \varphi(x, y, 0) = \mathcal{R} \cos \Theta + l_1, \\ \chi(x, y, 0) = \mathcal{R} \sin \Theta + l_2, \\ \varphi_t(x, y, 0) = 0, \\ \chi_t(x, y, 0) = 0, \end{cases} \quad \begin{cases} \mathcal{R}(r) = \frac{\mathcal{R}_0}{\cosh \frac{r_0}{r}}, \\ \Theta = \theta. \end{cases}$$

$\mathcal{R}_0, l_1, l_2, r_0$ — parameters.

Model 1

Potential³:

$$\mathcal{V} = d(\varphi^2 + \chi^2) + a \exp[-b(\varphi - \varphi_0)^2 - c(\chi - \chi_0)^2]$$

Parameters⁴: $a, d, b, c, \varphi_0 = -5, \chi_0 = 0$.

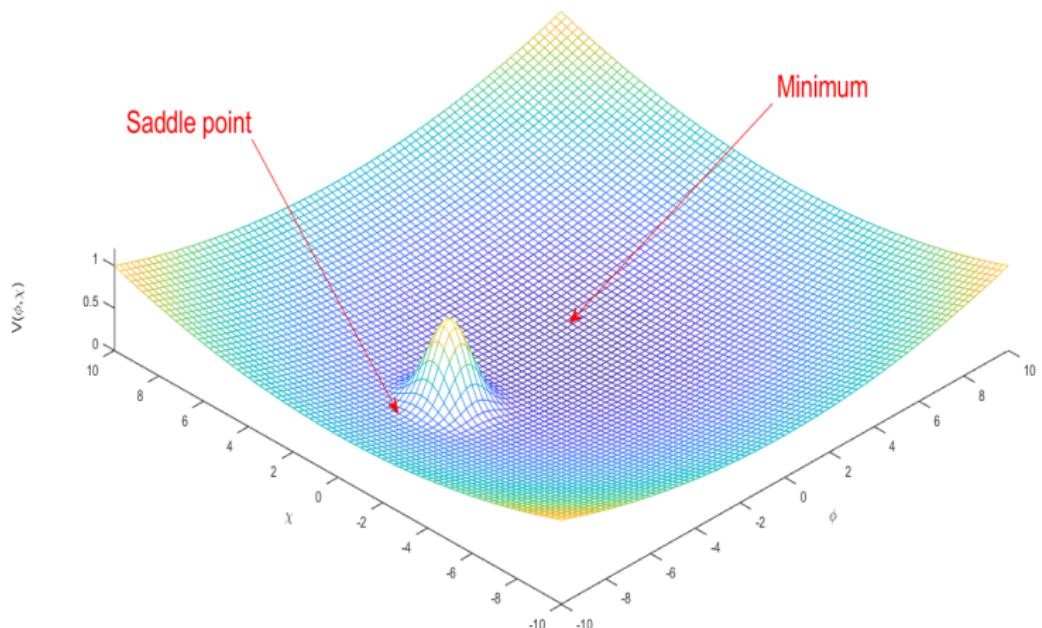
With those parameter values, the potential have local maximum at $\varphi = -5, \chi = 0$.

³V. Gani, A. Kirillov, S. Rubin JCAP 04 (2018) 042

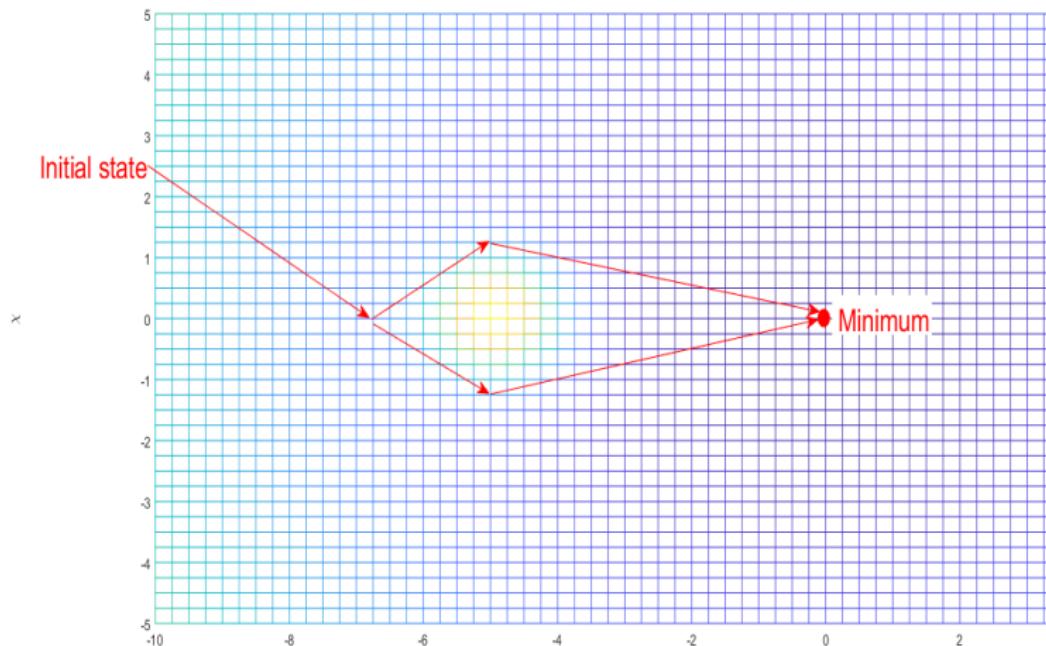
<https://arxiv.org/abs/1704.03688>

⁴Hereinafter all values in Hubble units

Model 1

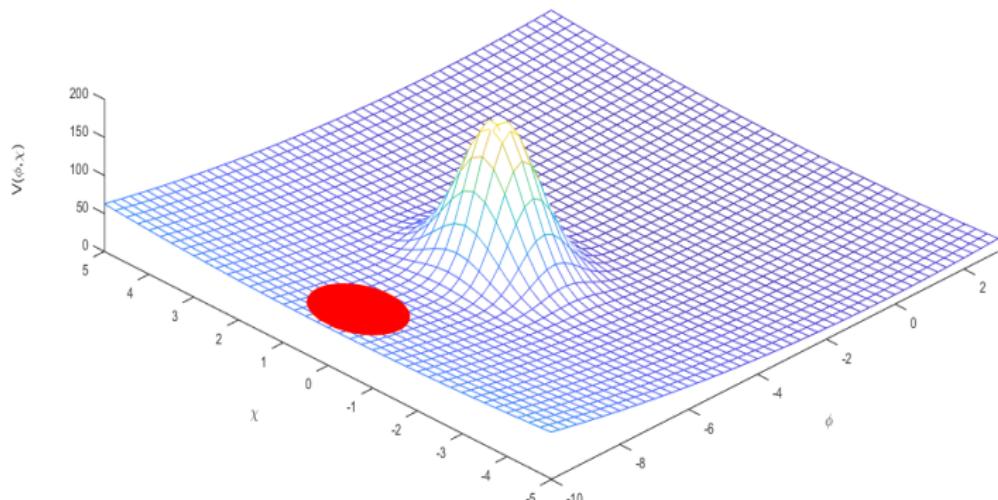


Model 1



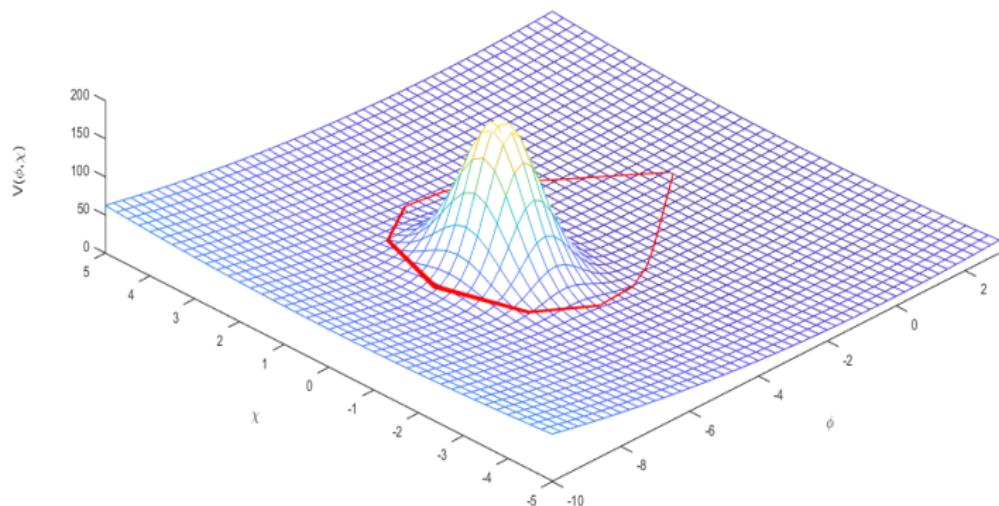
Model 1

Initial condition with parameter values: $\mathcal{R}_0 = 1$, $d = 0.2$, $a = 200$,
 $l_1 = -10$, $l_2 = 0$, $b = 1$, $c = 1$, $\varphi_0 = -5$, $\chi_0 = 0$, $r_0 = 1$



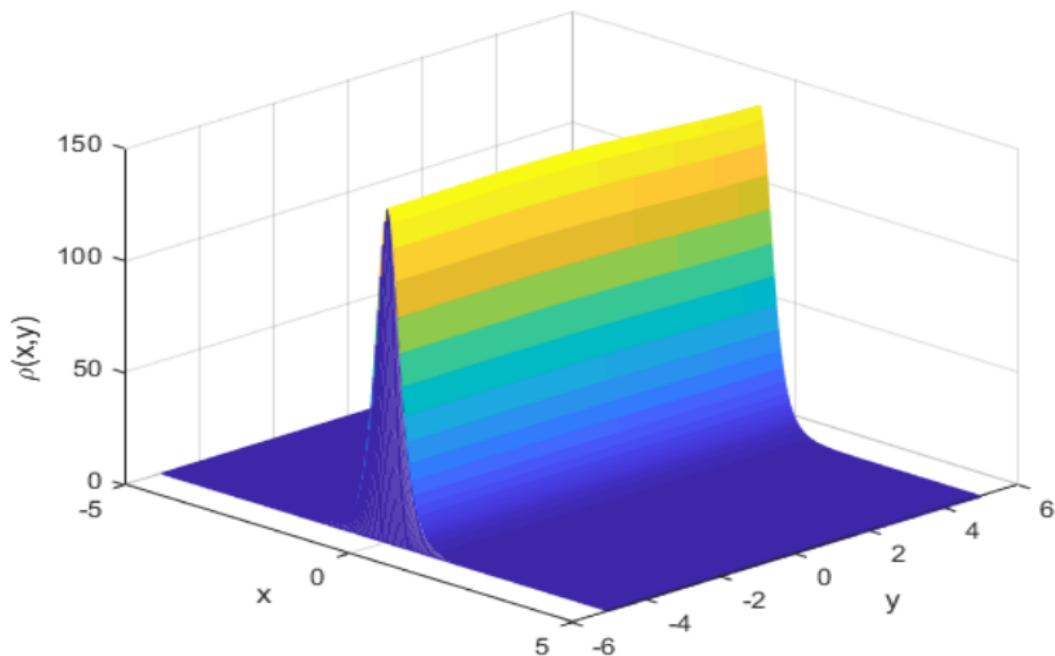
Model 1

Final state



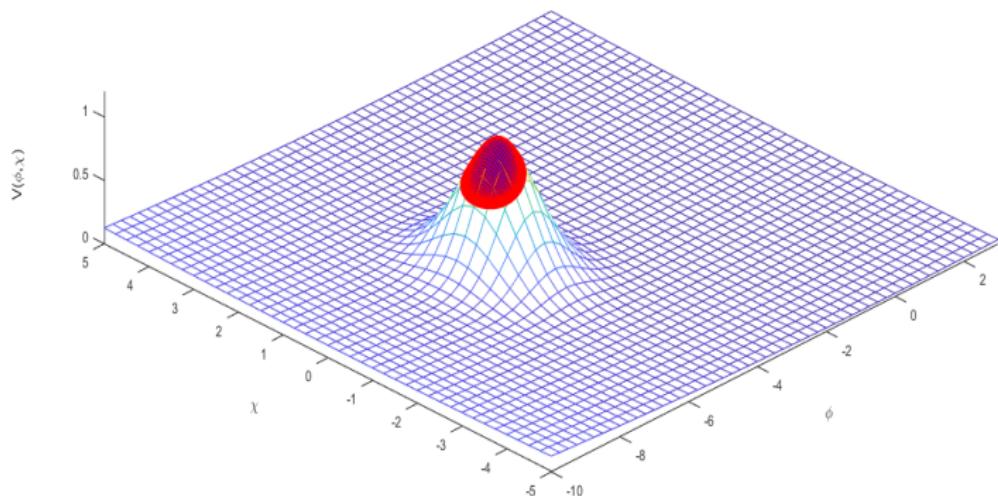
Model 1: energy density

Final state



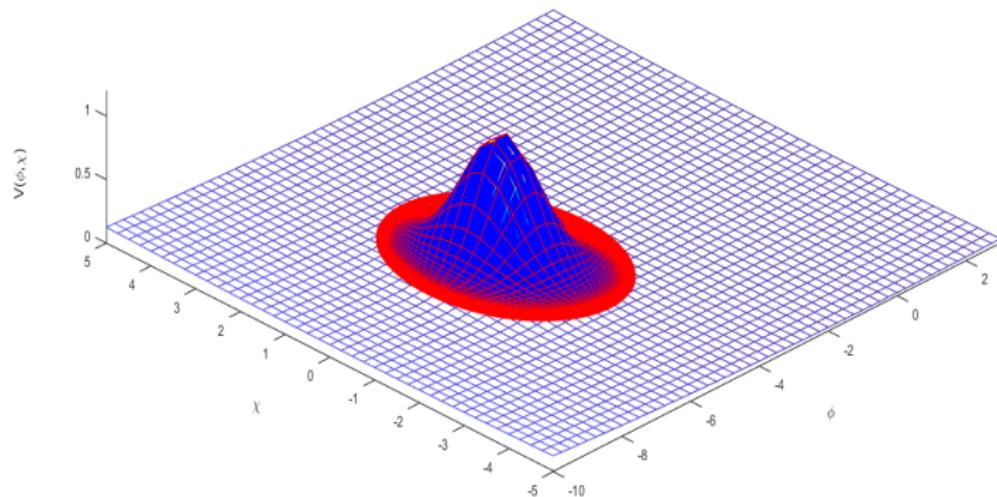
Model 2

Initial condition with parameter values: $\mathcal{R}_0 = 0.1$, $d = 5 \cdot 10^{-7}$,
 $a = 1$, $l_1 = -5.05$, $l_2 = 0$, $b = 1$, $c = 1$, $\varphi_0 = -5$, $\chi_0 = 0$, $r_0 = 1$



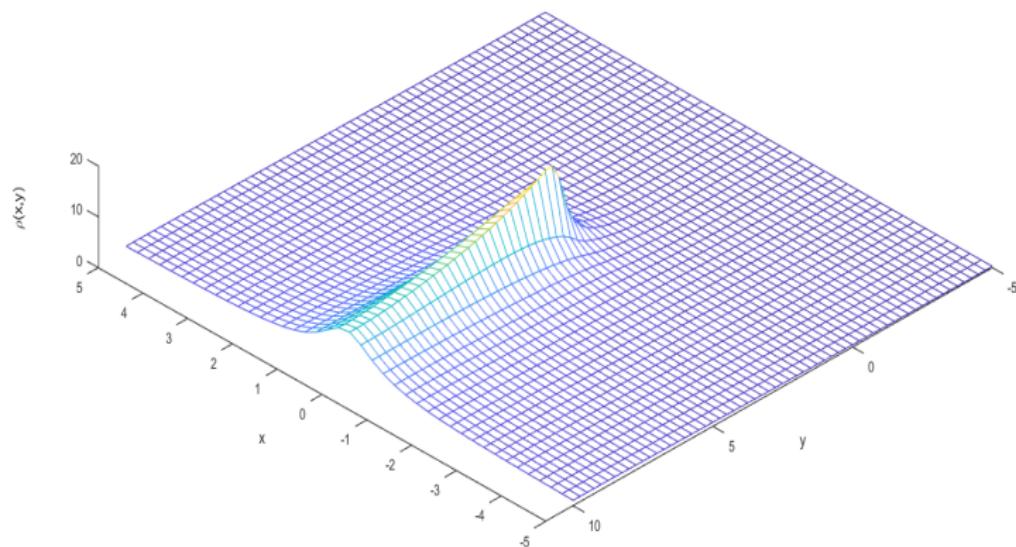
Model 2

Final state



Model 2: energy density

Final state



Model 3

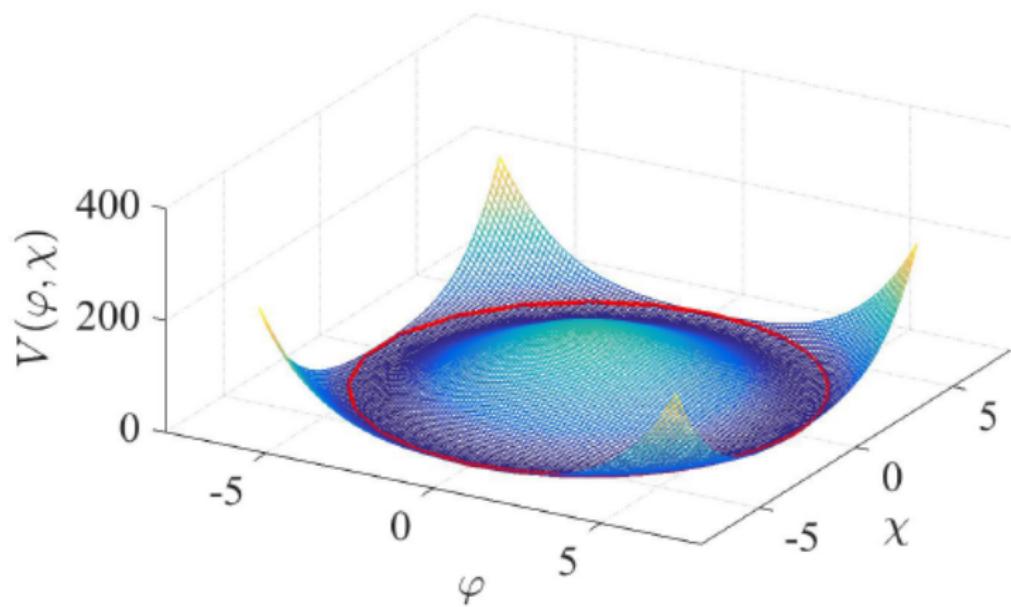
Potential⁵:

$$\mathcal{V} = \lambda \left(\varphi^2 + \chi^2 - \frac{g^2}{2} \right)^2 + \Lambda^4 \left(1 - \frac{\varphi}{\sqrt{\varphi^2 + \chi^2}} \right),$$

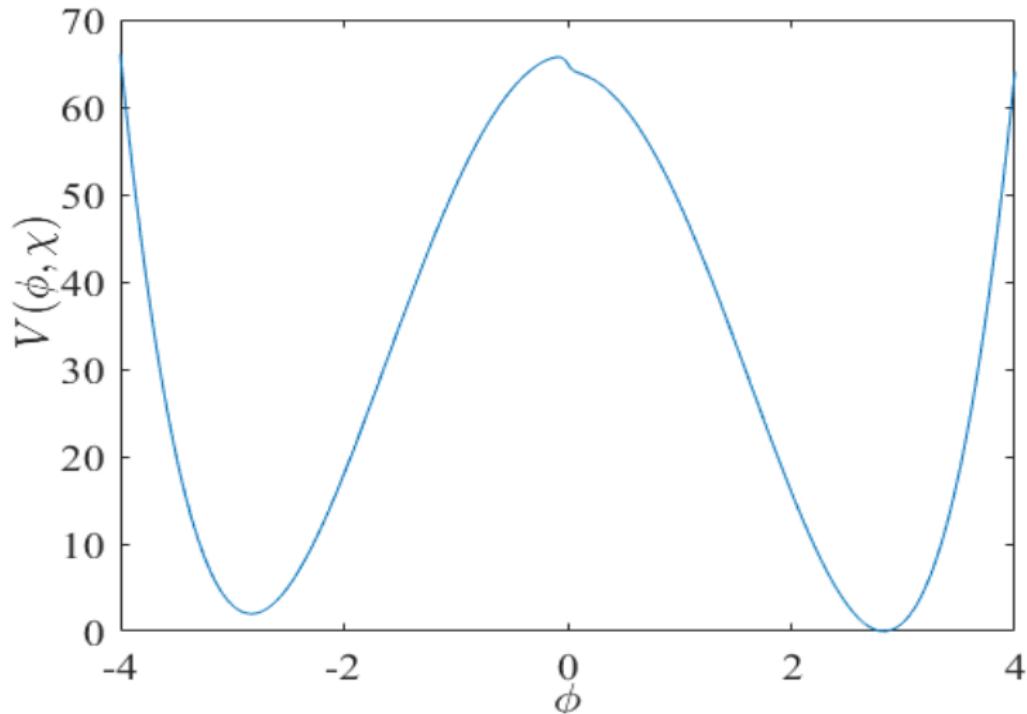
Parameters: $g = 1$, $\lambda = 1$, $\Lambda = 5 \cdot 10^{-13}$.

⁵A. Dolgov, K. Freese, R. Rangarajan, M. Srednicki Phys. Rev. D 56 (1997)

Model 3

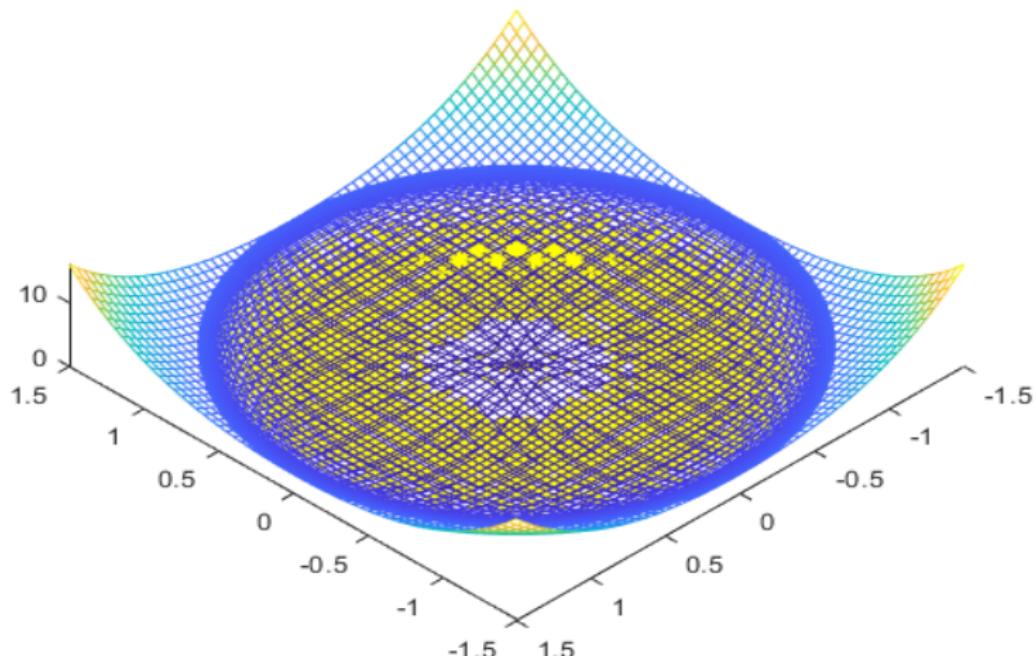


Model 3



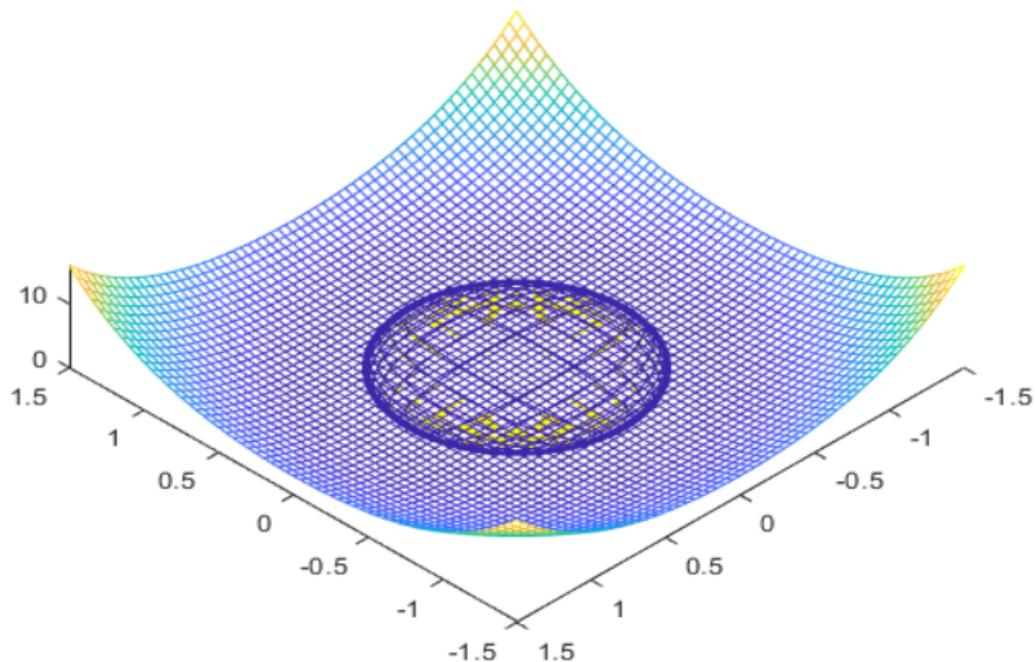
Model 3

Initial condition with parameter values: $\mathcal{R}_0 = 2$, $I_1 = 0$, $I_2 = 0$, $r_0 = 1$



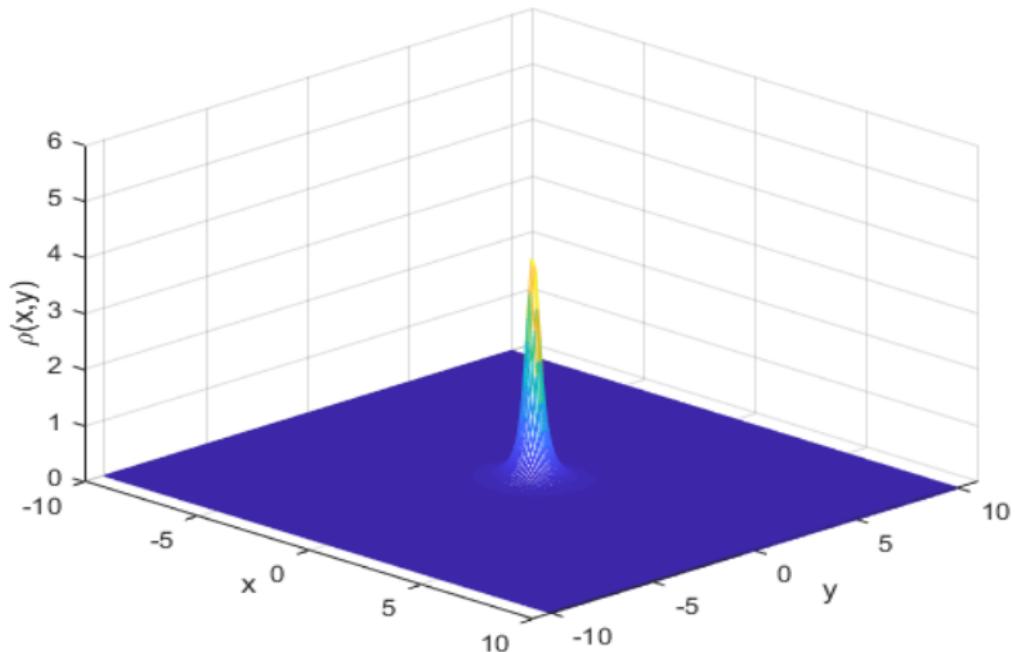
Model 3

Final state



Model 3: energy density

Final state



Conclusion

- ▶ It was shown that during the system evolution domain walls or strings formation is possible, depending on the initial conditions
- ▶ The string moves in space due to tension in the ridge
- ▶ If an inflationary potential contains a saddle point, the formation of domain walls and strings is probable, even it contains only one minimum!