Vacuum Decay in the N2HDM via Domain Walls

Mohamed Younes Sassi

Hamburg, 05/07/2024

DESY 2HDM Working Group Meeting

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Motivation and main idea

- When checking for viable parameter points in extended Higgs models, one needs to enforce the condition of vacuum stability.

- The SM-like VEV should be the global minimum **or** be metastable with a lifetime higher than the age of the universe.

- Criteria for a viable metastability is that the potential barrier between the two minima is large enough to make the bounce action (interpolating between both extrema) large.

- Domain walls related to the Z'_2 symmetry make the potential of the 2HDM dependent on space point x.

- What if the potential barrier inside the wall at x = 0 ($v_s = 0$) gets smaller or even disappears ?

- I show in this work that the formation of the domain walls can lead some parameter points that have a metastable vacuum with lifetime much larger than the age of the universe to decay into the true dangerous vacuum.

- This provides a new constraint for vacuum stability in the case of the standard N2HDM.

Introduction to Domain Walls

Simple definition

- **Domain walls** are a type of **topological defects** that arise after **spontaneous symmetry breaking** (SSB) of a **discrete symmetry** in the early universe.
- After SSB, **different regions** of the universe end up in different **degenerate vacua**. The universe is then divided into seperate cells with the **boundary between** them called a **“domain wall”**.

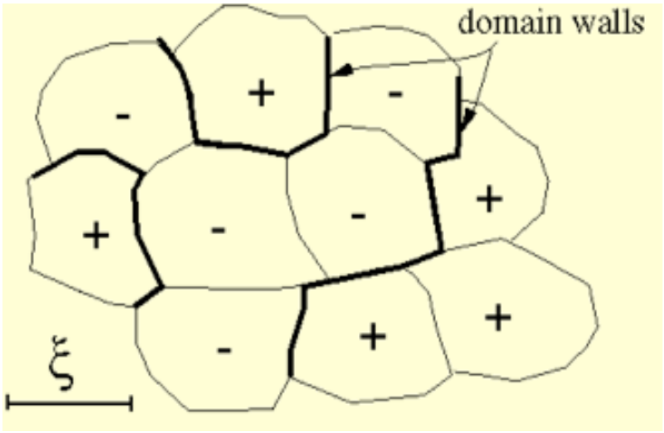


Fig from https://www.ctc.cam.ac.uk/outreach/origins/cosmic_structures_two.php

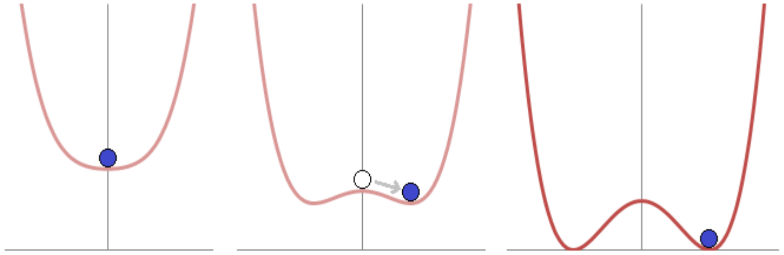


Fig from wikipedia

Simplest example (real singlet scalar)

$$V(\phi) = \mu\phi^2 + \lambda\phi^4$$

V(Φ) is **invariant** under **Z_2:** $\phi \to -\phi$

- Universe gets **seperated into different cells** with **positive** and **negative minima** having the same probability to occur.

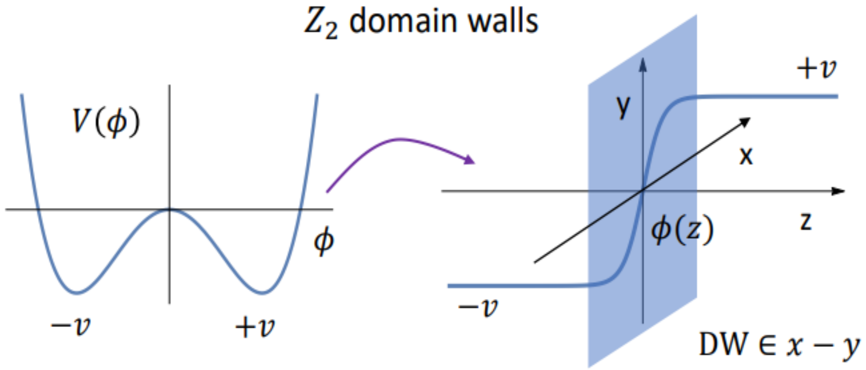


Fig from S.Blasi talk at DESY

The next-to-two-Higgs-doublet-model (N2HDM)

Add one extra doublet and one extra singlet to the Standard Model.

$$V_{N2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2$$

$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2\right)^2 + h.c\right]$$

Two Higgs doublets

$$+ \frac{m_S^2}{2} \Phi_s^2 + \frac{\lambda_6}{8} \Phi_s^4 + \frac{\lambda_7}{2} \Phi_s^2 (\Phi_1^\dagger \Phi_1) + \frac{\lambda_8}{2} \Phi_s^2 (\Phi_2^\dagger \Phi_2).$$

Singlet scalar component

The N2HDM admits several discrete symmetries

- **Z_2 Symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $\Phi_s \to \Phi_s$** (softly broken by m_{12} term). Used to forbid **Flavor-Changing-Neutral-Currents** at **tree level** when extended to the quarks in the Yukawa sector.

- **Z'_2 Symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to \Phi_2$, $\Phi_s \to -\Phi_s$** . **Unbroken** in the **standard N2HDM**. Leads to the formation of stable domain walls that are **cosmologically forbidden**. Problem solved by adding small soft breaking terms:

$$a\Phi_s,\ b\Phi_s^3,\ c_1\Phi_s\Phi_1^2,\ c_2\Phi_s\Phi_2^2,\ c_3\Phi_s\Phi_1\Phi_2,\ \ldots$$

- We assume those terms are **very small** making them irrelevant for the **DW profiles (only relevant for determining the annihilation time of the DW network)**

The next-to-two-Higgs-doublet-model (N2HDM)

Possible types of vacua in the N2HDM:

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}v_+\\ \pm v_2 e^{i\xi}\end{pmatrix}, \qquad \langle\Phi_s\rangle = \pm v_s .$$

The N2HDM admits several types of vacua after SSB:

- **Electrically charged vacuum:** **$v_+ \neq 0$.** Breaks **$U(1)_{em}$** and leads to **photons being massive → unphysical.**
- **CP-Violating vacuum:** **$\xi \neq 0$. CP-violation** due to phase between the doublets → **constrained by EDM**
- **Neutral vacuum:** **$v_+ = 0$, $\xi = 0$.** Same behavior as the SM Higgs vacuum → **used throughout this work**
- It was shown that it is possible to have **CP-violating** or **electric charge breaking vacua** localized **inside domain walls** of the **2HDM** (see **Pilaftsis, Law [2110.12550] PRD** and **MYS, Moortgat-Pick [2309.12398] JHEP**).
- Similar behavior in the **N2HDM** → Opportunity for **electroweak baryogenesis via domain walls**.

Domain Wall solutions in the N2HDM

We focus on domain walls related to the Z'_2 symmetry breaking:

To get the domain wall solution:

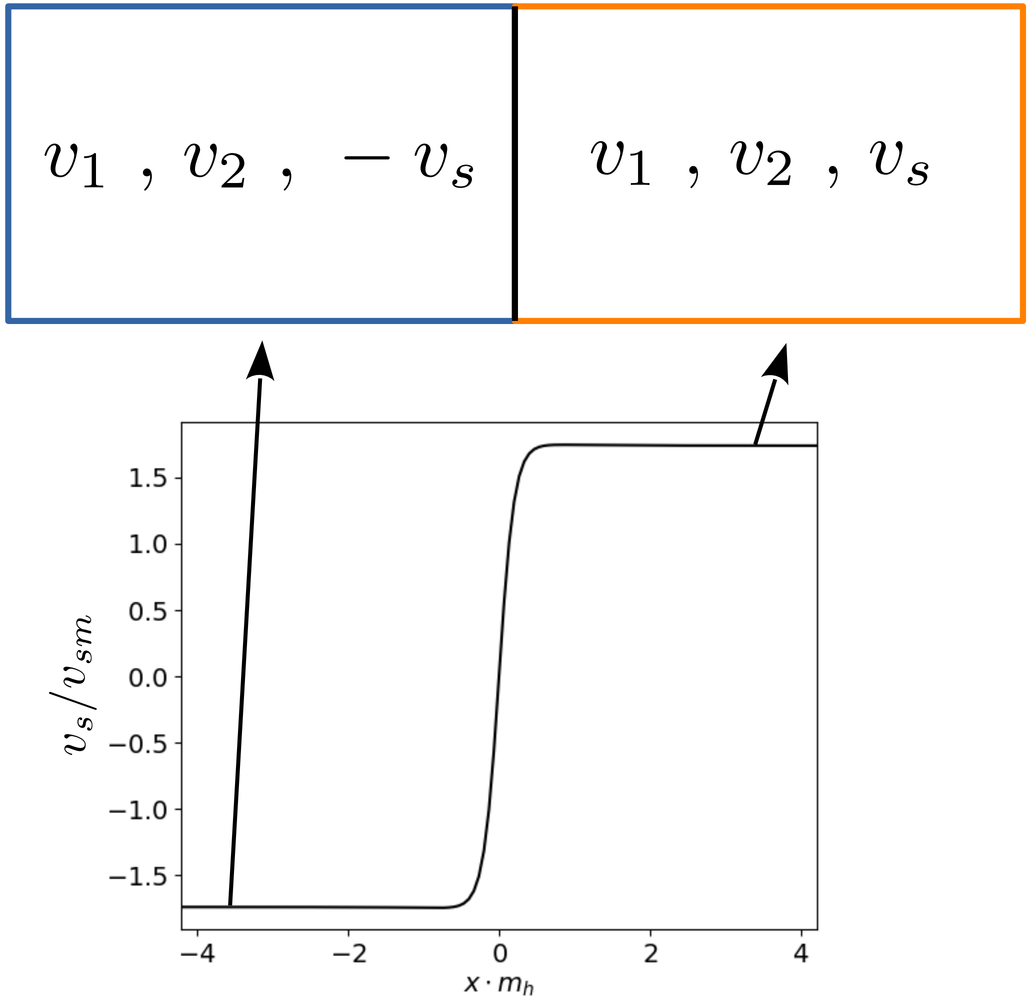
- Determine the boundary conditions
- Solve the equation of motion of the scalar fields:

$$\frac{d^2 v_s}{dx^2} - \frac{dV_{N2HDM}}{dv_s} = 0$$

$$\frac{d^2 v_1}{dx^2} - \frac{dV_{N2HDM}}{dv_1} = 0$$

$$\frac{d^2 v_2}{dx^2} - \frac{dV_{N2HDM}}{dv_2} = 0$$

- This is done numerically using the gradient flow algorithm, see **Battye, Brawn, Pilaftsis 2011 (JHEP)**



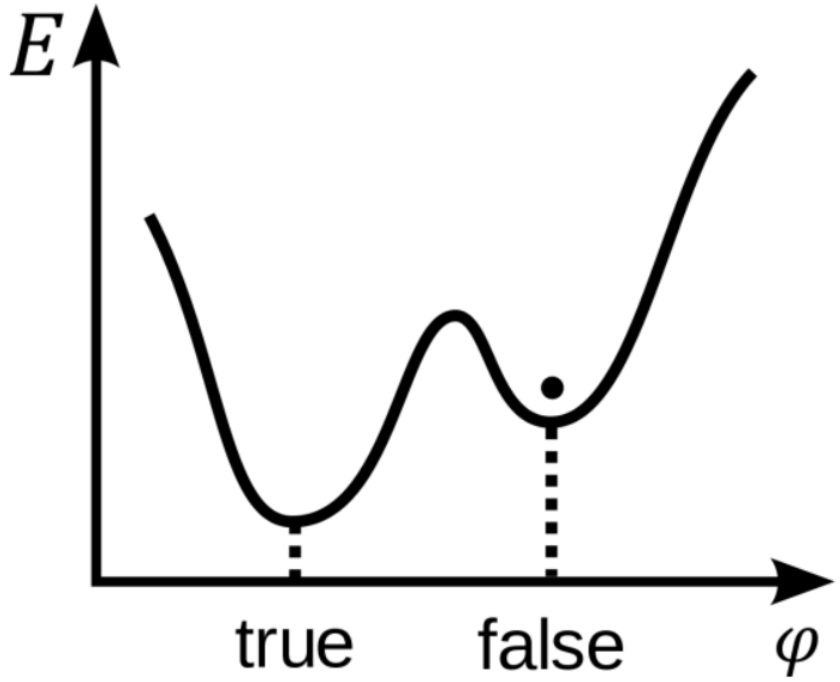
Vacuum stability

- If a the SM-like minimum is the global minimum then the **vacuum is stable.**
- If a parameter point of the model has a global minimum different than the SM-like minimum, then one needs to calculate the **bounce action S_E** to determine the **decay rate** of the SM-like minimum.

$$\Gamma/V = Ke^{-S_E}$$

- For **$S_E < 390$** the SM-like vacuum is short lived and decays quickly to the true deeper vacuum. Such parameter points are **unphysical**.
- For **$390 < S_E < 440$** the outcome is **uncertain**.
- For **$S_E > 440$** the SM-like vacuum is **long lived** (longer than the age of the universe) and the parameter point is **allowed**.

Fig. from Biekötter's talk at SUSY24



Vacuum stability in the N2HDM

- Only focus on these vacua (in this work I ignore CP and charge breaking vacua) and assume the **Ns vacuum** is the **SM-like** one:

$$\langle\Phi_1\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}} = 0. \qquad \langle\Phi_1\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1'\end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2'\end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}s} = v_S'$$

Difference in the potential between the two vacua determines the **true** and the **false minimum**:

$$V_{\mathcal{N}s} - V_{\mathcal{N}} = \frac{1}{4}\left[\left(\frac{m_{H^\pm}^2}{4v^2}\right)_{\mathcal{N}} - \left(\frac{m_{H^\pm}^2}{4v^2}\right)_{\mathcal{N}s}\right](v_1 v_2' - v_2 v_1')^2 + \frac{1}{4} m_D^2\, s^2$$

$$m_{H^\pm}^2 = m_{12}^2 \frac{v^2}{v_1 v_2} - \frac{1}{2}(\lambda_4 + \lambda_5)\, v^2 \qquad\qquad m_D^2 = m_S^2 + \frac{1}{2}(\lambda_7 v_1^2 + \lambda_8 v_2^2)$$

- If the difference is **negative**, then the **SM-like vacuum is the false minimum** and **EVADE** calculates the bounce action between the two vacua to determine whether the parameter point has **metastability longer than the age of the universe**.

- In the N2HDM the SM-like vacuum can have a **large lifetime much larger than the age of the universe**. Such a parameter point is then **allowed**.

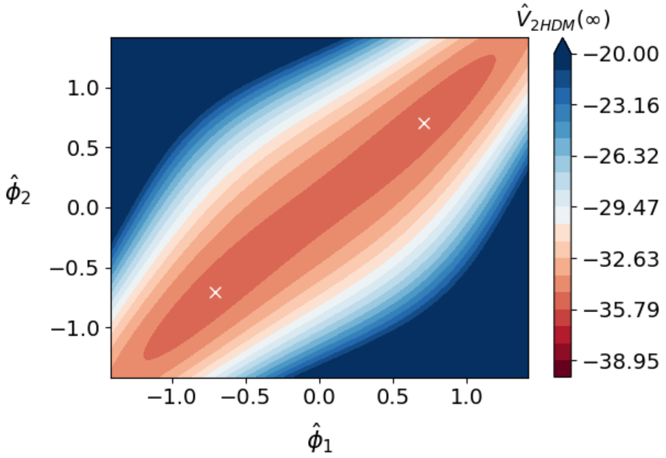
- However, a **non-zero v_s** breaks the Z'_2 and leads to the **formation of domain walls**.

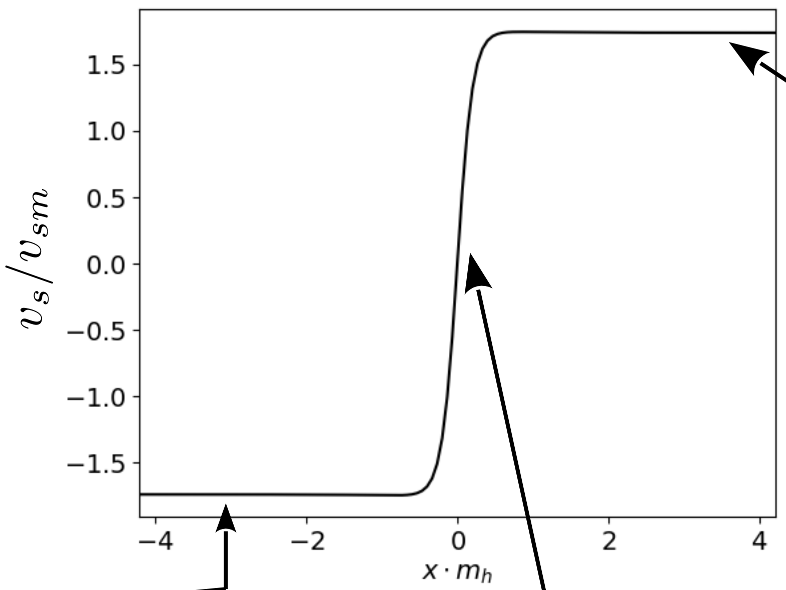
- Domain wall solutions **necessarily** lead to **$v_s = 0$** inside the **core of the domain wall**.

- Is it possible that the **transition to the true vacuum** occurs **inside the wall** ?

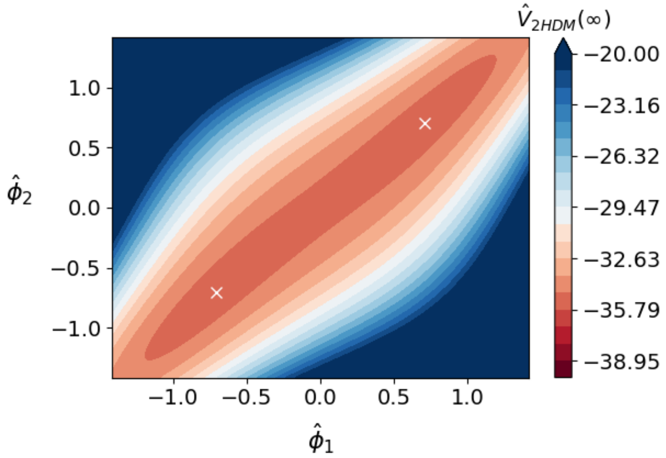
The potential for the Higgs doublets is now space-dependent

Potential at -∞ ($-v_s$)

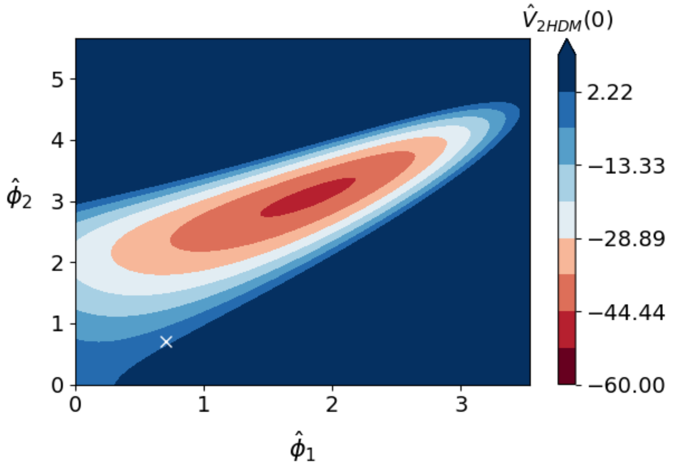




Potential at +∞ (v_s)



Potential at x=0
($v_s = 0$)



Solve the domain wall equation of motion:

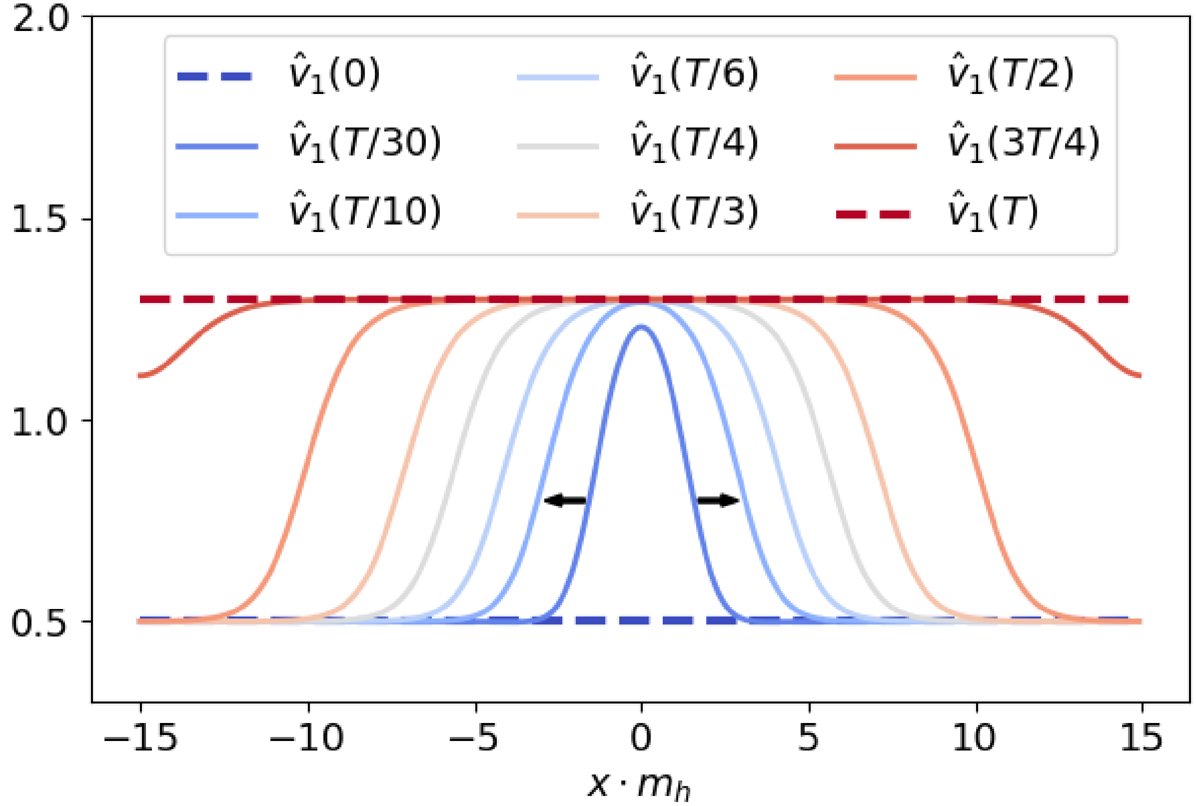
$$\frac{d^2 v_s}{dx^2} - \frac{dV_{N2HDM}}{dv_s} = 0 \qquad \frac{d^2 v_2}{dx^2} - \frac{dV_{N2HDM}}{dv_2} = 0$$

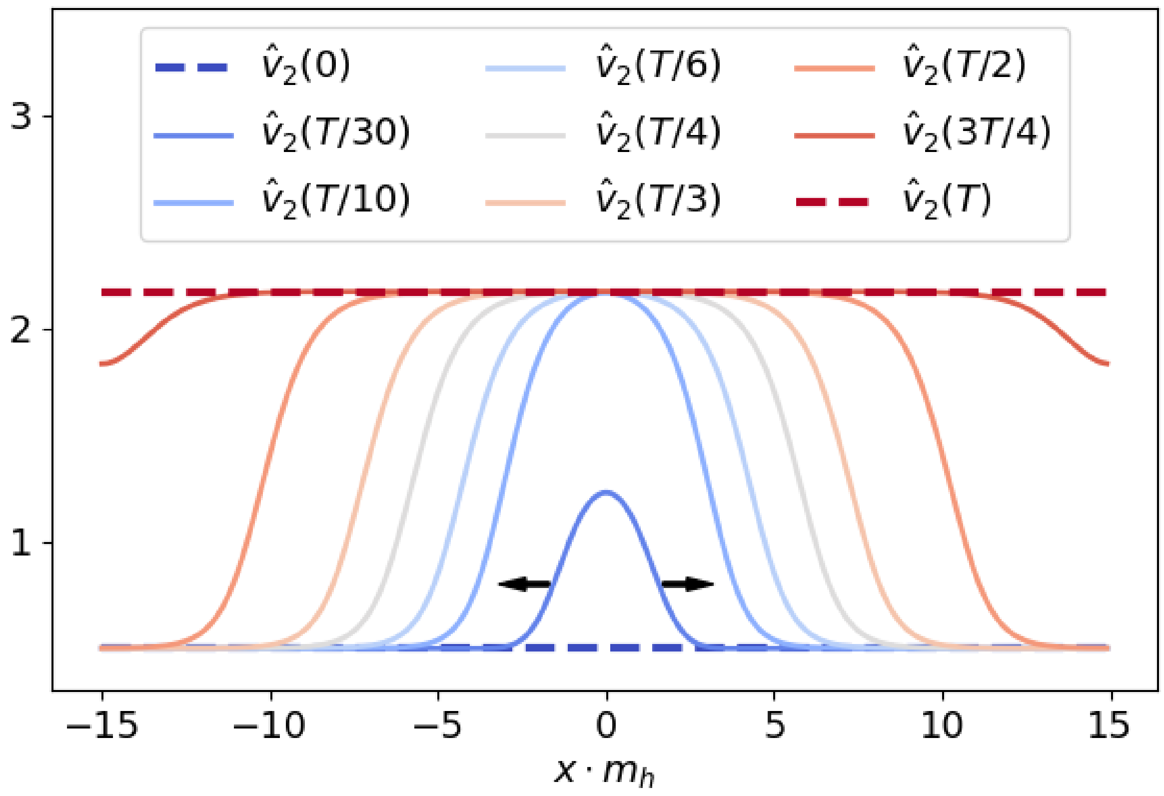
$$\frac{d^2 v_1}{dx^2} - \frac{dV_{N2HDM}}{dv_1} = 0$$

- **Boundary conditions:**

$$\Phi_1(\pm\infty) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \Phi_s(-\infty) = -v_s$$

$$\Phi_2(\pm\infty) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad \Phi_s(+\infty) = v_s$$



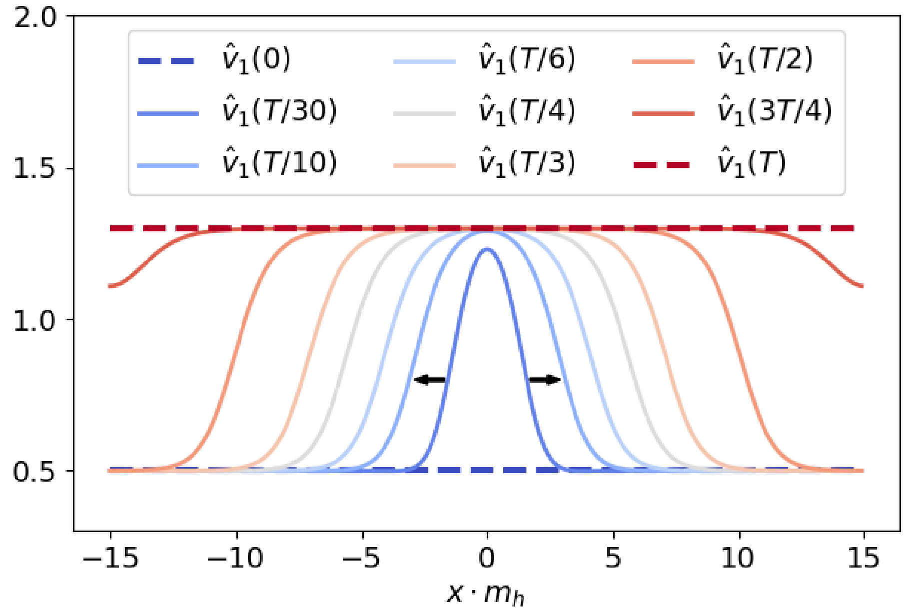


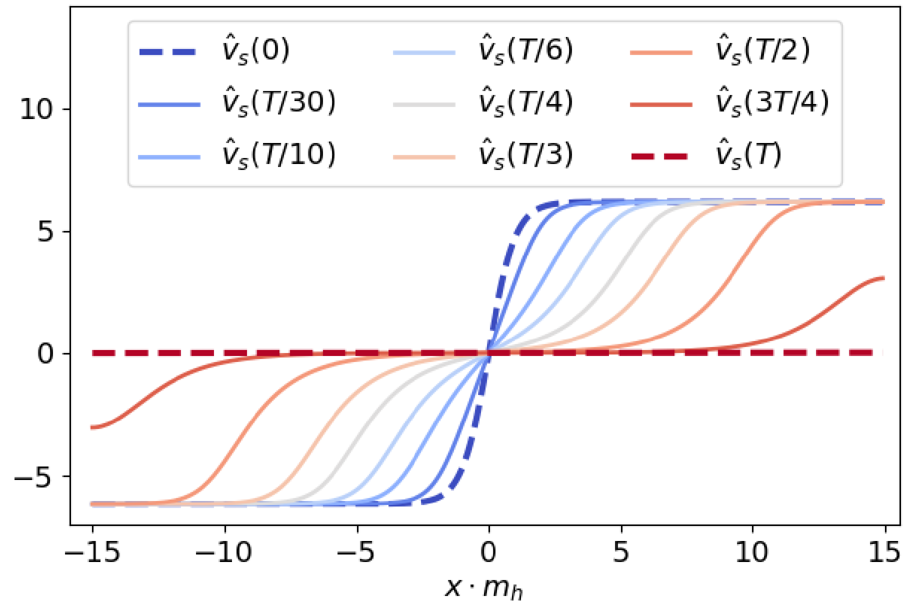
- The true minimum **develops** inside the domain wall.

- This is a **classical roll-over**, because there is **no potential barrier** separating the two vacua inside the wall !

- Once the core of the wall transitions to the true minimum, the wall **“explodes”** and the **true minimum expands** in the region of the false vacuum. This is similar to the expansion of **bubbles in a FOPT**.

- In the end the domain wall profile for the singlet disappears and the domain wall is annihilated !





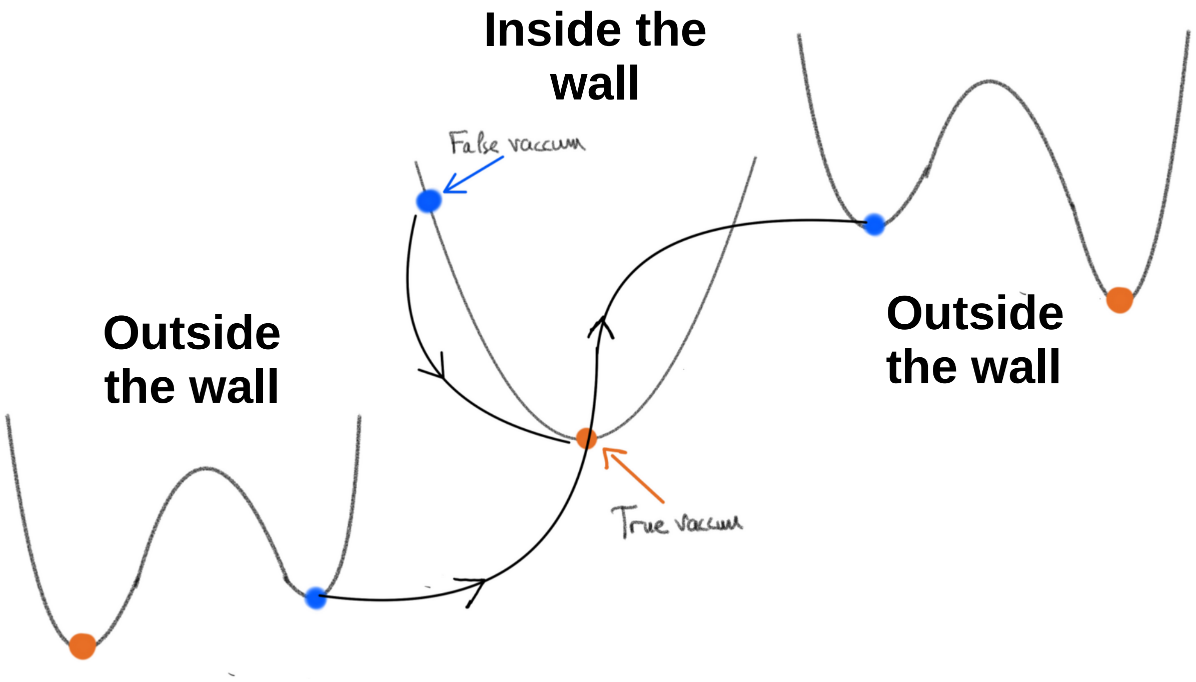
- The roll-over to the true vacuum and the “explosion” of the domain wall only happens when the **difference in potential energy** between the true and false vacua is larger than **the kinetic energy (tension) of the wall**, otherwise the value of the doublet fields inside the wall will not go exactly to the values of the true vacuum !

$$\sigma_V = \int dx \; V(\Phi_1^{false}, \Phi_2^{false}, \Phi_s(x)) - V(\Phi_1^{true}(x), \Phi_2^{true}(x), \Phi_s(x))$$

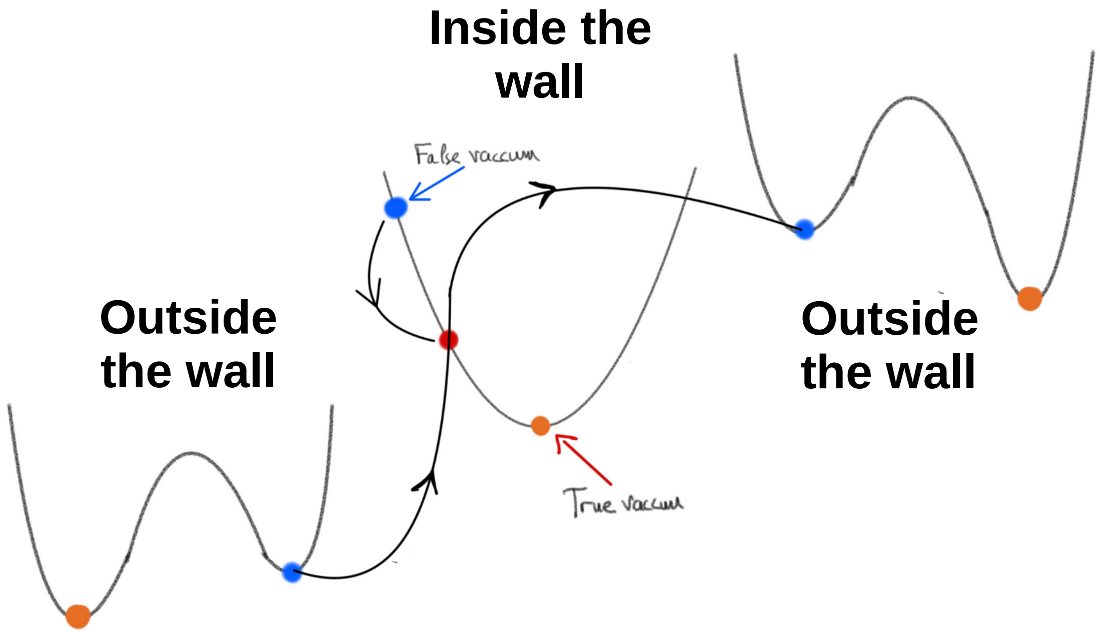
$$\sigma_{kin} = \int dx \left(\frac{d\Phi_{true,1,2}(x)}{dx} \right)^2$$

- For $\boldsymbol{\sigma_V > \sigma_{kin}}$ the **true vacuum “nucleates”** inside the wall and then expands in the region of the false vacuum.

- For $\boldsymbol{\sigma_V < \sigma_{kin}}$ the values of v_1 and v_2 inside the wall are either **the asymptotic ones** or **tend to approach** the true vacuum but **does not reach it**.



Case when $\sigma_V > \sigma_{kin}$



Case when $\sigma_V < \sigma_{kin}$

Conclusions and Outlook

- Domain walls can induce false vacuum decay even for metastable vacua with very large lifetimes, much larger than the age of the universe.

- This decay can be in the form of a classical roll-over, as the barrier between the two minima disappears inside the wall.

- This mechanism works for parameter points that have a non-zero v_s in the false vacuum and $v_s = 0$ in the true vacuum.

- Parameter points that feature this effect are ruled out. Therefore, for metastable vacua in the standard N2HDM, a lifetime larger than the age of the universe is not a sufficient constraint for the validity of the parameter point.

- In the future, investigate this mechanism for the opposite scenario : the SM-like minimum is the true vacuum but the thermal evolution led to the universe falling in the false one.

Thank you

Contact

Deutsches Elektronen-Synchrotron DESY

www.desy.de

Mohamed Younes Sassi

mohamed.younes.sassi@desy.de