EW VACUUM DECAY INDUCED BY DOMAIN WALLS IN THE N2HDM.

EPS 2025, Marseille

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Work in collaboration with Gudrid Moortgat-Pick.

based on: 2506.14880 (MYS, Moortgat-Pick)

08/07/2025

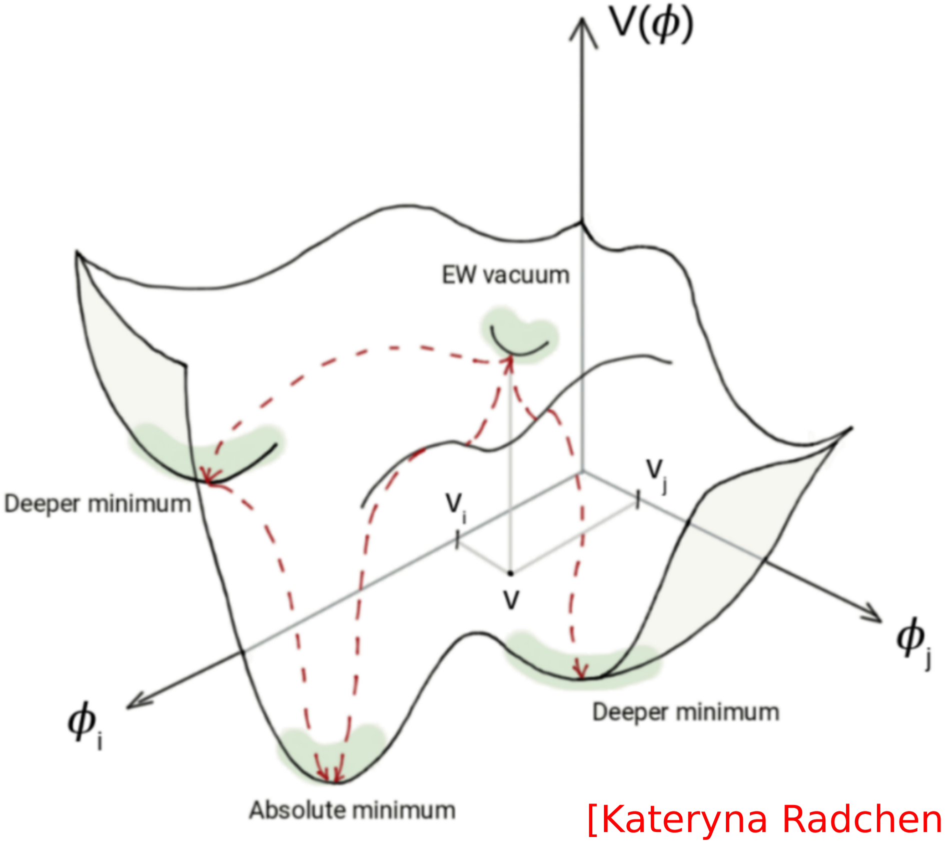
HELMHOLTZ

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Electroweak Vacuum Decay via Domain Walls

Motivation

- In several extended Higgs sectors, the EW minimum **is not** the global minimum.
- The EW minimum is then either metastable or unstable.
- EW vacuum decay was investigated in homogeneous scalar field backgrounds.
- **Can domain walls induce EW vacuum decay in the vicinity of the wall ?**



[Kateryna Radchenko]

EW Vacuum Decay

- If the EW minimum is the global minimum then the **vacuum is stable.**

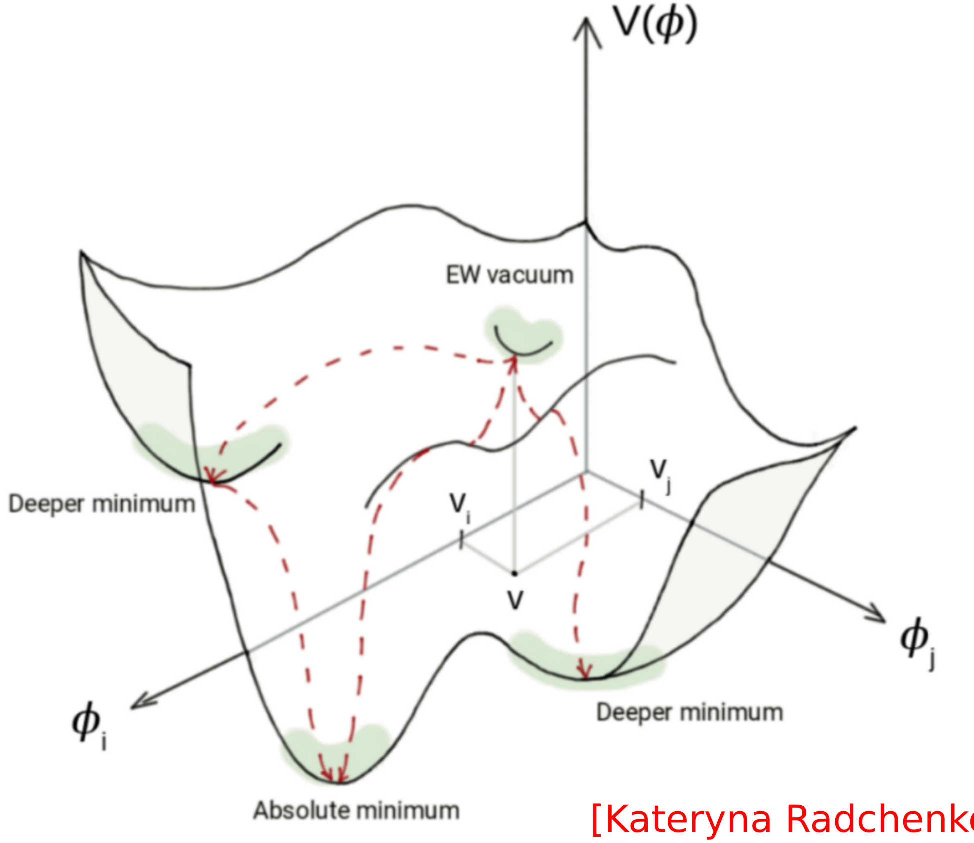
- If a parameter point of the model has a global minimum different than the SM-like minimum, then one needs to calculate the **bounce action S_b** to determine the **decay rate** of the EW vacuum.

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

- For **S_b < 390** the EW vacuum is short lived and decays quickly to the true deeper vacuum. Such parameter points are **unphysical**.

- For **390 < S_b < 440** the outcome is **uncertain**.

- For **S_b > 440** the EW vacuum is **long lived** (longer than the age of the universe) and the parameter point is **allowed**.



[Kateryna Radchenko]

Calculating the bounce action S_b

$$S_E = \int dt_E d^3x \left[\frac{1}{2}\left(\frac{\partial\phi}{\partial x}\right)^2 + V(\phi)\right]$$

The bounce action S_b corresponds to the action of a scalar field solution that is **an extremum of S_E** and satisfies the differential equation:

$$\frac{\partial^2\phi_b}{\partial\rho^2} + \frac{3}{\rho}\frac{\partial\phi_b}{\partial\rho} - \frac{\partial V}{\partial\phi_b} = 0 \quad \text{with: } \rho = \sqrt{t_E^2 + x^2 + y^2 + z^2}$$

And boundary conditions: $\frac{\partial\phi_b}{\partial\rho}(\rho = 0) = 0$ and $\phi_b(\rho = \infty) = \phi_{ew}$

Such a profile for ϕ_b can usually only be determined **numerically:**

Use tools such as **EVADE (Wittbroadt et al)**, **VEVACIOUS (Camarigo-Molina et al), ...**

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.

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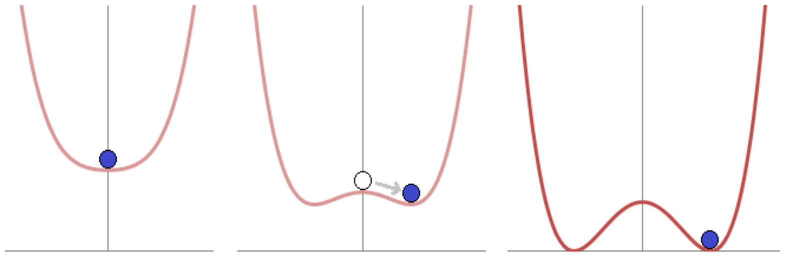
⚠

The spontaneous breaking of these discrete symmetries leads to the formation of topological defects, known as domain walls!

What are domain walls ?

Domain walls are a type of **topological defects** that arise after **spontaneous symmetry breaking** (SSB) of a **discrete symmetry** in the early universe.



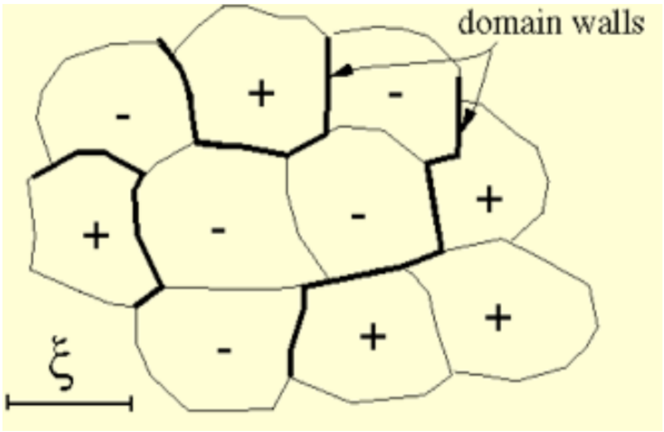
[Wikipedia]

Simplest example (real singlet scalar)

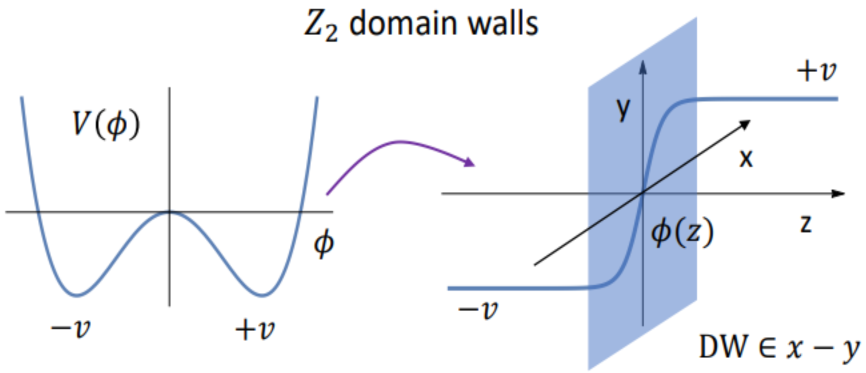
$\mathrm{V}(\phi) = \mu\phi^2 + \lambda\phi^4$ is **invariant** under **Z_2:** $\phi \to -\phi$

Vacuum manifold: two points v and -v.

Universe is divided into different cells with different signs for v.



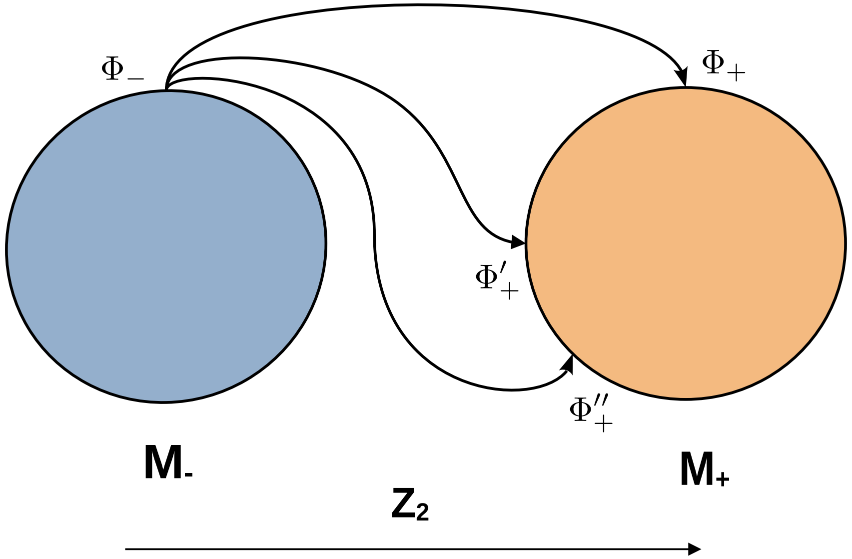
[CTC Outreach]



[Simone Blasi]

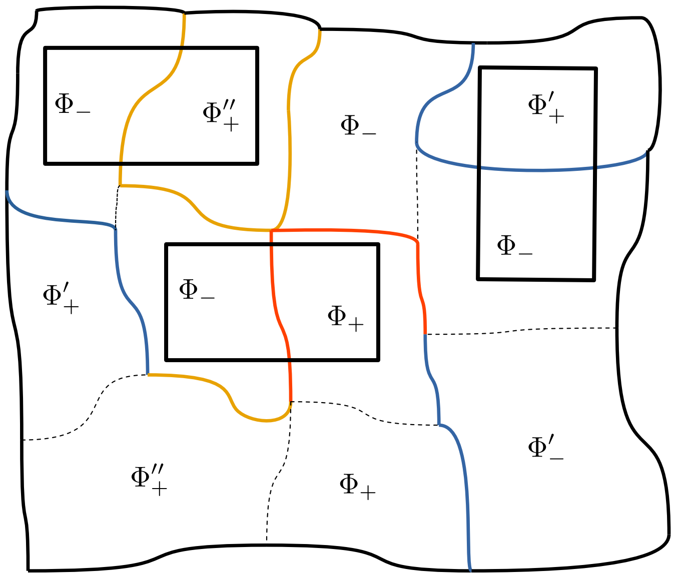
Domain walls in the 2HDM

In the 2HDM the Z_2 symmetry is broken alongside the EW symmetry.



Vacuum manifold of the 2HDM is a two disconnected 3-spheres.

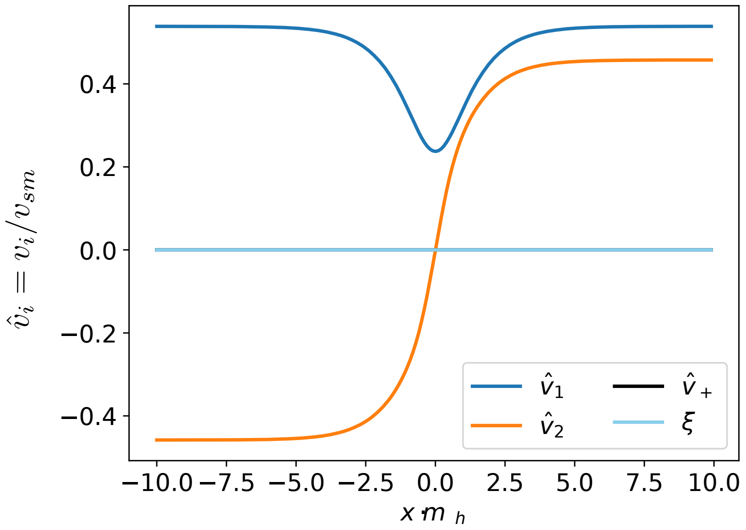
Leading to several different types of domain wall solutions.



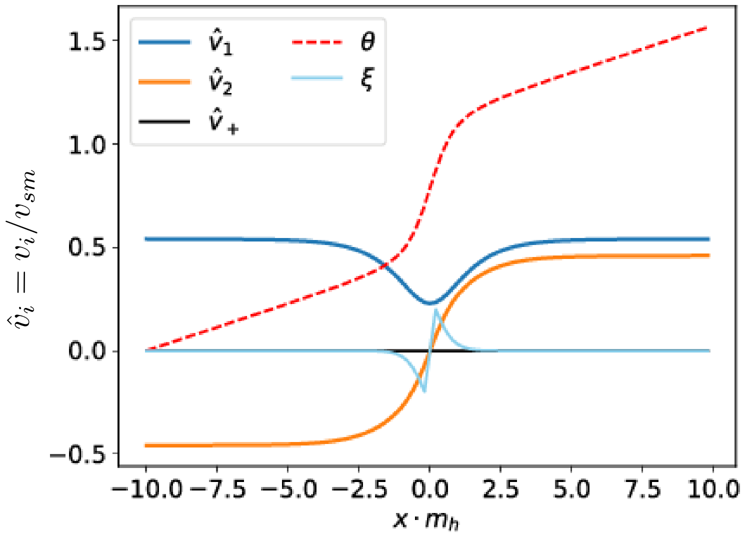
Domain walls in the 2HDM

(MYS, Moortgat-Pick) JHEP 04 (2024) 101

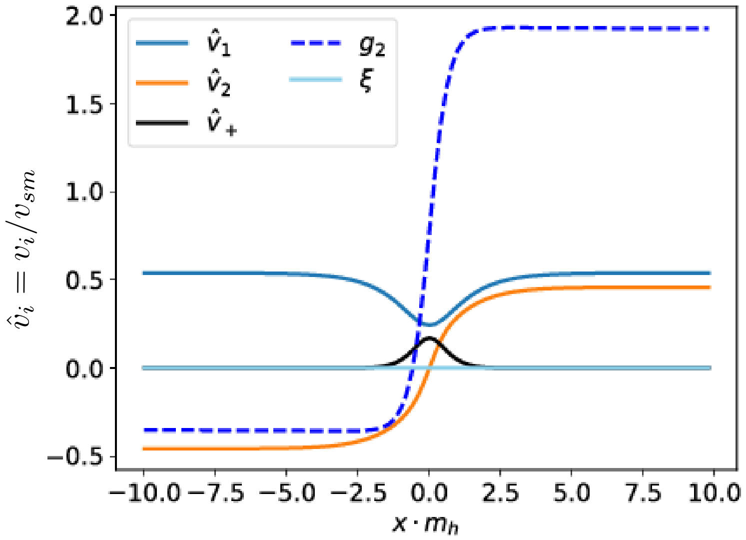
$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\,\mathrm{U}\begin{pmatrix}0\\ v_1\end{pmatrix}, \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\,\mathrm{U}\begin{pmatrix}v_+\\ \pm v_2 e^{i\xi}\end{pmatrix}, \quad U \in SU(2)_L \times U(1)_Y$$



Neutral DW solution
Same Goldstone modes



CP-breaking DW solution
different Goldstone mode θ

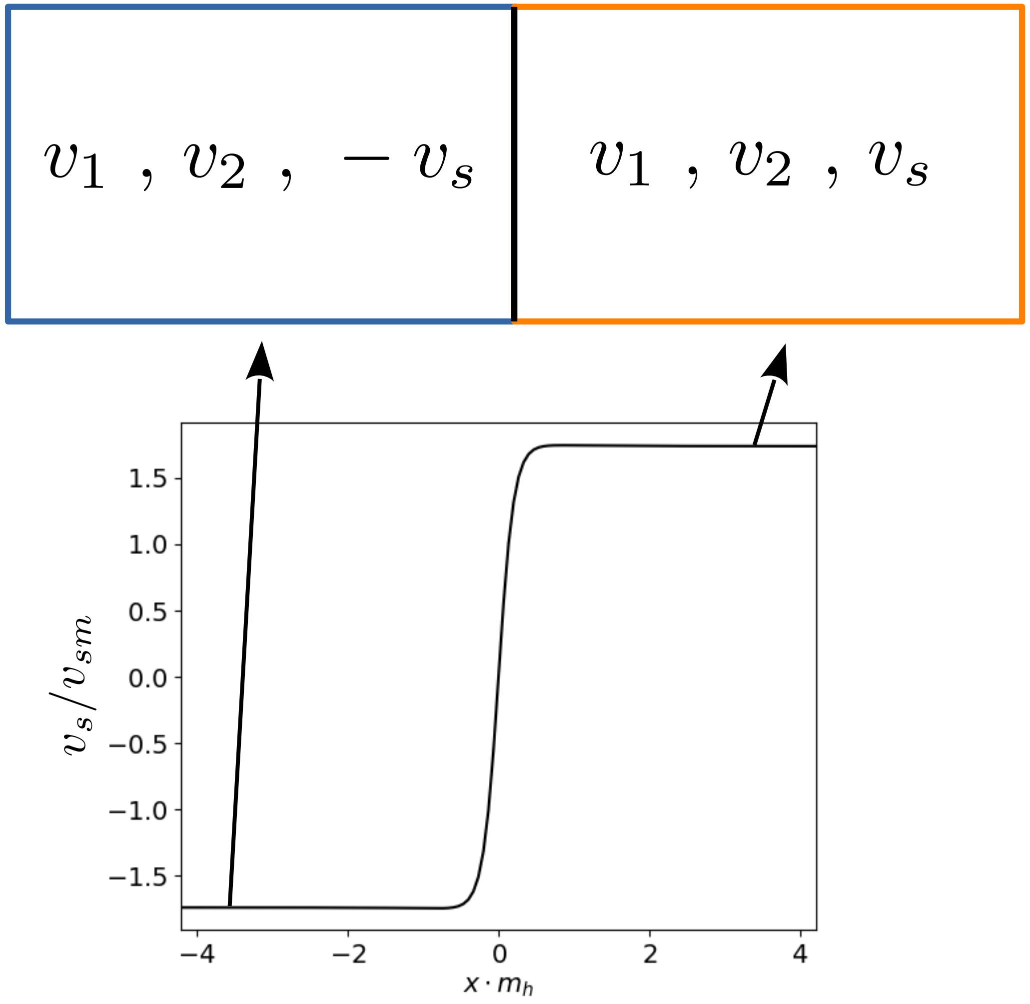


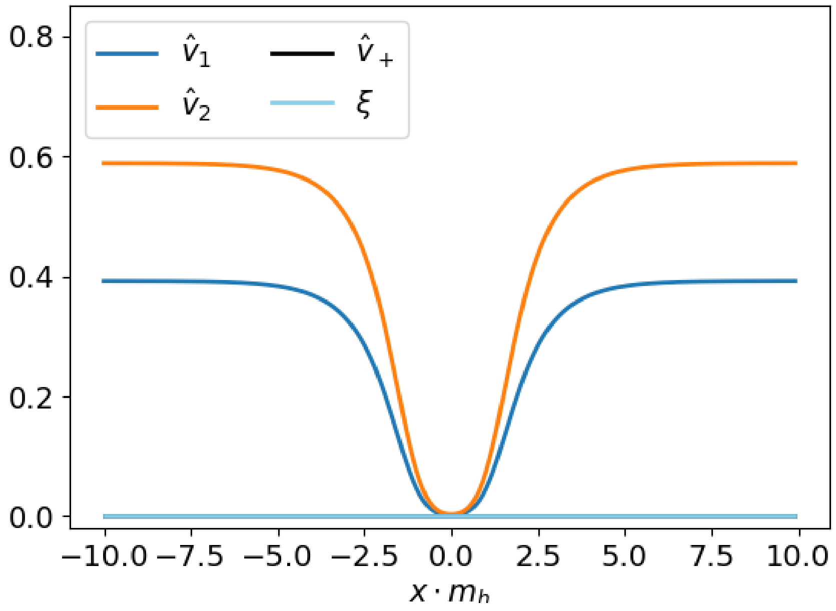
Electric charge breaking DW solution
different Goldstone mode g_2

For more info: Poster session, (Battye, Pilaftsis, Viatic) [2006.13273] JHEP, (Pilaftsis, Law) [2110.12550] PRD and (MYS, Moortgat-Pick) [2309.12398] JHEP.

Domain walls in the N2HDM

(MYS, Moortgat-Pick) JHEP 06 (2025) 072





- **One can use the singlet domain wall to induce electroweak symmetry restoration inside the wall.**
- **Sphalerons are unsupressed inside the wall relative to the sphalerons outside the wall.**
- **Baryon number is efficiently broken inside the wall!**

EW Vacuum Decay in the N2HDM

- In the N2HDM deeper minima than the EW minimum can occur.

$$\langle\Phi_1\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1'\end{pmatrix}$$
$$\langle\Phi_2\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2'\end{pmatrix}$$
$$\langle\Phi_s\rangle_{\mathcal{N}} = \{v_s', \quad 0\}$$

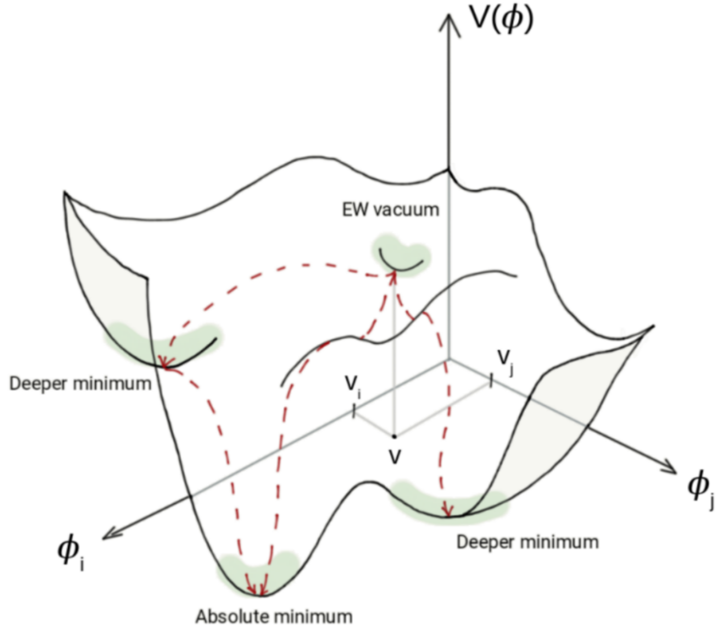
Neutral deeper minima

$$\langle\Phi_1\rangle_{\mathcal{CP}} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1'\end{pmatrix}$$
$$\langle\Phi_2\rangle_{\mathcal{CP}} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2' e^{i\xi}\end{pmatrix}$$
$$\langle\Phi_s\rangle_{\mathcal{CP}} = 0$$

CP-breaking deeper minima

$$\langle\Phi_1\rangle_{\mathcal{CB}} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1'\end{pmatrix}$$
$$\langle\Phi_2\rangle_{\mathcal{CB}} = \frac{1}{\sqrt{2}}\begin{pmatrix}v_+\\ v_2'\end{pmatrix}$$
$$\langle\Phi_s\rangle_{\mathcal{CB}} = 0$$

Charge breaking deeper minima



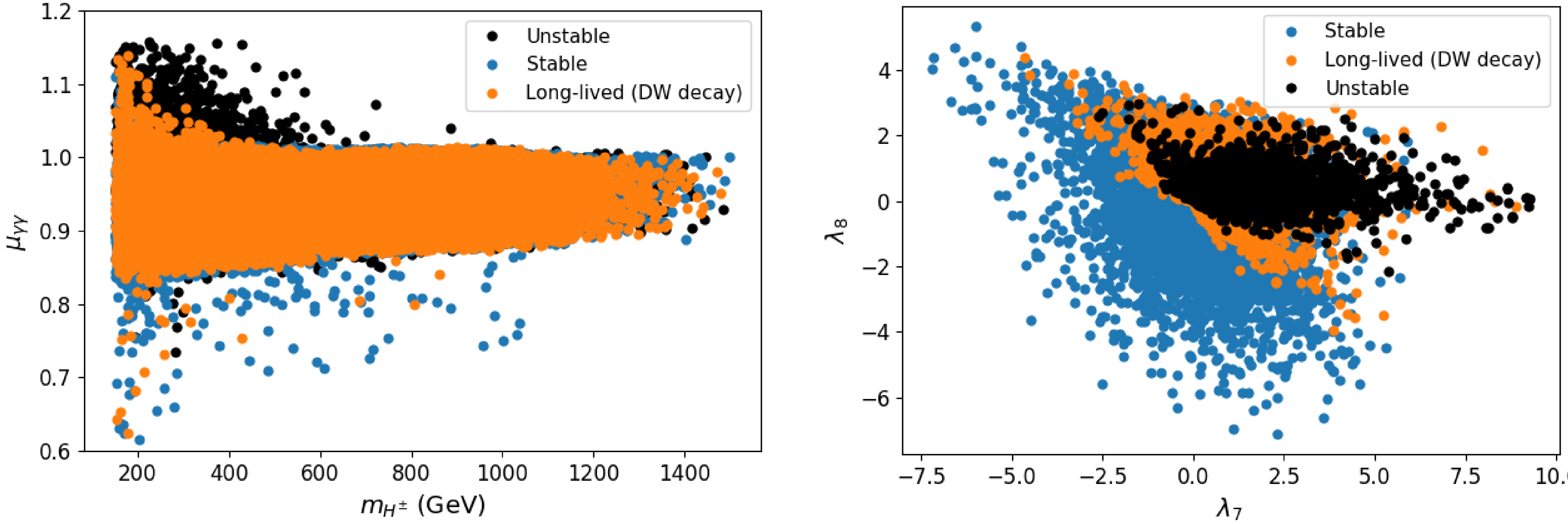
[Kateryna Radchenko]

- Study the **vacuum metastability** of the N2HDM using numerical tools like **EVADE** (homogeneous scalar field background). **(Wittbrodt et al) JHEP09(2019)006**

- **CP and electric charge breaking minima with non-zero v_s always lie higher in the potential than the EW minimum.**

EW vacuum stability so far

Random scan of the N2HDM parameter points

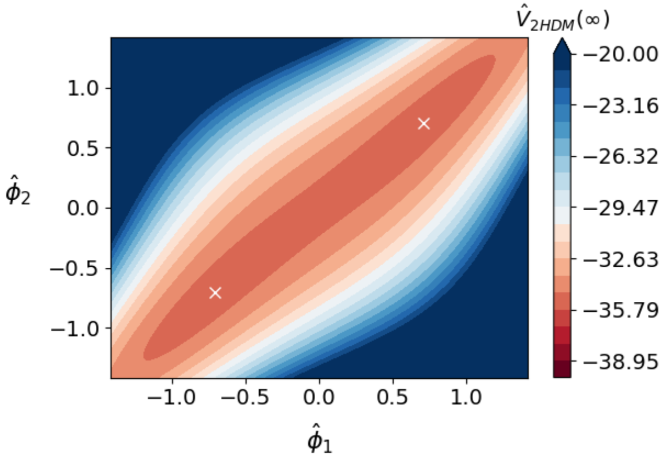


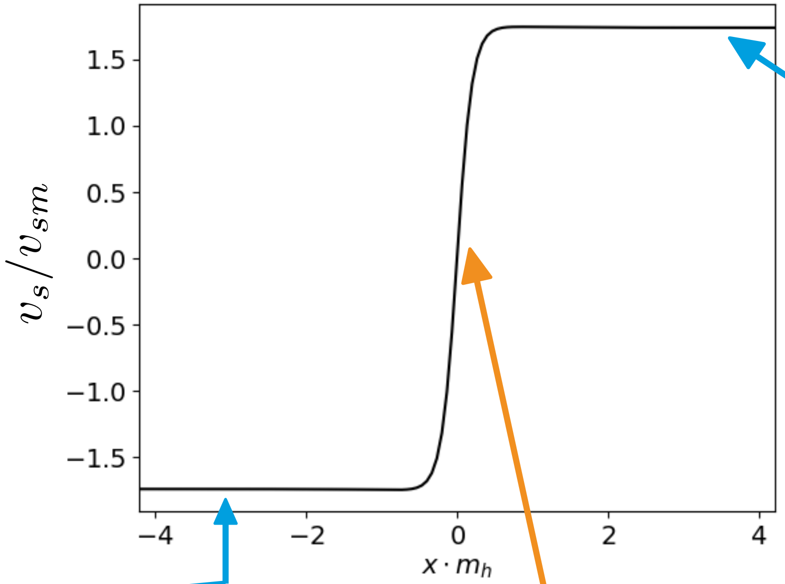
Regions of parameter space can be excluded due to EW vacuum instability.
Metastable points are, in principle, still allowed.

Can domain walls influence EW vacuum decay ?

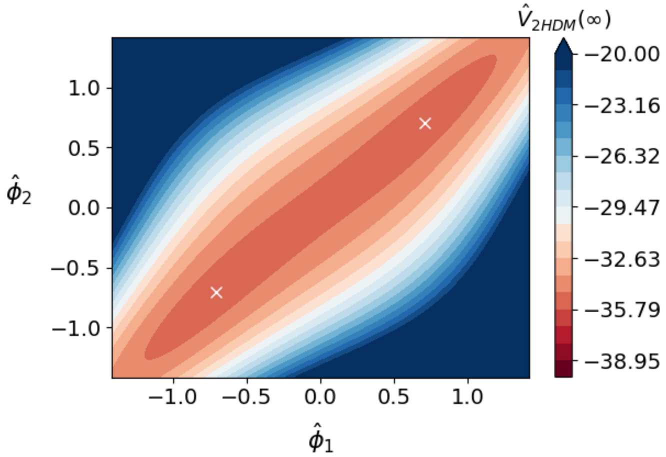
Electroweak Vacuum Decay via Domain Walls

Potential at -∞ ($-v_s$)

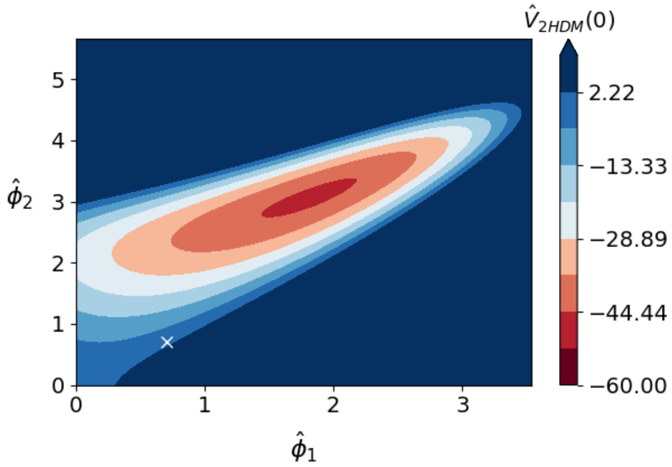




Potential at +∞ (v_s)



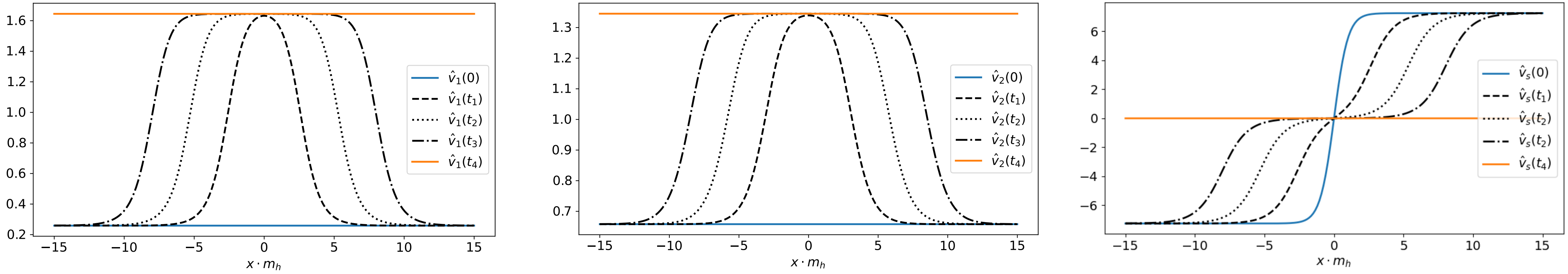
Potential at x=0 (v_s = 0)



No barrier to the global minimum inside the wall !

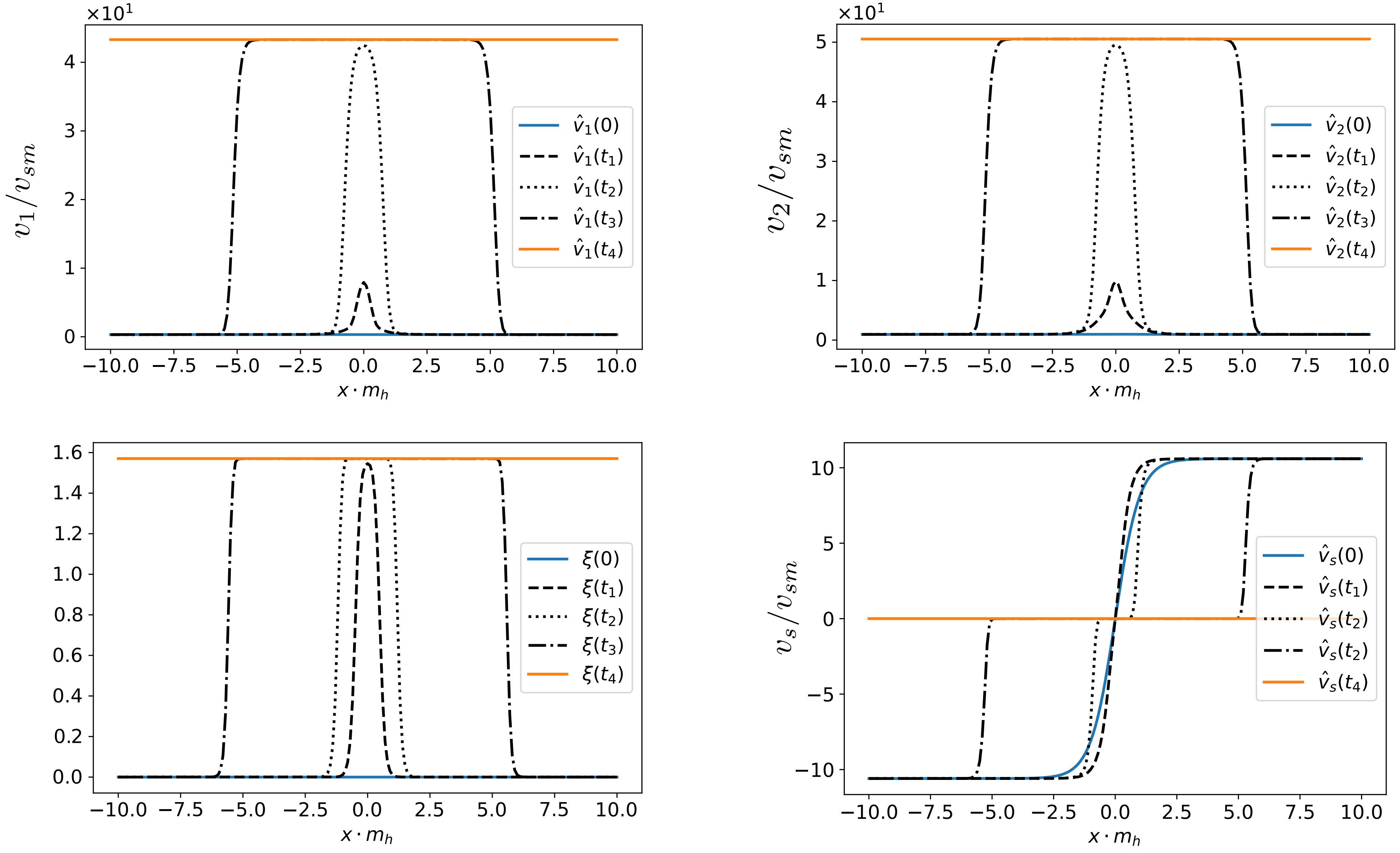
Electroweak Vacuum Decay via Domain Walls

Verify the decay of the EW minimum inside the wall by calculating the real time evolution of the scalar field configuration in the background of a singlet domain wall.

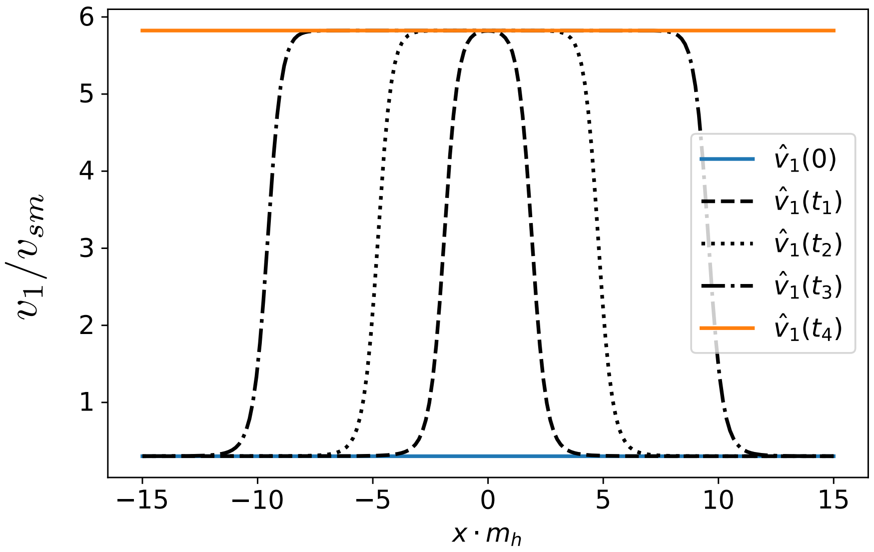


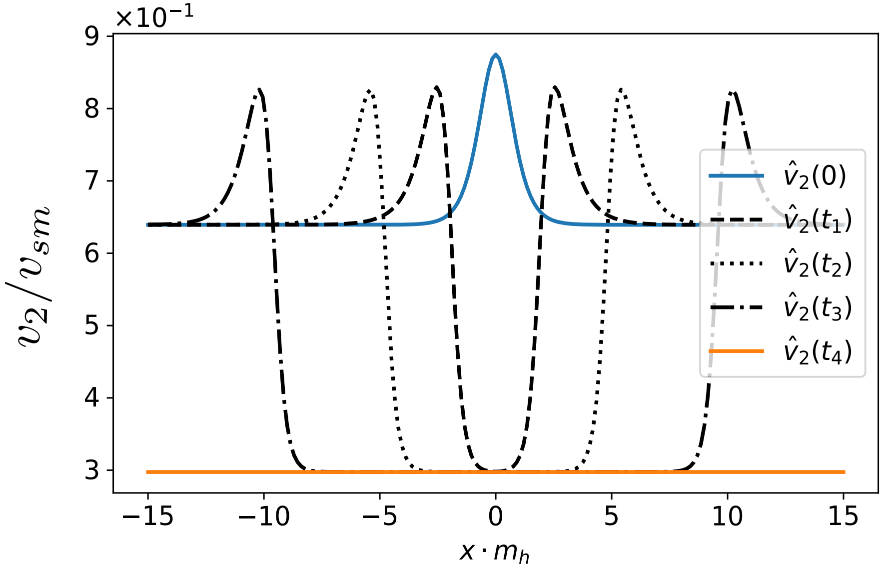
The global minimum is nucleated inside the wall via a classical roll over. The global minimum subsequently expands outside the wall and fills the whole universe, causing vacuum decay. Such metastable parameter points should be ruled out.

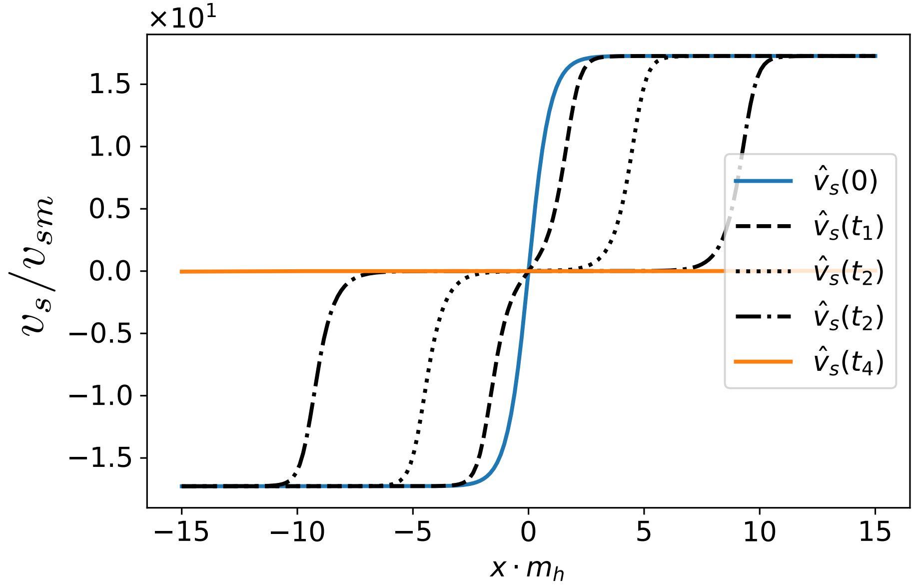
Decay of the EW vacuum into a CP-violating deeper minimum

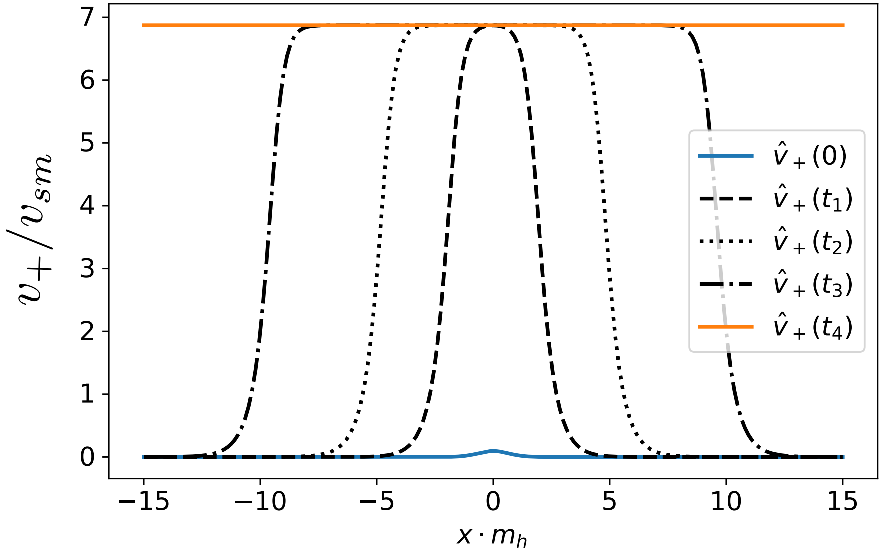


Decay of the EW vacuum into an electric charge violating deeper minimum







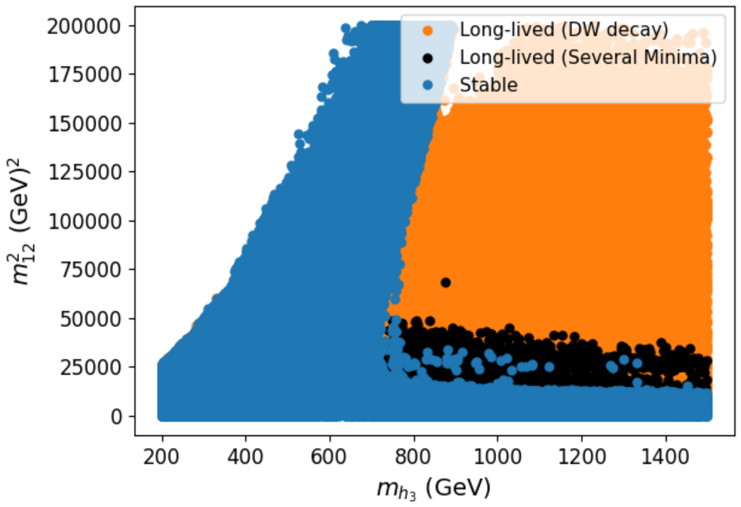


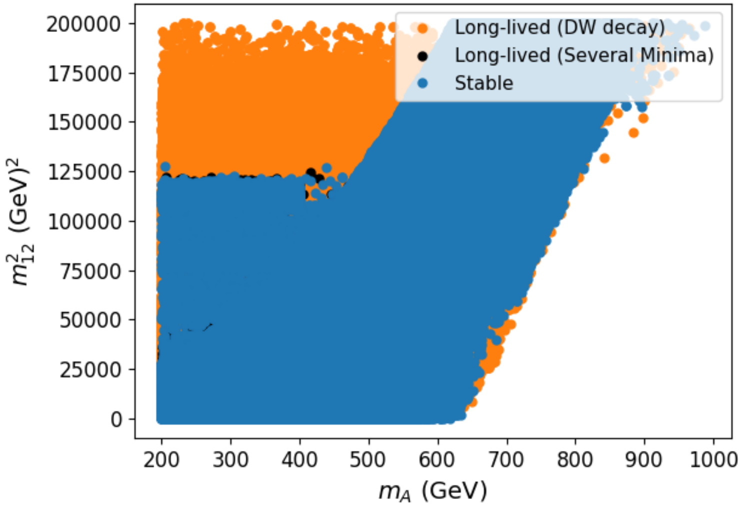
Phenomenological Scenarios of Decay via Domain Walls

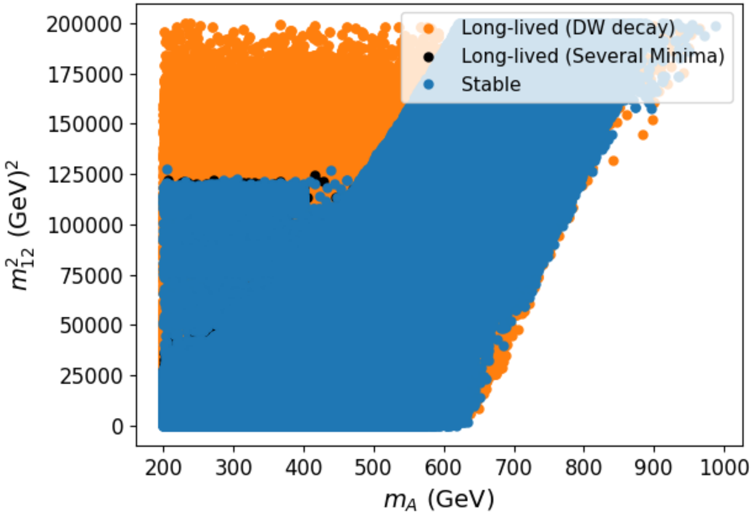
Parameter scan using **ScannerS** [Wittbrodt et al] with perturbative unitarity and boundedness from below conditions imposed.

$$m_{h_1} \approx 95 \text{ GeV}$$
$$m_{h_2} = 125.09 \text{ GeV}$$

All other parameters are free



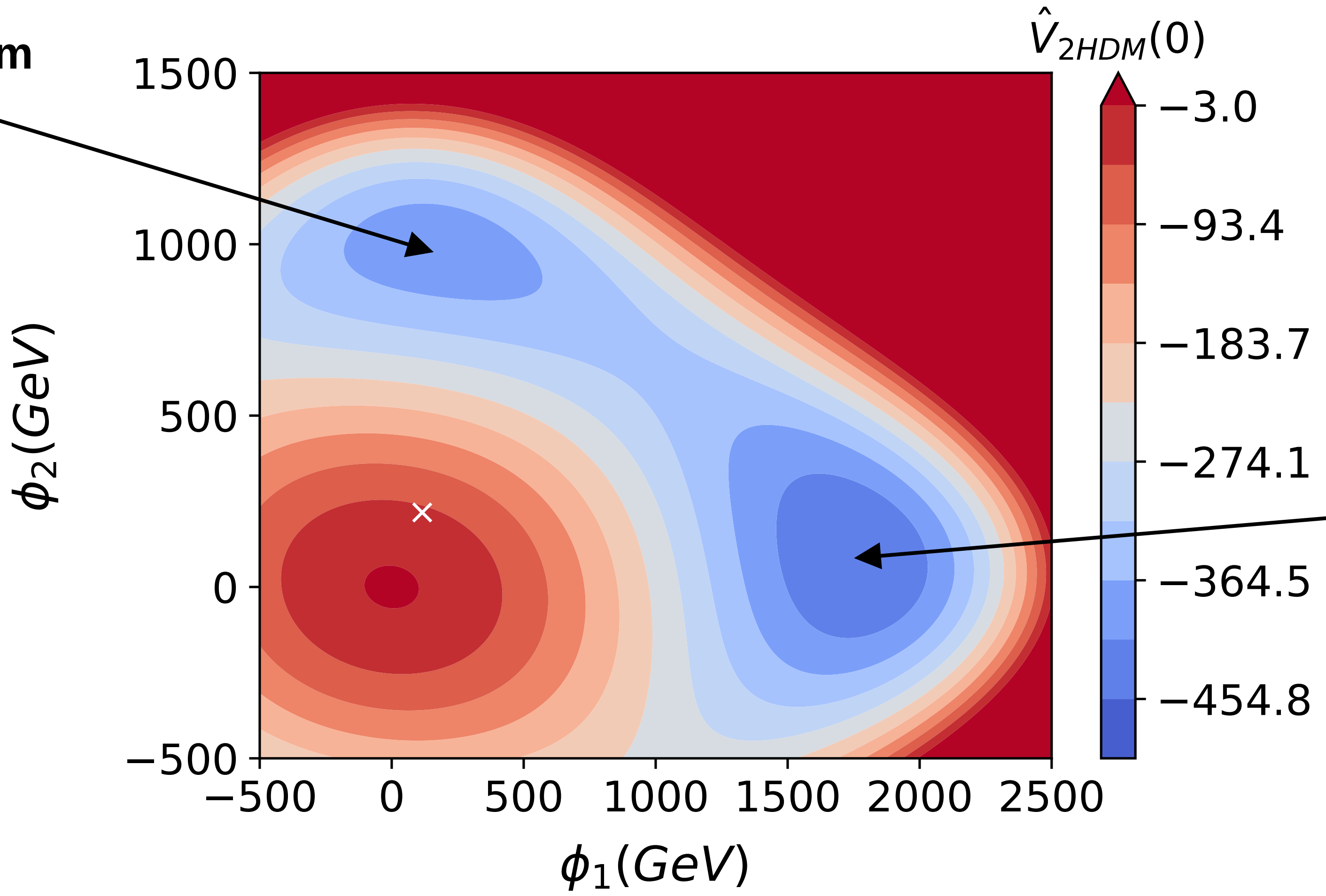




Use EW vacuum decay via domain walls in order to rule out parameter regions that are only metastable.

What if there are multiple minima inside the wall ?

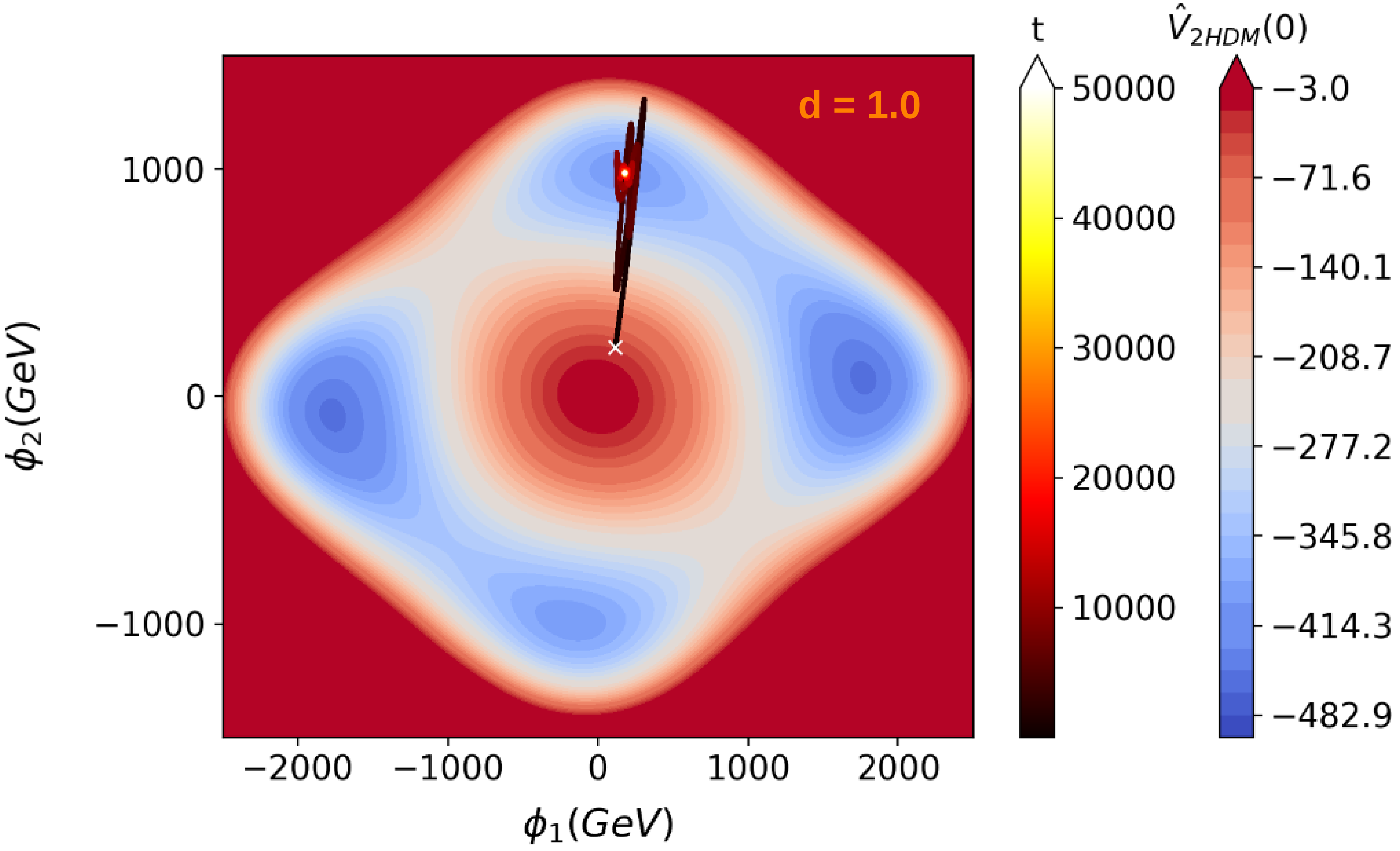
Minimum lies higher than the EW minimum outside the wall

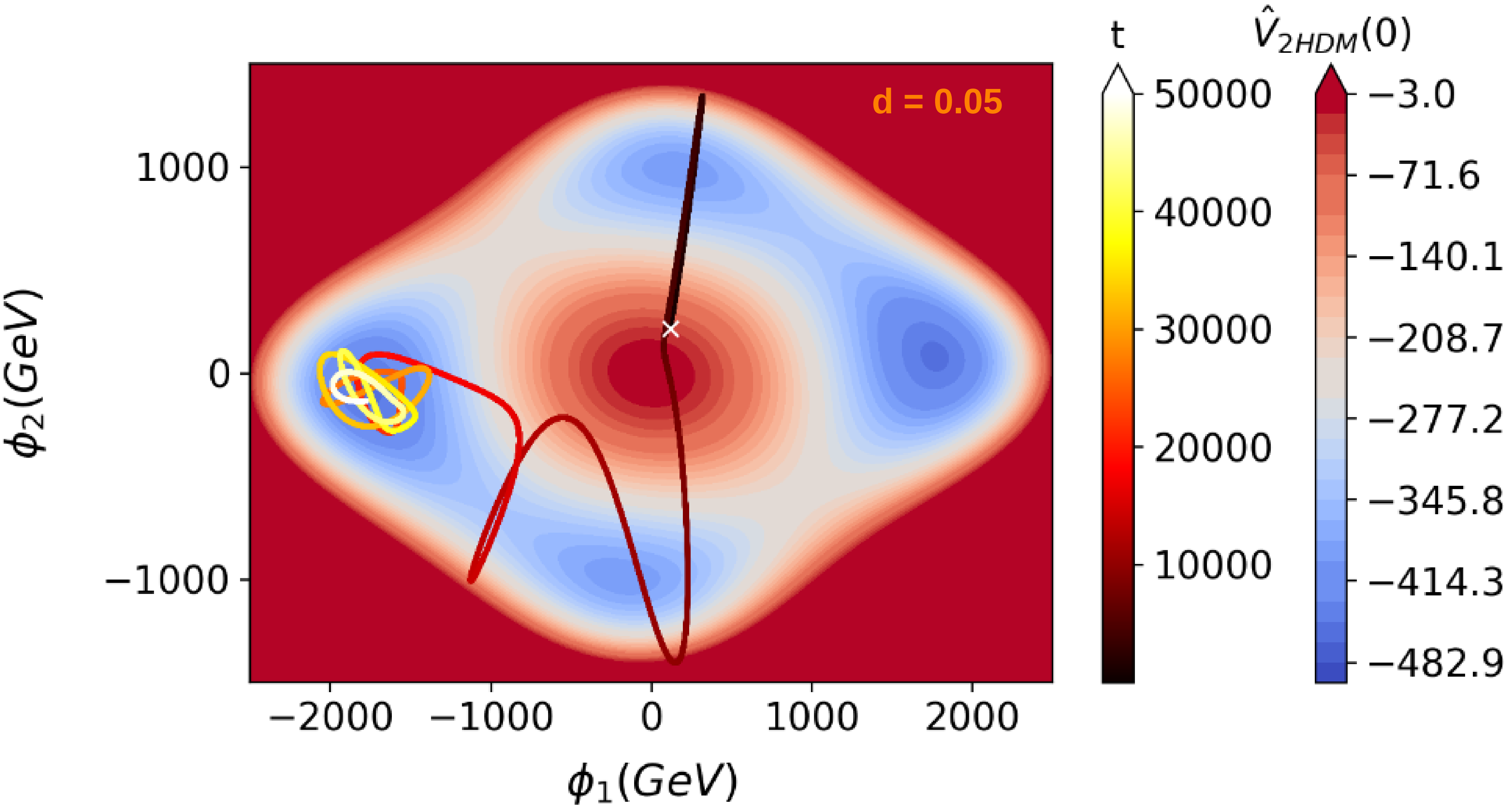


Global minimum

$$\frac{d^2 v_i}{dt^2} - \frac{d^2 v_i}{dx^2} + d\frac{dv_i}{dt} - \frac{dV_{N2HDM}}{dv_i} = 0$$

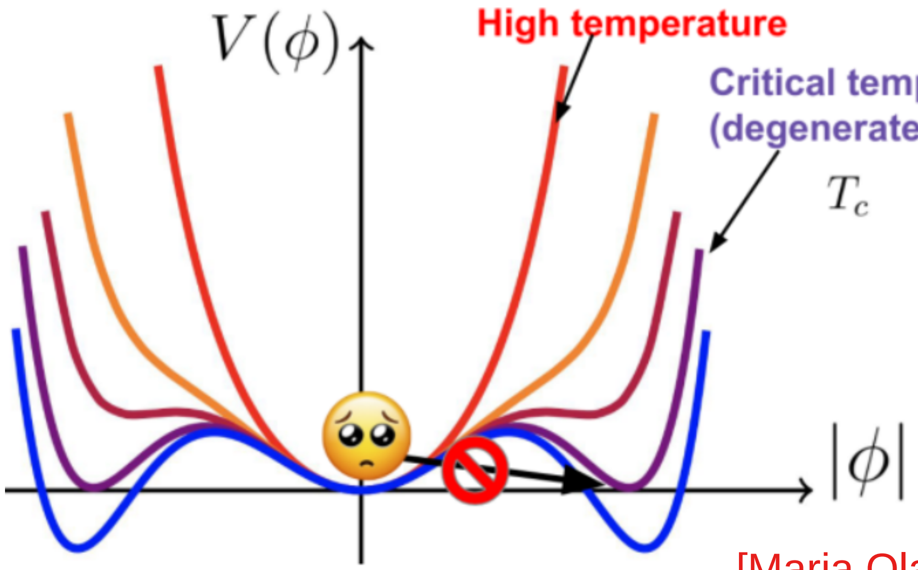
Friction term d dissipates the initial energy of the field configuration.




d = 0.05
1000
0
−1000
−2000
−1000
0
1000
2000
$\phi_1(GeV)$
$\phi_2(GeV)$
t
50000
40000
30000
20000
10000
$\hat{V}_{2HDM}(0)$
−3.0
−71.6
−140.1
−208.7
−277.2
−345.8
−414.3
−482.9

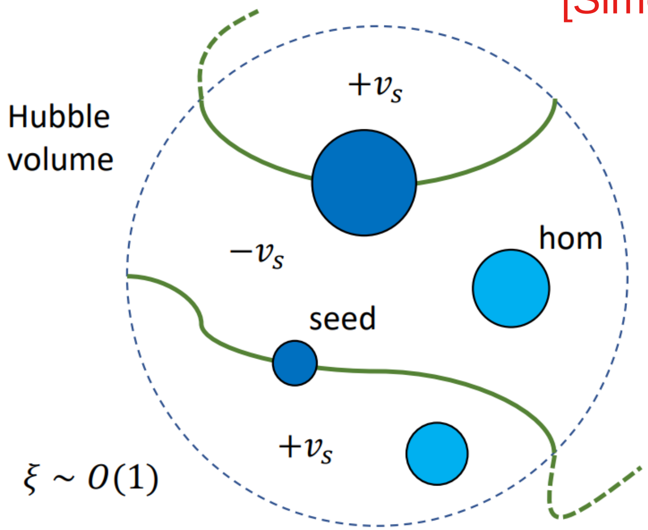
Domain walls and vacuum trapping

Potential barrier is too large for EW phase transition to occur. → **The universe remains trapped in the symmetric phase where v = 0.**



[Maria Olalla]

[Simone Blasi]



Nucleation prob. no longer the same everywhere, enhanced at DW location

The transition to the EW vacuum can be easier inside the wall, therefore rescuing these parameter points from vacuum trapping.

[Nee et al] 2312.06749
[Blasi et al] 2203.16450
[Jiang et al] 2401.08801

Summary and outlook

- **Domain walls** in the N2HDM can induce **EW vacuum decay** by **removing/lowering** the barrier between the EW vacuum and deeper minima.
- This decay can occur very fast as a **classical roll-over**.
- Serves as a new strong **constraint** on the N2HDM where domain walls form and are long-lived.
- Check metastability of the potential at **finite temperatures**.
- Check EW vacuum decay induced by domain walls where deeper minima are nucleated via a **quantum tunneling inside the wall**.

Backup

Symmetry restoration in the early universe

Thermal scalar potential:

$$V_{N2HDM}(\Phi_1, \Phi_2, \Phi_s, T) = V^{tree}_{N2HDM} + V^{CW}_{N2HDM} + V^{T}_{N2HDM} + V^{daisy}_{N2HDM}$$

In summary:

$$V_{N2HDM}(T, \Phi_1, \Phi_2, \Phi_s) = m_{11}^2(T)|\Phi_1|^2 + m_{22}^2(T)|\Phi_2|^2 + m_S^2(T)\Phi_s^2 + m_{12}^2\Phi_1\Phi_2 + ...,$$

At higher temperature, $m^2_{11}(T)$, $m^2_{22}(T)$, $m^2_s(T)$ can turn positive and the minimum of the potential is at the origin. In this case the VEVs of the fields vanish and the symmetries are restored.

To determine whether the symmetries are restored or not, go to the high temperature limit and calculate the Hessian matrix at the field space origin $(\Phi_1, \Phi_2, \Phi_s) = (0, 0, 0)$.

$$H^0_{i,j} = \partial^2 V/\partial\phi_i\partial\phi_j|_{(0,0,0)}$$ and define $$c_{ii} \equiv \lim_{T\to\infty} H^0_{ii}/T^2$$ **[Olea et al]**

At leading order:

[Olea et al]

$$c_1 = \frac{1}{16}(g'^2 + 3g^2) + \frac{\lambda_1}{4} + \frac{\lambda_3}{6} + \frac{\lambda_4}{12} + \frac{\lambda_7}{24},$$

$$c_2 = \frac{1}{16}(g'^2 + 3g^2) + \frac{\lambda_2}{4} + \frac{\lambda_3}{6} + \frac{\lambda_4}{12} + \frac{\lambda_8}{24} + \frac{1}{4}y_t^2,$$

$$c_3 = \frac{1}{6}(\lambda_7 + \lambda_8) + \frac{1}{8}\lambda_6,$$

For points with possible metastable EW vacua, c_3 is always positive. → **The Z'_2 symmetry is always restored at this order.**

Adding Daisy resummation:

$$c_{11} \simeq -0.025 + c_1 - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_1\sqrt{c_1} + \lambda_3\sqrt{c_2} + \frac{1}{2}\lambda_4\sqrt{c_2} + \frac{1}{4}\lambda_7\sqrt{c_3}\right),$$

$$c_{22} \simeq -0.025 + c_2 - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_2\sqrt{c_2} + \lambda_3\sqrt{c_1} + \frac{1}{2}\lambda_4\sqrt{c_1} + \frac{1}{4}\lambda_8\sqrt{c_3}\right),$$

$$c_{33} = c_3 - \frac{1}{2\pi}\left(\lambda_7\sqrt{c_1} + \lambda_8\sqrt{c_2} + \frac{3}{4}\lambda_6\sqrt{c_3}\right),$$ **[Olea et al]**

Effective mass terms can stay negative at high temperature !!!

No symmetry restoration

No Domain wall formation

These expressions are only valid in the Arnold-Espinosa Daisy resummation method.

In other resummation schemes, symmetry restoration was always the outcome for