Domain Walls in extended Higgs Models

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2HDM Working Group Report

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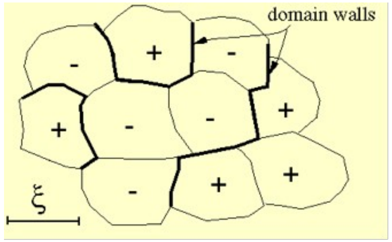
Outline

1) Introduction to topological defects
2) Results Domain Walls in 2HDM
3) Possible Future Directions (Baryogenesis, Gravitational Waves, …)

Introduction to topological defects

- Topological defects (domain walls, cosmic strings, monopoles, ...) can arise after a spontaneous symmetry breaking of a theory with particular vaccum manifolds.
- After spontenous symmetry breaking, different regions of the universe can get different vacua which are degenerate with each other



A theory with the symmetry group G **broken** to a subgroup H

$$G \longrightarrow H$$

For h element of unbroken group H and a vacuum point Φ_0: $h\Phi_0 = \Phi_0$

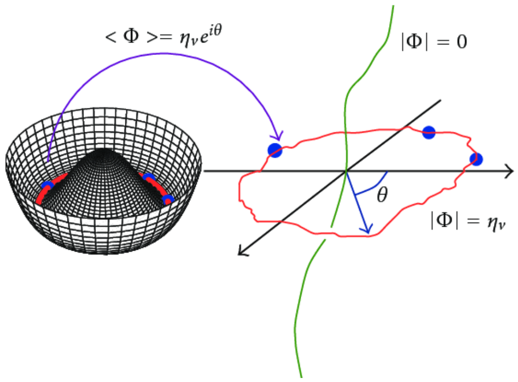
H keeps vacuum points invariant

For g element of symmetry group G : $g\Phi_0 = \Phi'$

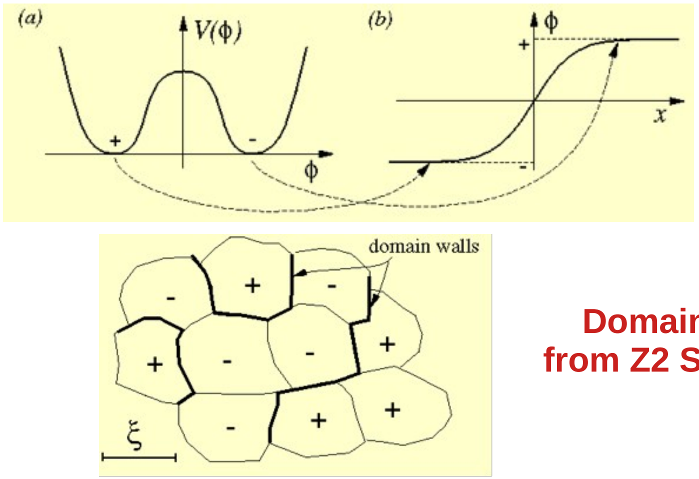
Acting on Φ_0 with G generates other degenerate vacuum points

The space of all cosets G/H give the vacuum manifold of all degenerate vacuas $M = G/H$

Defect Type	Homotopy Group	Dimension	Relic Abundance
Domain Walls	$\pi_0(M) \neq 1$ M is disconnected	D=2 **Sheets in Space**	t^{-1}
Cosmic Strings	$\pi_1(M) \neq 1$ M contains non shrinkable circles **(Holes)**	D=1 **Lines in Space**	t^{-2}
Monopoles	$\pi_2(M) \neq 1$ M contains non shrinkable 2-spheres **(Spherical Holes)**	D=0 **Points in Space**	t^{-1}



Cosmic Strings



Domain Walls
from Z2 Symmetry

What about the Standard Model ?

$$SU_L(2) \otimes U_Y(1) \longrightarrow U_{em}(1)$$

$$M = SU_L(2) \otimes U_Y(1)/U_{em}(1) \cong SU(2)$$

The vaccum manifold has the same topology as SU(2)

SU(2) has the ***topology*** of a ***3-Sphere***

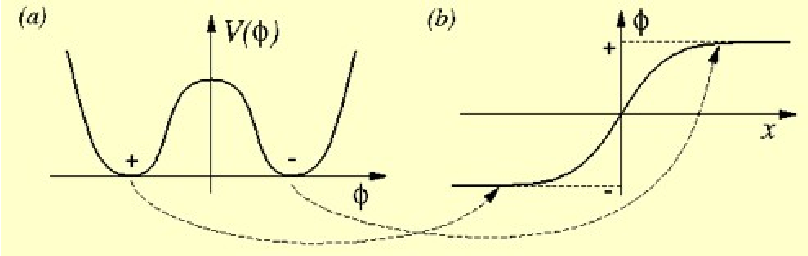
- M is not disconnected : **NO Domain Walls**
- M is simply connected (no holes) : **NO Cosmic Strings or Monopoles**
- ***Standard Model can only contain textures which are cosmologically harmless***

Possibility to get topological defects in BSM models

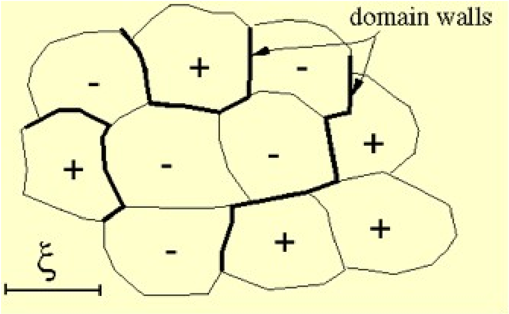
Domain Walls

Domain Walls occur when a discrete symmetry of the model is spontaneously broken, such as Z2 symmetry

$$\Phi \rightarrow -\Phi$$



The vacuum manifold contains points which are ***disconnected*** and ***degenerate*** in energy.



Regions between the domains are regions with ***restored symmetry***.

Symmetries and Topological Defects of extended Higgs models

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.]$$

Symmetry	μ_1^2	μ_2^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5
Z_2	-	-	0	-	-	-	-	Real
$U(1)_{PQ}$	-	-	0	-	-	-	-	0
$SO(3)_{HF}$	-	μ_1^2	0	-	λ_1	-	$2\lambda_1 - \lambda_3$	0
CP1	-	-	Real	-	-	-	-	Real
CP2	-	μ_1^2	0	-	λ_1	-	-	-
CP3	-	μ_1^2	0	-	λ_1	-	-	$2\lambda_1 - \lambda_3 - \lambda_4$

From D. Viatic PhD thesis 2020

Symmetry	Defect
Z2	Domain Walls
CP1	Domain Walls
CP2	Domain Walls
$U(1)_{pq}$	Cosmic Strings
SO(3)	Monopoles

D. Viatic PhD thesis 2020

For N2HDM, we add an extra real scalar and the theory gets an extra Z_2' symmetry.

$$+\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

In the following, I focus on Z_2 and Z_2' symmetries

Z_2: $\Phi_1 \longrightarrow \Phi_1 \quad \Phi_2 \longrightarrow -\Phi_2$

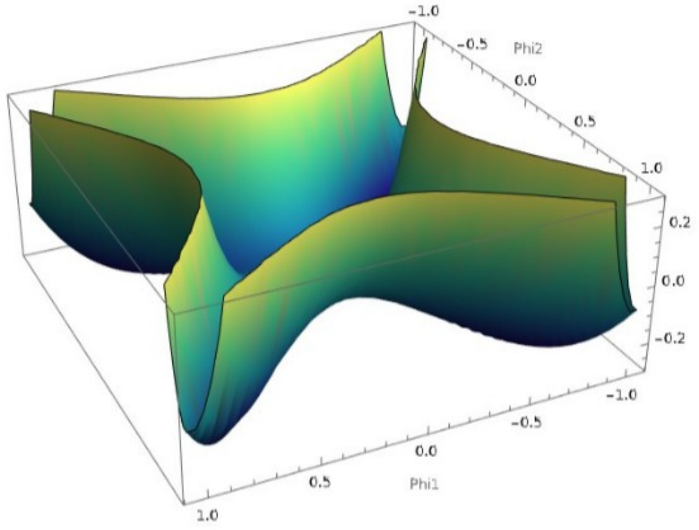
Z_2': $\Phi_S \longrightarrow -\Phi_S$

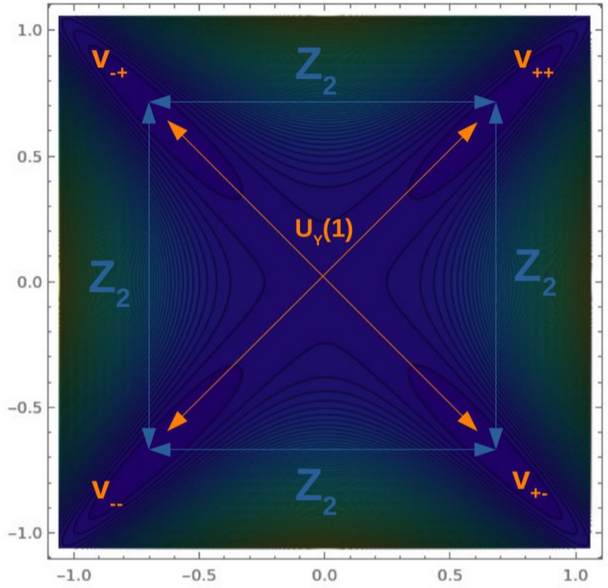
Full symmetry of the model:

$$SU_L(2) \otimes U_Y(1) \otimes Z_2(\otimes Z_2') \longrightarrow U_{em}(1)$$

$M = SU(2) \otimes Z_2$ **Two disconnected 3-Spheres**

Example of parameter point in 2HDM for exact Z_2 symmetry (m_{12}=0):





The **4 minima are degenerate to each other** (they give the same value for the potential). The ones related by the Z_2 symmetry lead to formation of domain walls, while those related by the $U_Y(1)$ do not lead to domain walls.

Possible Parametrizations of the Higgs Vacua:

Linear Parametrization

$$\Phi_1 = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}$$

Can be rotated using a matrix $U(x) \in SU_L(2) \otimes U_Y(1)$

Vacuum Parametrization

$$\Phi_1(x) = \begin{pmatrix} 0 \\ v_1(x) \end{pmatrix}, \Phi_2(x) = \begin{pmatrix} v_+(x) \\ v_2(x)e^{i\xi(x)} \end{pmatrix}$$

$$U = e^{i\theta} \begin{pmatrix} \cos(\gamma_1)\exp(i\gamma_2) & \sin(\gamma_1)\exp(i\gamma_3) \\ -\sin(\gamma_1)\exp(-i\gamma_3) & \cos(\gamma_1)\exp(-i\gamma_2) \end{pmatrix}$$

Taken from D.Viatic PhD Thesis

Possible Vacua in the 2HDM/N2HDM:

- Neutral Vacua $v_+ = 0,\ \xi = 0$
- CP breaking Vacua $\xi \neq 0,\ v_+ = 0$
- Charge breaking Vacua $v_+ \neq 0$

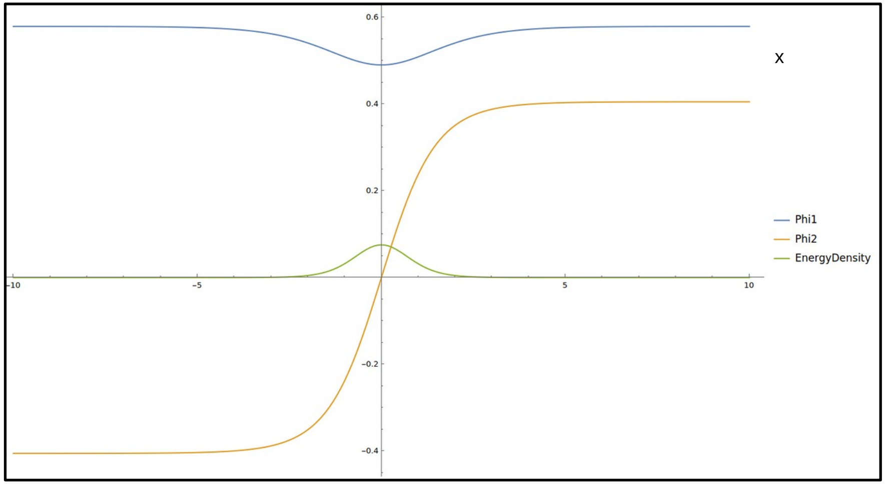
Here we only consider **neutral vacua at the boundaries** and take the general Vacuum Parametrization at each point in x (***possibility of getting CP and/or Charge violation inside the domain wall)***

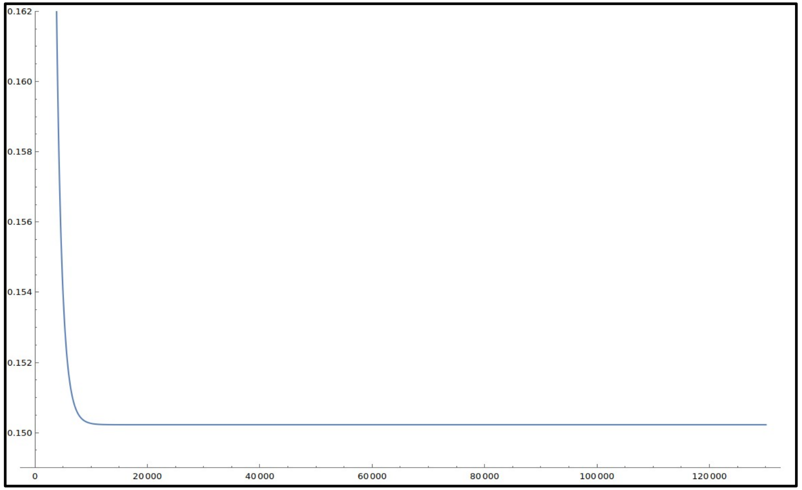
- **Start with no relative phase between the doublets at + and – infinity boundaries:**

$$\Phi_1(-\infty) = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \Phi_2(-\infty) = \begin{pmatrix} 0 \\ -v_2 \end{pmatrix} \qquad \Phi_1(+\infty) = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \Phi_2(+\infty) = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$\begin{aligned}
\frac{\partial v_1}{\partial t} &= \frac{\partial^2 v_1}{\partial x^2} + \mu_1^2 v_1 - \lambda_1 v_1^3 - \frac{1}{2}\lambda_3 v_1 v_+^2 - \frac{1}{2}\left(\lambda_{34} - |\lambda_5|\, c_{2\xi}\right) v_1 v_2^2, \\
\frac{\partial v_2}{\partial t} &= \frac{\partial^2 v_2}{\partial x^2} - v_2 \left(\frac{\partial \xi}{\partial x}\right)^2 + \mu_2^2 v_2 - \lambda_2 v_2 \left(v_2^2 + v_+^2\right) - \frac{1}{2}\left(\lambda_{34} - |\lambda_5|\, c_{2\xi}\right) v_1^2 v_2, \\
\frac{\partial \xi}{\partial t} &= v_2^2 \frac{\partial^2 \xi}{\partial x^2} + 2 v_2 \left(\frac{\partial v_2}{\partial x}\right)\left(\frac{\partial \xi}{\partial x}\right) - \frac{1}{2}|\lambda_5|\, v_1^2 v_2^2 s_{2\xi}, \\
\frac{\partial v_+}{\partial t} &= \frac{\partial^2 v_+}{\partial x^2} + \mu_2^2 v_+ - \lambda_2 v_+ \left(v_2^2 + v_+^2\right) - \frac{1}{2}\lambda_3 v_1^2 v_+.
\end{aligned}$$

Solve numerically using Gradient Flow method





CP Violating Domain Walls

- Rotate **one of the vacua at the boudaries** with a Gauge Transformation $U(x) \in SU_L(2) \otimes U_Y(1)$

$$U = e^{i\theta} \begin{pmatrix} \cos(\gamma_1)\exp(i\gamma_2) & \sin(\gamma_1)\exp(i\gamma_3) \\ -\sin(\gamma_1)\exp(-i\gamma_3) & \cos(\gamma_1)\exp(-i\gamma_2) \end{pmatrix}$$

This is motivated by assumption that all degenerate vacua have same probability to occur at the early universe

$$\Phi_1(-\infty) = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \Phi_2(-\infty) = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad \Phi_1(+\infty) = U\begin{pmatrix} 0 \\ -v_1 \end{pmatrix}, \Phi_2(+\infty) = U\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

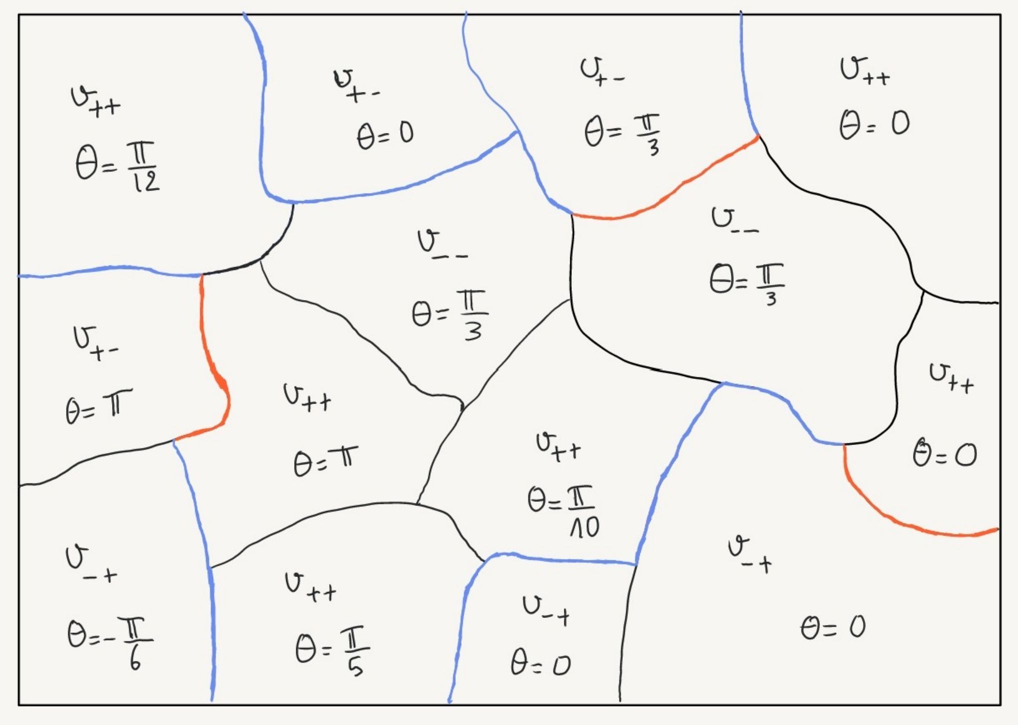
Still a Neutral Vacuum

Depending on the vacuum parameter we get:

- For θ ≠ 0, 2π : **CP Violation inside the Domain Wall**

$$\Phi_1(+\infty) = e^{i\theta}\begin{pmatrix} 0 \\ -v_1 \end{pmatrix}, \Phi_2(+\infty) = e^{i\theta}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \longleftarrow \longrightarrow \Phi_1(+\infty) = \begin{pmatrix} 0 \\ -v_1 \end{pmatrix}, \Phi_2(+\infty) = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

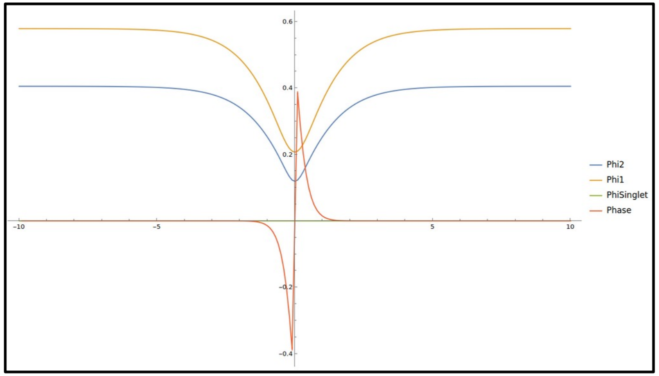
These vacua are **degenerate** but **not identical** **(can't remove the phase using a $U_{em}(1)$ transformation)**

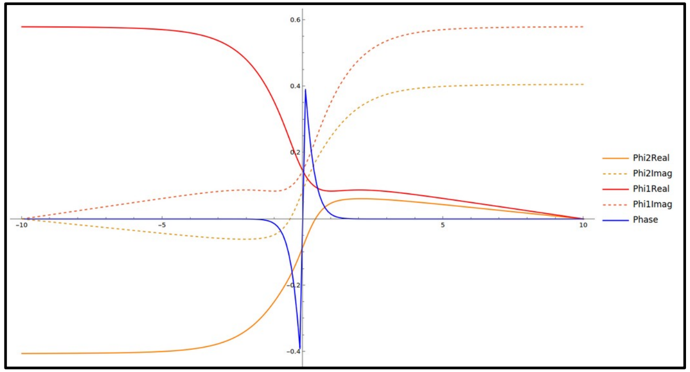


Blue walls contain CP violation, **Orange walls** are not CP violating.

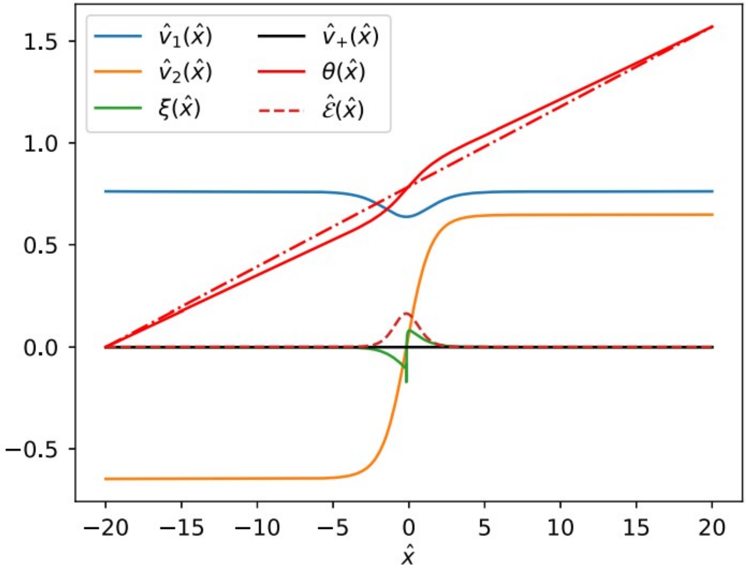
$$\Phi_1(x) = \begin{pmatrix} 0 \\ v_1(x) \end{pmatrix}, \Phi_2(x) = \begin{pmatrix} v_+(x) \\ v_2(x)e^{i\xi(x)} \end{pmatrix}$$

$$\Phi_1 = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}$$

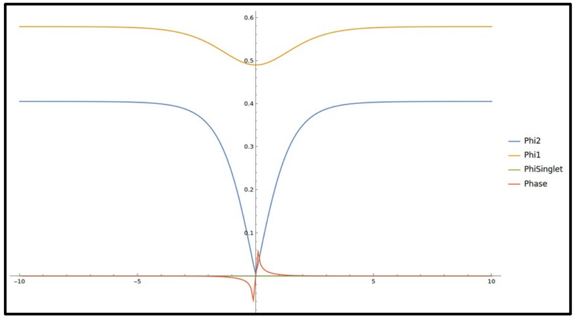


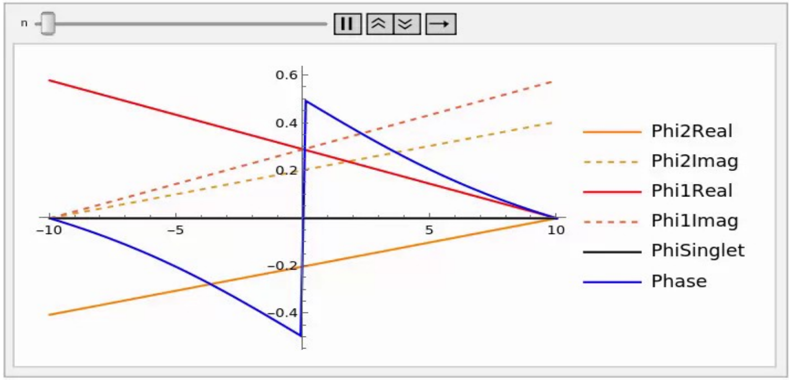


Tension with results from 2110.12550. In the **linear parametrization** only possible to get the **absolute value of the fields $v_1(x)$ and $v_2(x)$**. Problem with **$v_2(0) \neq 0$** in contrast with **$v_2(0) = 0$** the case with the **non-linear vacuum parameters representation**.



From 2110.12550

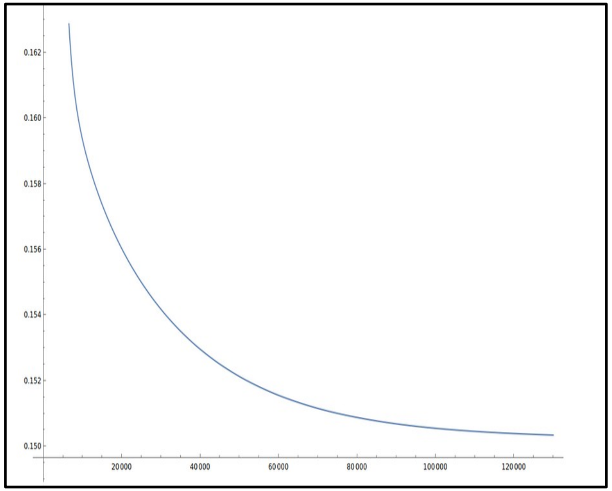




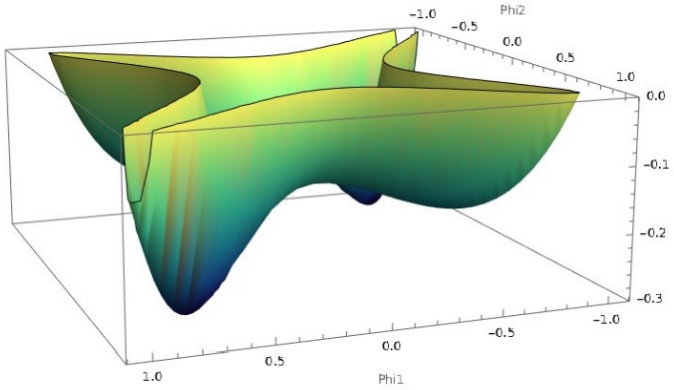
- This is not a problem when we consider **von Neumann boundary conditions**. The CP violation gets **smaller with time and the value of $v_2(0)$ gets smaller and eventually becomes 0**.

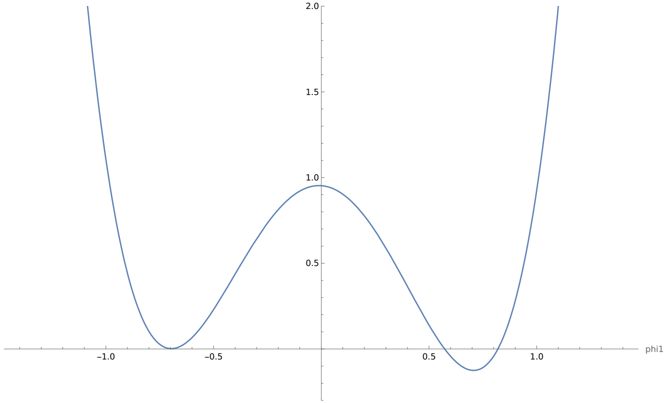
- The phase between the 2 boundaries **disappears** and the **whole universe gets the same phase θ**.

- The energy of the domain wall relaxes to the same energy of domain walls between boundaries having the same phase θ **(this is the minimal energy solution)**.



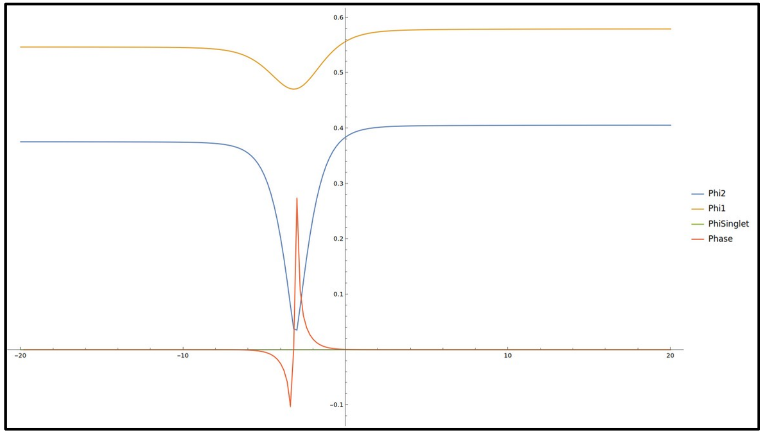
Example of parameter point in 2HDM for slightly soft broken Z_2 symmetry (m_{12} small):



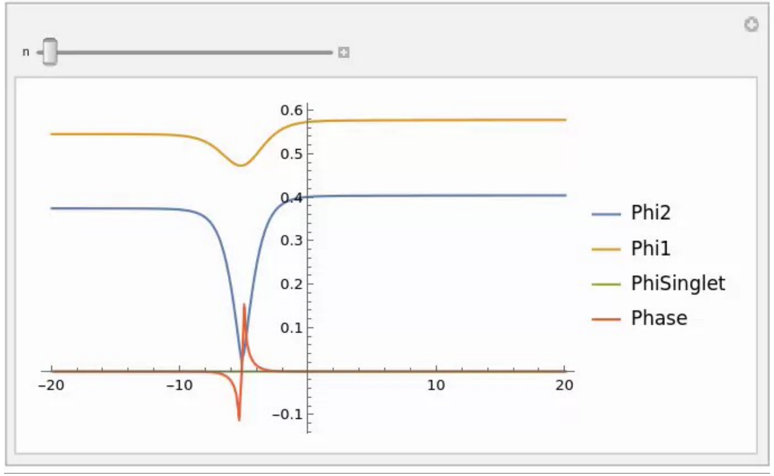


The bias term m_{12} breaks the Z_2 symmetry and **lifts 2 of the minima**.

- The **potential difference** acts as a **pressure force** that annihilates the domain wall as the domain with lower energy ***(true vacuum)*** expands in the domain with higher energy ***(false vacuum)***.



- **CP violation** inside the domain wall is **not antisymmetric** and follows the propagation of the domain wall.

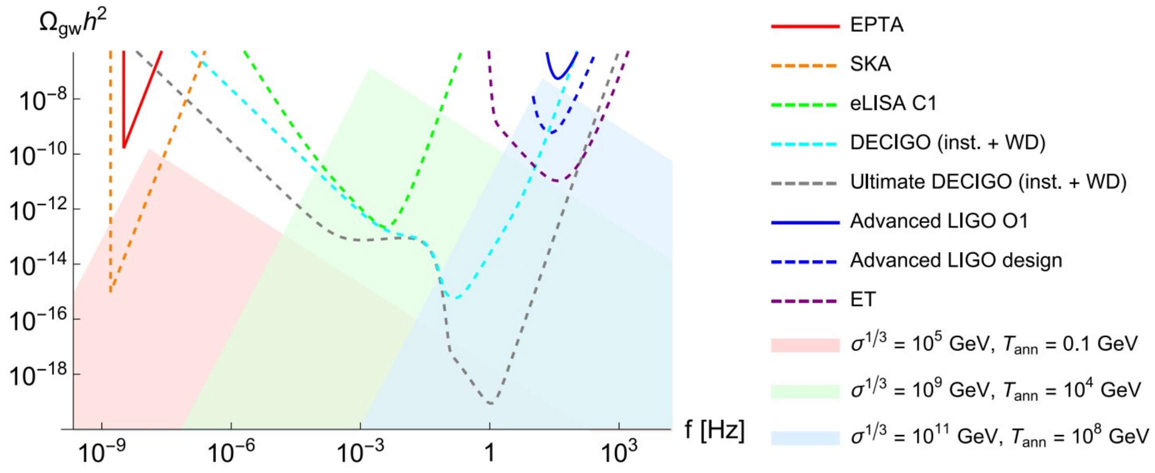


Gravitational Waves from Collapse of biased Domain Walls

- Signal depends on energy density of the domain wall σ and annihilation time of the domain wall network.

$$\sigma = \int_{-\infty}^{+\infty} \rho_{dw} dx$$

$$\Omega_{\rm gw} h^2(t_0)_{\rm peak} = 7.2 \times 10^{-18}\, \tilde{\epsilon}_{\rm gw} \mathcal{A}^2 \left(\frac{g_{*s}(T_{\rm ann})}{10}\right)^{-4/3} \left(\frac{\sigma}{1\,{\rm TeV}^3}\right)^2 \left(\frac{T_{\rm ann}}{10^{-2}\,{\rm GeV}}\right)^{-4}$$

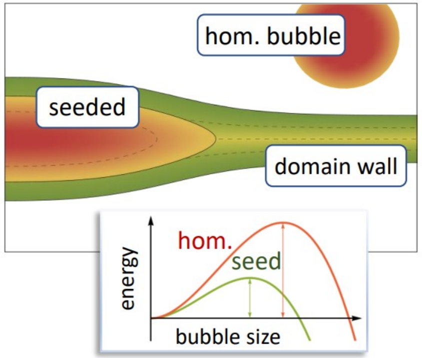


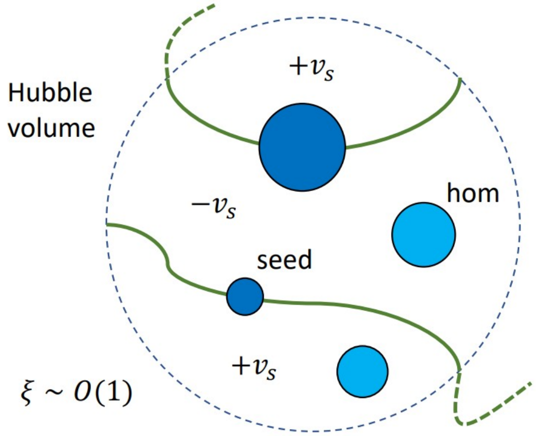
- For 2HDM and N2HDM, the signal is very small for most parameter space. Detectable signal requires a large v_s

$$\sigma_{2HDM}^{\frac{1}{3}} \simeq 10^2 GeV$$

N2HDM Electroweak Symmetry Breaking seeded in Domain Walls

Domain Walls from **singlet Z_2 symmetry breaking** act as **impurities** and **enhance the nucleation of EWSB bubbles.**

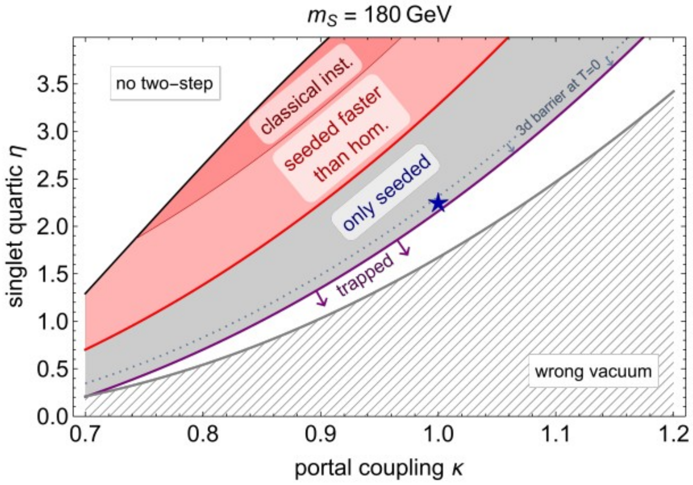




Nucleation prob. no longer the same everywhere, enhanced at DW location

- Different nucleation condition:

$$\frac{S_3}{T} \sim 140 \quad \text{vs} \quad \frac{S_{\text{inh}}}{T} \sim 100$$

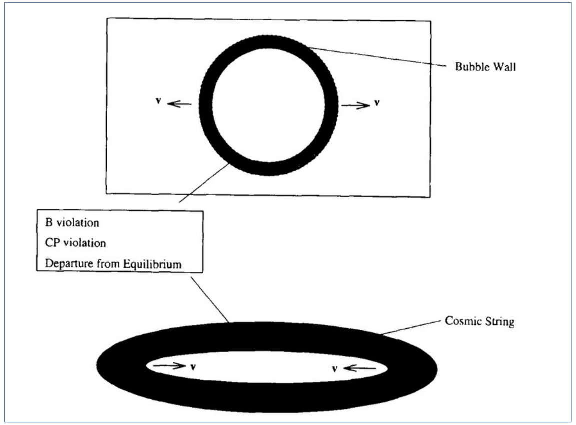


Figures from Simone Blasi DESY theory Seminar Talk 02.05.22

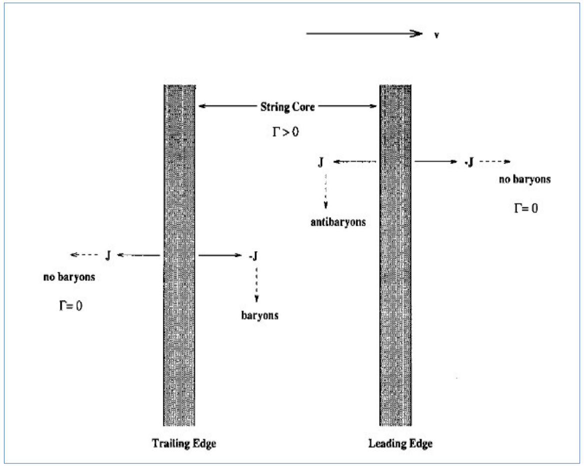
Baryogenesis with Topological Defects

Idea discussed in the 90s :

- **Local and nonlocal defect-mediated electroweak baryogenesis**
  hep-ph/9409281
- **Baryogenesis from Domain Walls in the Next-to-Minimal Supersymmetric Standard Model**
  hep-ph/9505241
- **Electroweak Baryogenesis with Cosmic Strings ?**
  Hep-ph/9901310
- **...**



From Physics Letters B 335 (1994) 123-130



Main idea:

- **The topological defect acts as the bubble wall.**
- **Sphalerons** are **less supressed** inside the topological defect
- **CP violation in the defect walls.**

Main Problems discussed in past papers:

- **Volume suppression factor** due to defect **not spanning the whole universe.**

$$\Delta n_B = \frac{1}{V}\frac{\Gamma_B}{T} V_{\rm BG}\Delta\theta$$

- **Symmetry restoration region not large enough to contain Sphalerons.**

$$R_{restoration} \sim \frac{1}{\sqrt{\lambda}v} \qquad R_{Sphalerons} \sim \frac{1}{g^2 T}$$

For N2HDM/2HDM Domain walls thickness 5-10 times smaller than Sphalerons

For cosmic strings

String-mediated electroweak baryogenesis: A critical analysis

J. M. Cline,[1,*] J. R. Espinosa,[2,†] G. D. Moore,[1,‡] and A. Riotto[2,§]
[1]*Department of Physics, McGill University, 3600 University Street, Montréal, Québec, Canada H3A 2T8*
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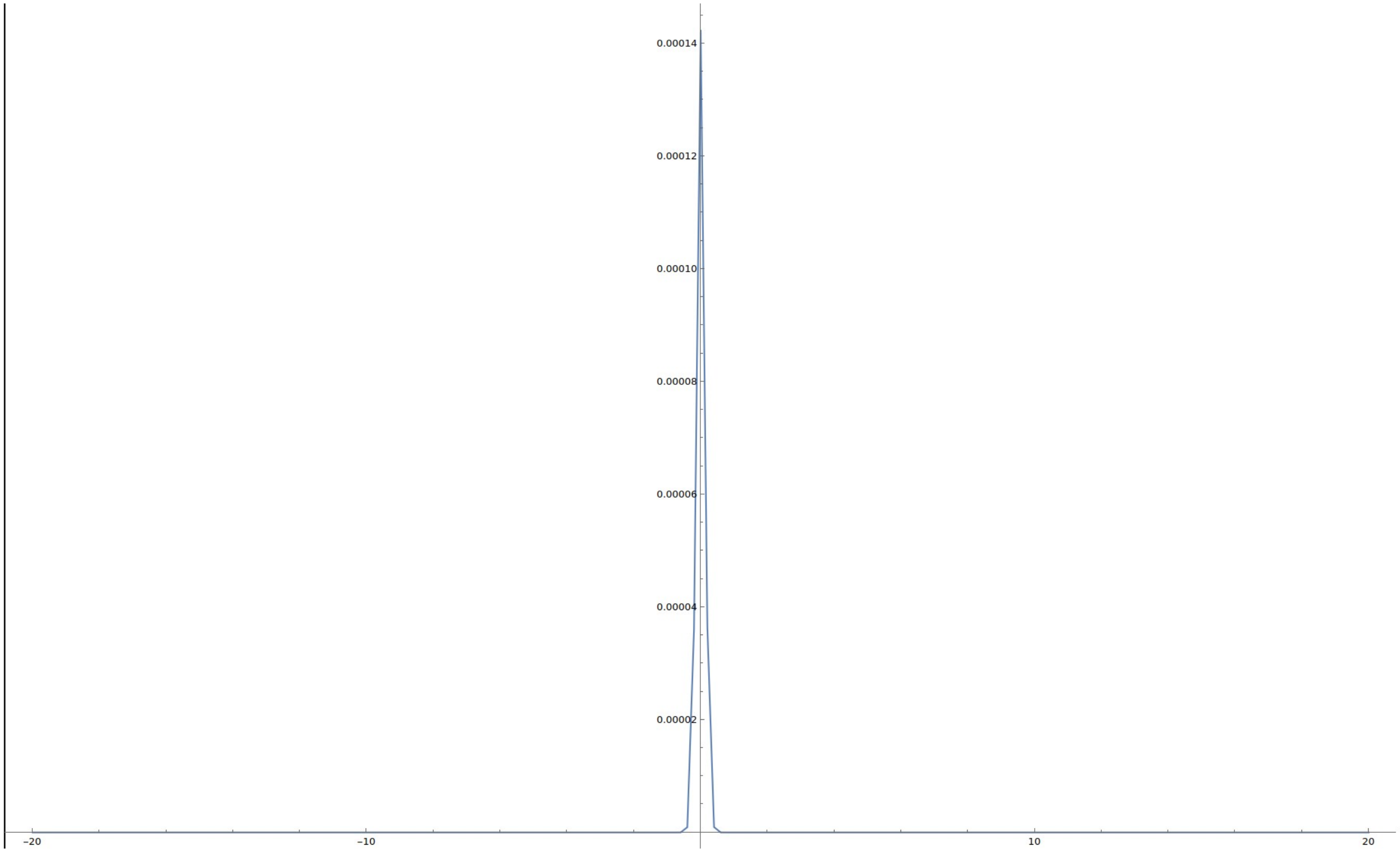
(Received 6 October 1998; published 22 February 1999)

Very Suppressed!

$$\left[\frac{N_B}{N_\gamma}\right]_{strings} \lesssim 10^{-10}\left[\frac{N_B}{N_\gamma}\right]_{observed}. \qquad (4)$$

That is, the mechanism just studied is uncapable of generating a sufficiently large matter-antimatter asymmetry.

What about Domain Walls ?



Exponential suppression of sphaleron rate