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# DOMAIN WALLS IN EXTENDED HIGGS MODELS

**YOUNGST@RS - Shaping the Universe: Framework and Footprints of Cosmological Phase**

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Work in collaboration with **Gudrid Moortgat-Pick (DESY, Hamburg).**

**Based on:**

**2309.12398 [JHEP] (MYS, Moortgat-Pick),**

**2407.14468 [JHEP] (MYS, Moortgat-Pick),**

28/01/2026



## ● Key ideas for this talk

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- **Extended Higgs sectors allow for new symmetries, which, upon spontaneous symmetry breaking lead to the creation of topological defects, such as Domain Walls (DW).**
- **In the literature, DW are mainly studied in the context of gravitational waves emission**  
→ I discuss some other interesting consequences of DW after Electroweak symmetry breaking:
  - 1) In the **2HDM**, the **spontaneous breaking of discrete symmetries** leads to the formation of different types of domain walls with phenomena such as **electric charge violation, and CP-violation.**  
→ Can generate exotic interactions in the thermal plasma: conversion of electrons into neutrinos, massive photons, ect...
  - 2) The interaction of domain walls and the Higgs field can lead to **electroweak symmetry restoration** inside the wall  
→ Useful for Baryogenesis.

- **Brief Intro to Domain Walls.**
- **BSM Higgs Models.**
- **Domain Walls in the 2HDM and Electric Charge Violation.**
- **Electroweak Symmetry Restoration via Domain Walls.**
- **Summary and outlook.**

# What are Domain Walls?

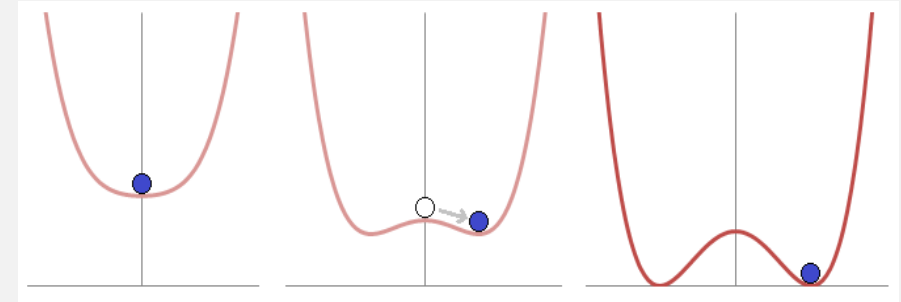
**Domain walls** are a type of **topological defects** that arise after **spontaneous symmetry breaking** (SSB) of a **discrete symmetry** in the early universe.

## Simplest example (real singlet scalar)

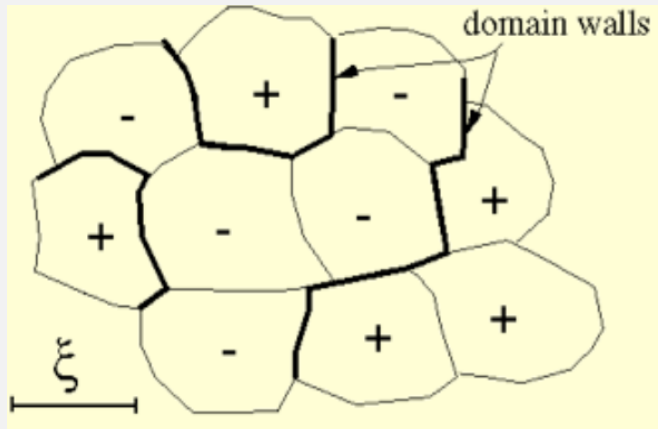
$V(\phi) = \mu\phi^2 + \lambda\phi^4$  is **invariant** under  $\mathbf{Z}_2: \phi \rightarrow -\phi$

**Vacuum manifold: two points  $v$  and  $-v$ .**

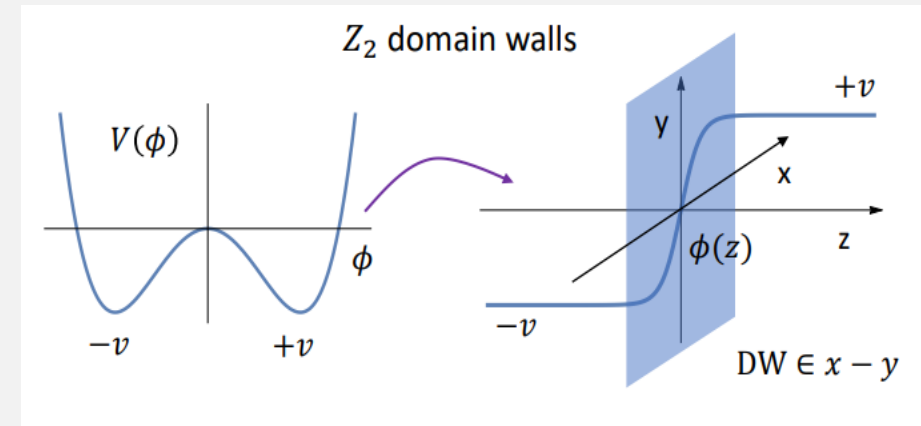
**Universe is divided into different cells with different signs for  $v$ .**



[Credit: Wikipedia]



[Credit: CTC Outreach]



[Credit: Simone Blasi]

## • The 2HDM and N2HDM

**Add extra doublets and/or extra singlets to the Standard Model.**

Focus on the **2HDM (Two-Higgs-Doublet models)** and **N2HDM (Next-To-2HDM)**:

$$V_{N2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c. \right] \quad \text{2HDM}$$

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

**Singlet scalar component**

**The (N)2HDM admits several discrete symmetries:**

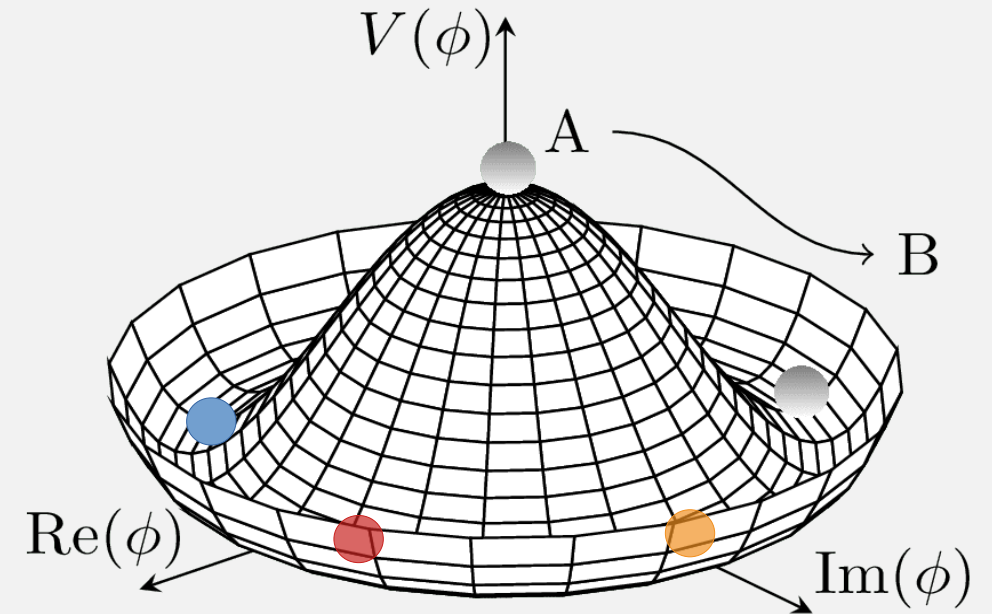
- **Z<sub>2</sub> Symmetry:**  $\Phi_1 \rightarrow \Phi_1$ ,  $\Phi_2 \rightarrow -\Phi_2$ ,  $\Phi_s \rightarrow \Phi_s$  (**softly broken by  $m_{12}$  term**). Used to forbid **Flavor-Changing-Neutral-Currents** at **tree level** when extended to the quarks in the Yukawa sector.
- **Z'<sub>2</sub> Symmetry:**  $\Phi_1 \rightarrow \Phi_1$ ,  $\Phi_2 \rightarrow \Phi_2$ ,  $\Phi_s \rightarrow -\Phi_s$ .

## • The 2HDM and N2HDM

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

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**  $\rightarrow$  **unphysical at  $T=0$** .
- **CP-Violating vacuum:**  $\xi \neq 0$ . **CP-violation** due to phase between the doublets  $\rightarrow$  **constrained by EDM (electric dipole moment experiments)**.
- **Neutral vacuum:**  $v_+ = 0, \xi = 0$ . Similar behavior to the SM Higgs vacuum  $\rightarrow$  **used throughout this work**.

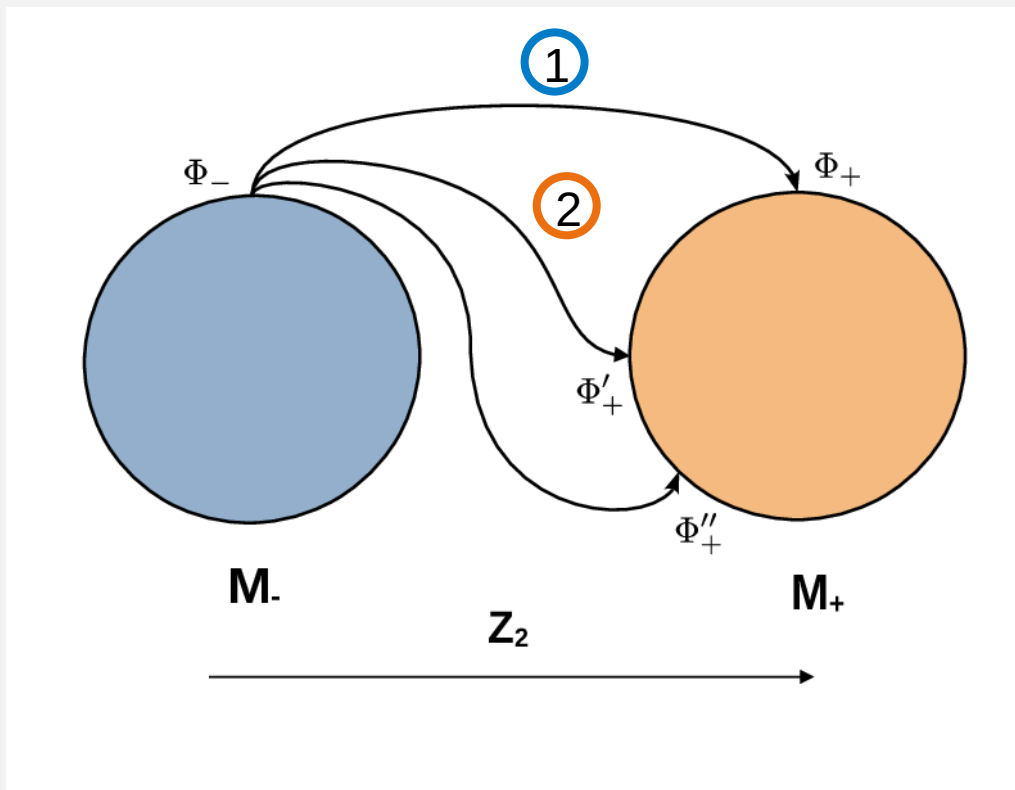


**Vacua with different matrix  $U$  are degenerate and are related by a gauge transformation**

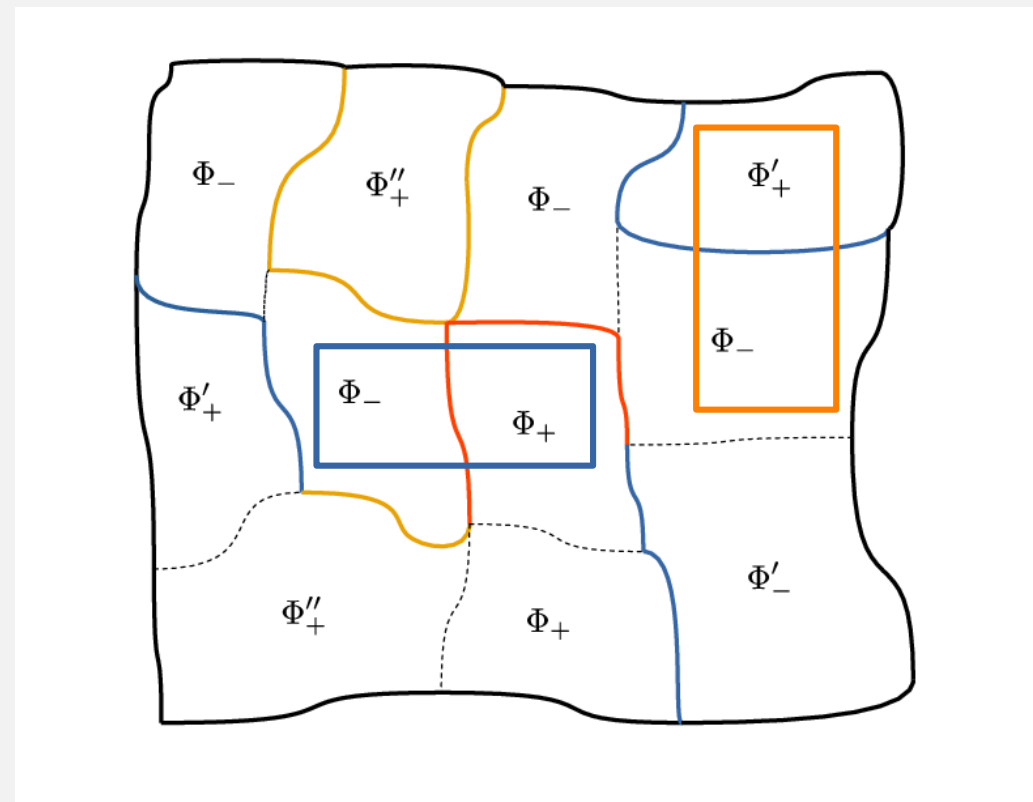
# Domain Walls solutions in the 2HDM

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

$$U = \exp(ig_k \sigma_k / v_{sm}) e^{i\theta}$$

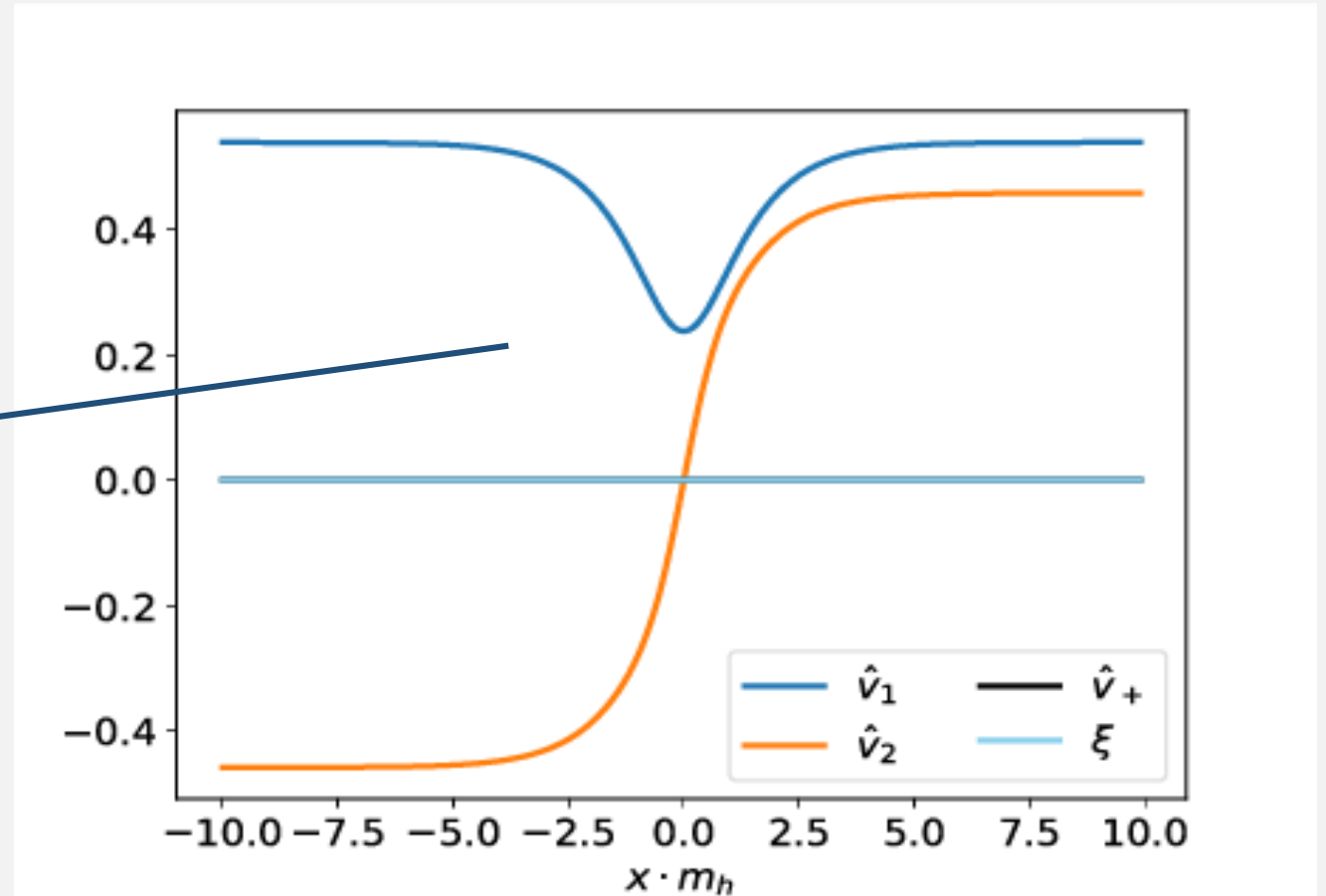
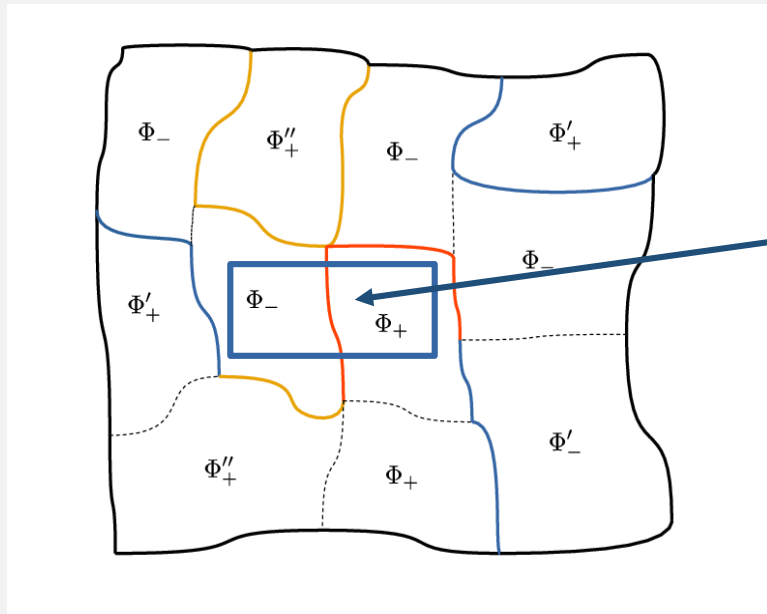


Vacuum manifold in the 2HDM



# Domain Walls solutions in the 2HDM

$$\Phi_- = (v_1, -v_2) \quad \Phi_+ = (v_1, v_2)$$

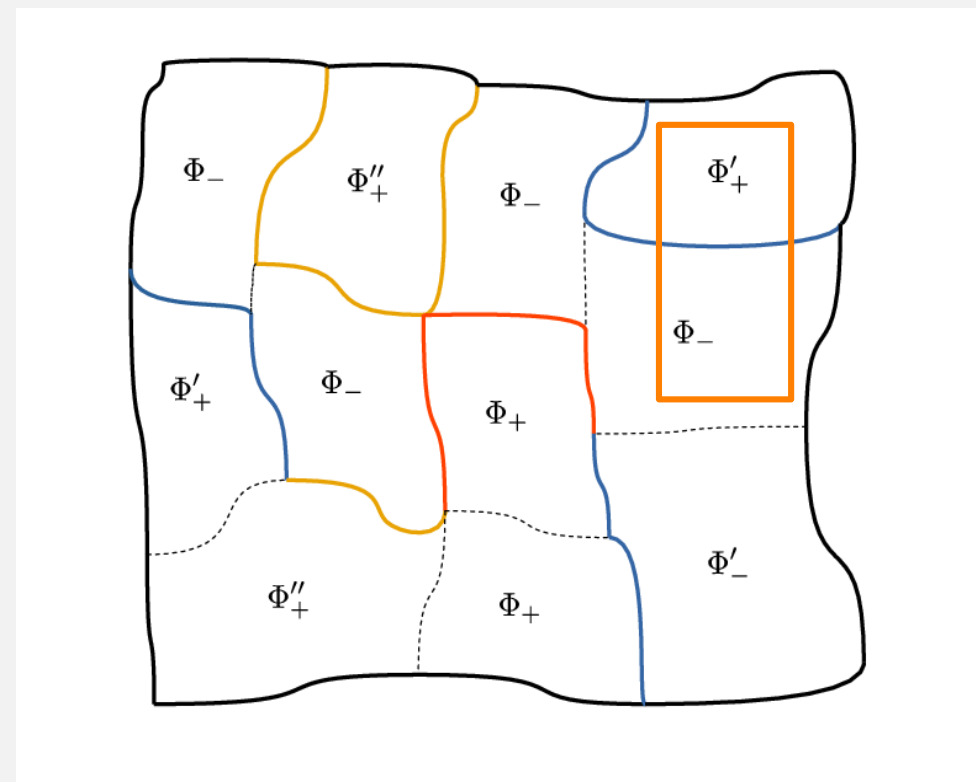
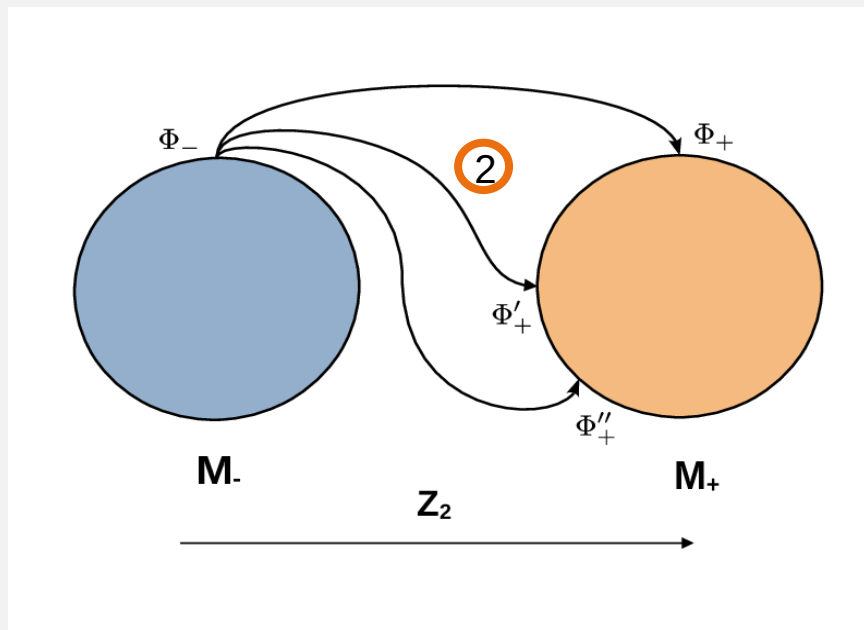


# Domain Walls solutions in the 2HDM

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

Now we choose vacua that have a relative gauge rotation to each other.

$$\Phi'_+ = U \Phi_+$$

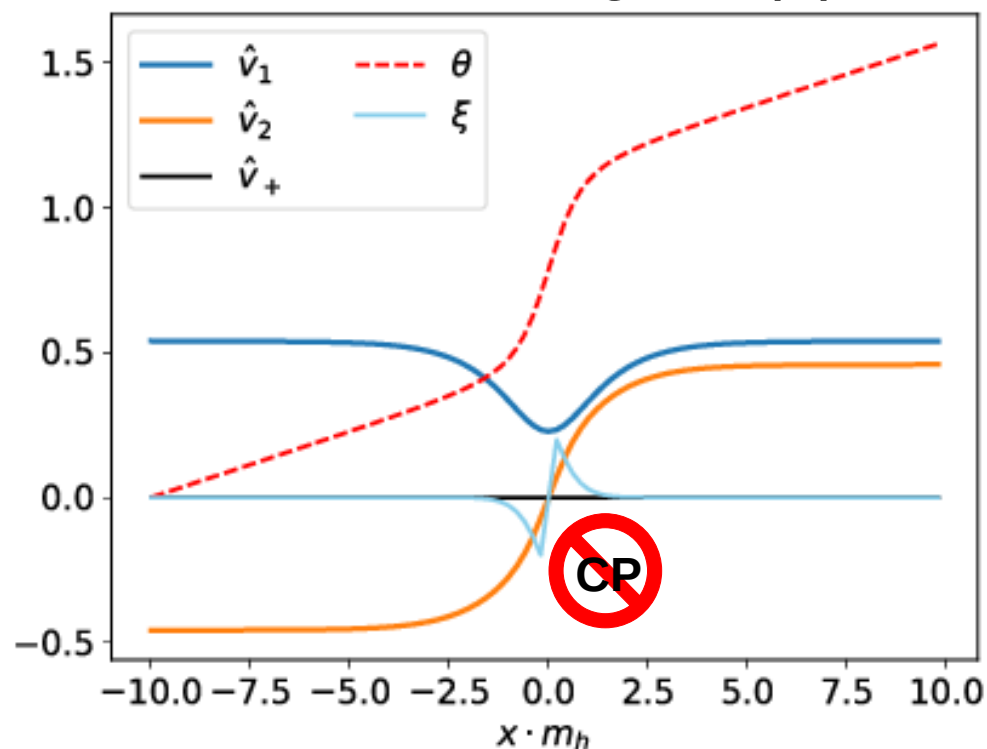


# Domain Walls solutions in the 2HDM

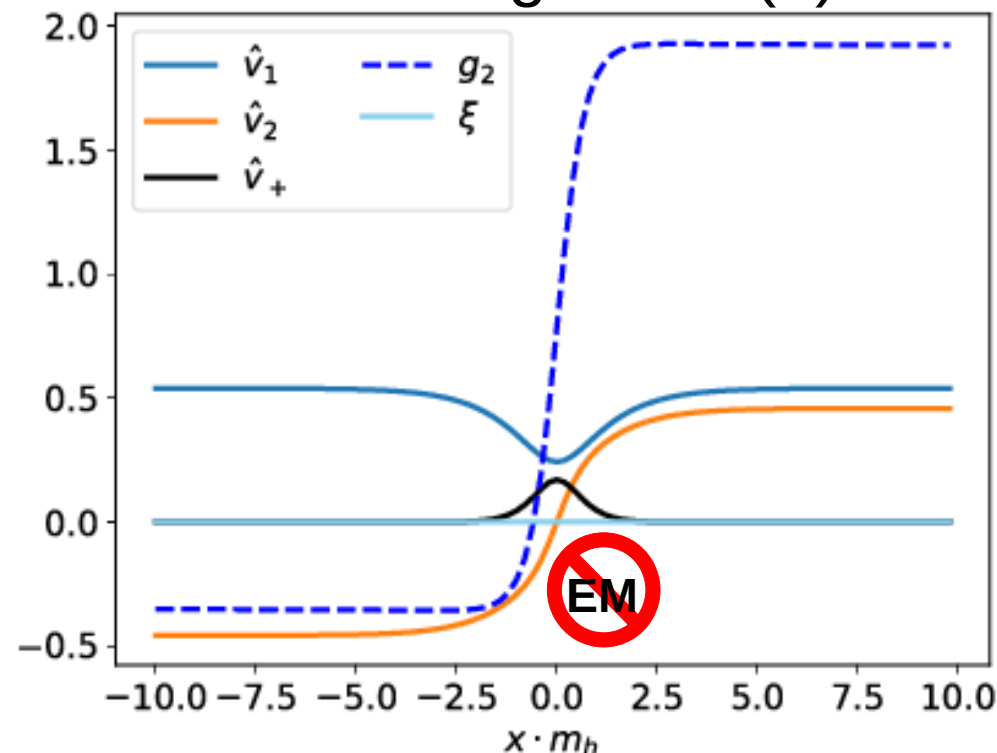
$$\Phi_- = (v_1, -v_2) \quad \Phi'_+ = (v_1, v_2), U \neq I$$

$$U \in SU(2)_L \times U(1)_Y$$

### Different angle $U(1)_Y$



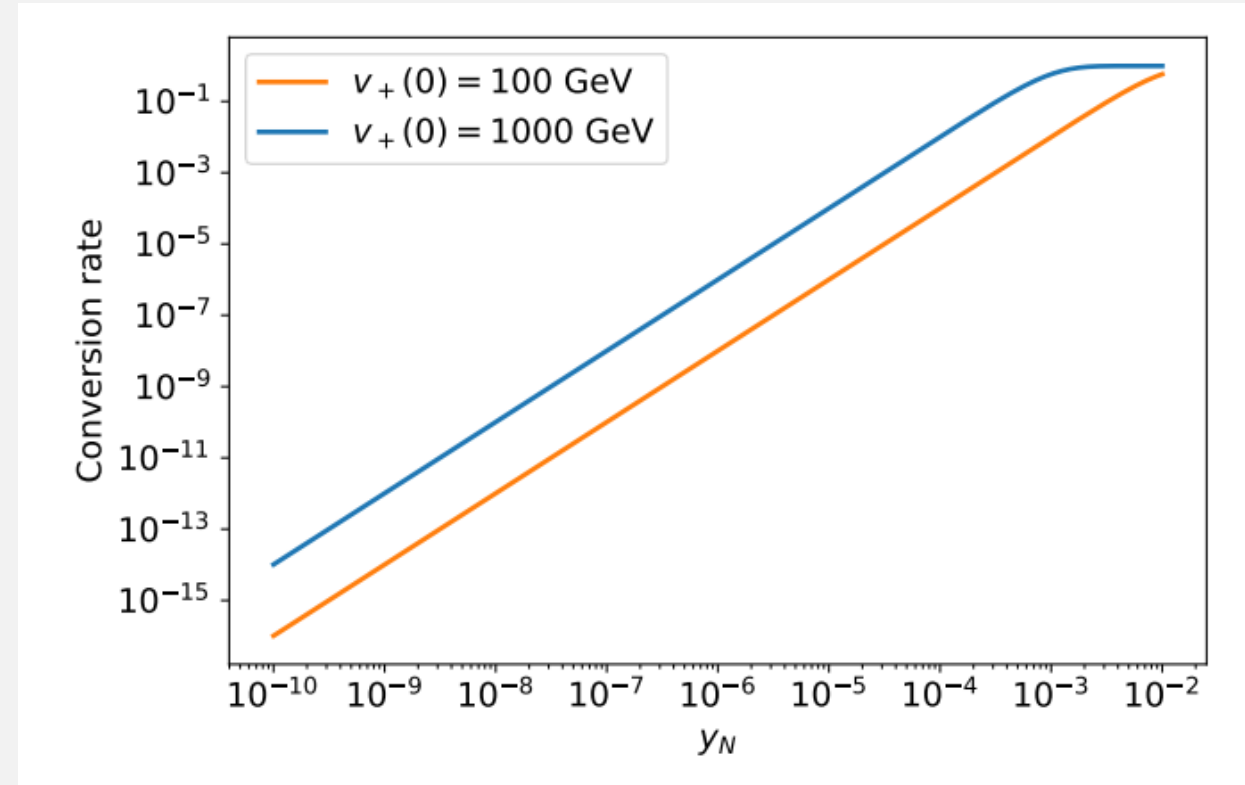
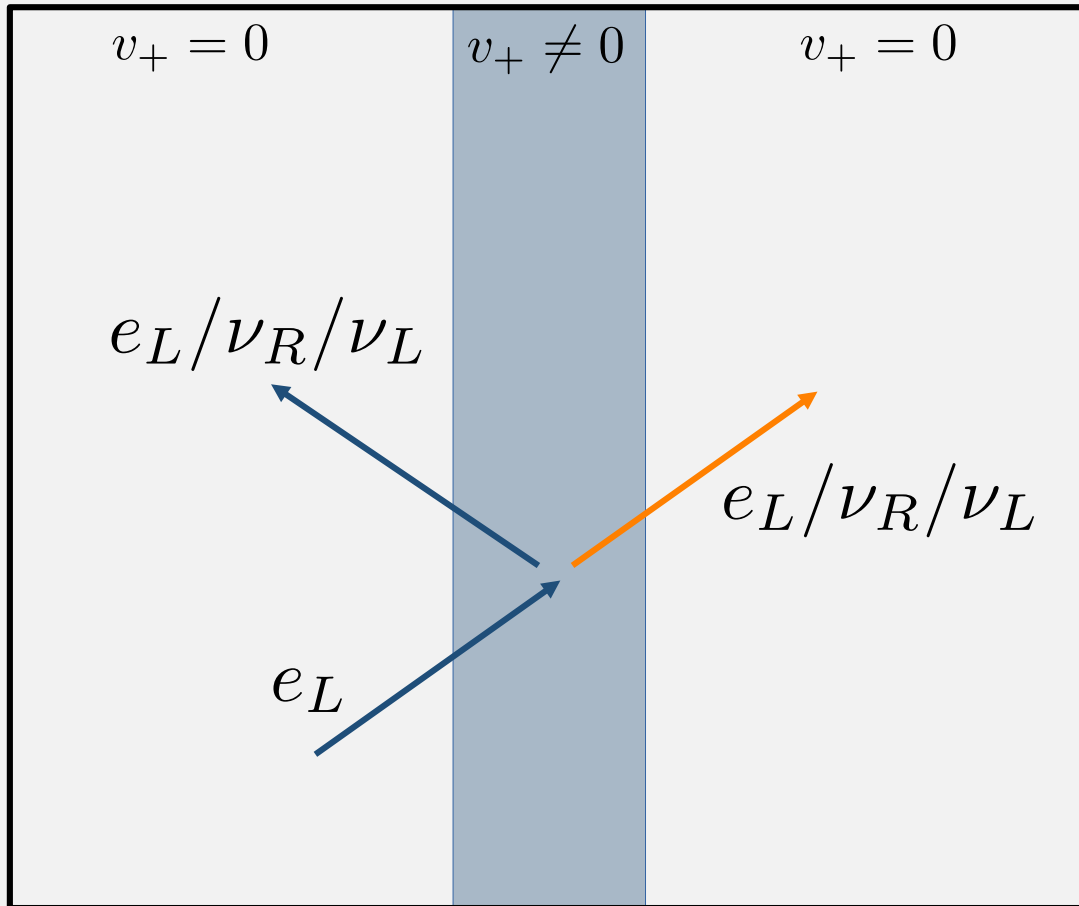
### Different $g_2$ of $SU(2)_L$



# Electric charge scattering off the domain wall

Upon hitting an electric charge breaking wall, electrons can be transformed into Neutrinos!

$$\mathcal{L}_Y \supset y_l v_+(x) \bar{e}_L \nu_R + y_t v_+(x) \bar{t}_L d_R + h.c. + \dots$$



- The **simultaneous** spontaneous symmetry breaking of both the **discrete symmetry and the Electroweak symmetry** in the early universe leads to different types of domain walls in the 2HDM.
- Domain walls in the 2HDM can have exotic properties like **localized electric charge breaking** inside the wall.
- Upon scattering with these walls, **electrons can turn into Neutrinos**, providing a useful mechanism to produce sterile Neutrinos!

For more infos: 2010.09840 [Battye, Pilaftsis, Viatic], 2509.23332 [Battye, Cotterill, Thomasson],  
2509.23332 [Battye, Cotterill, Thomasson], 2110.12550 [Pilaftsis, Law],  
Phys.Rev.D 73 (2006) 105021 [Vachaspati, Steer]

# ● Electroweak Symmetry Restoration in the N2HDM

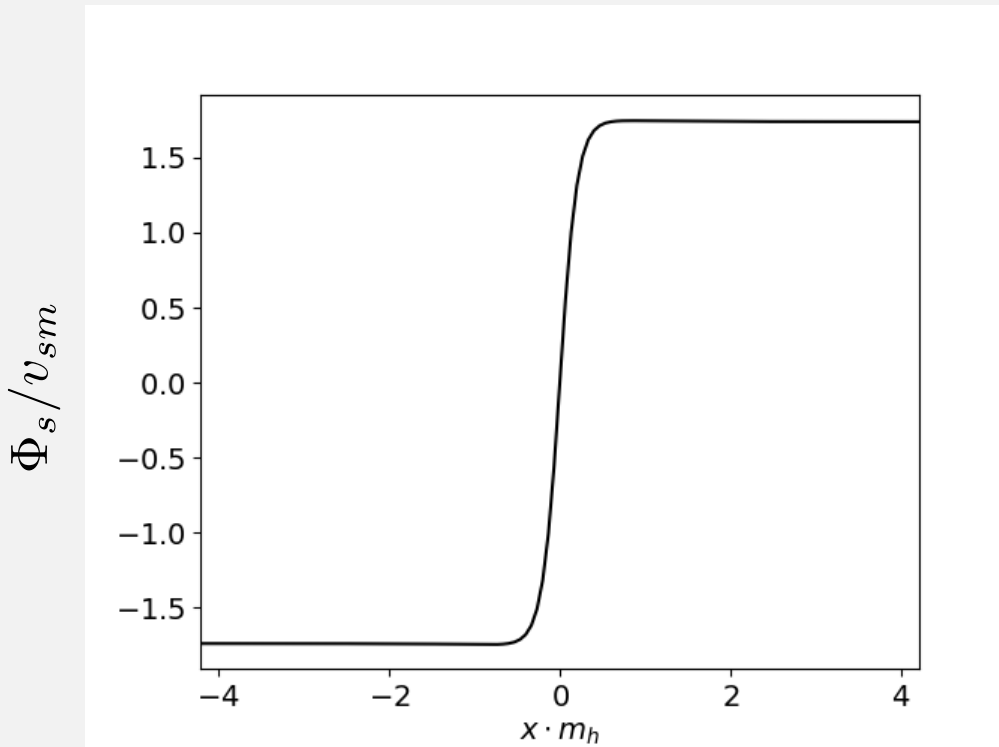
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- **Sphalerons** play a crucial role in **Baryogenesis**. They are **active before EWSB** and **exponentially suppressed when the Higgs VEV is non-zero**.
- Domain walls **influence the profile** of other scalar fields **coupled** to the scalar field causing the wall.
- Can a **singlet domain wall** influence the doublet scalar field(s) to **cause electroweak symmetry restoration**, Leading to Sphalerons being **unsuppressed inside the wall** ?

# Electroweak Symmetry Restoration in the N2HDM

## Z'<sub>2</sub> symmetry in the N2HDM

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow \Phi_2, \quad \Phi_s \rightarrow -\Phi_s$$



$$V_{N2HDM} = V_{2HDM} + \frac{m_S^2}{2} \Phi_s^2 + \frac{\lambda_6}{8} \Phi_s^4$$

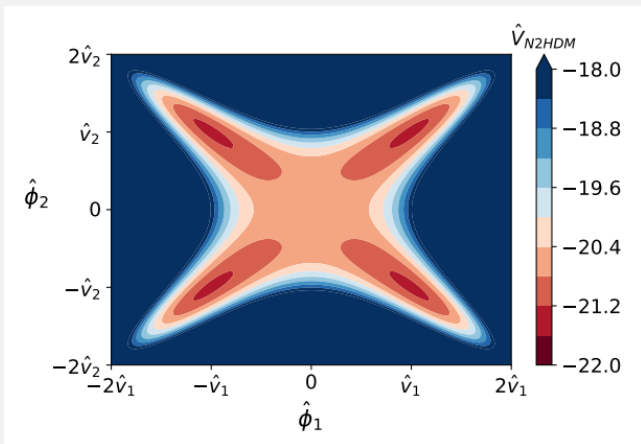
~~$$+ \frac{\lambda_7}{2} \Phi_s^2(x) \Phi_1^\dagger \Phi_1 + \frac{\lambda_8}{2} \Phi_s^2(x) \Phi_2^\dagger \Phi_2$$~~

Terms vanish inside the wall

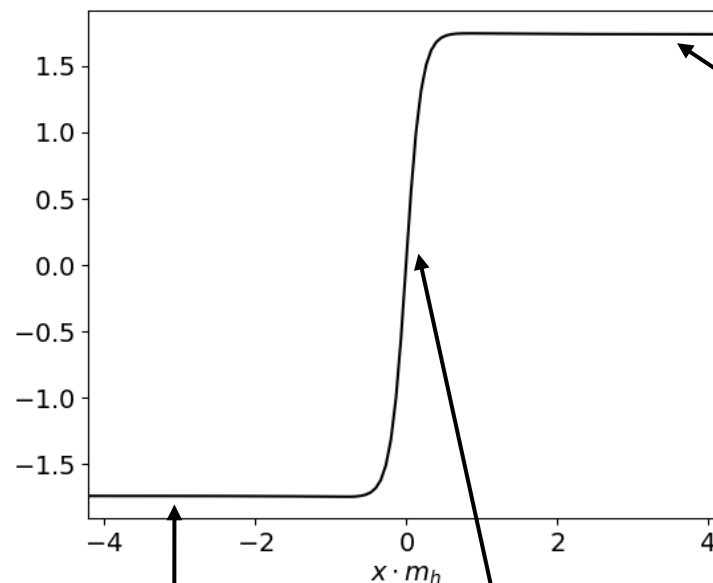
Effective mass terms of the doublet can turn positive inside the wall!

# Electroweak Symmetry Restoration in the N2HDM

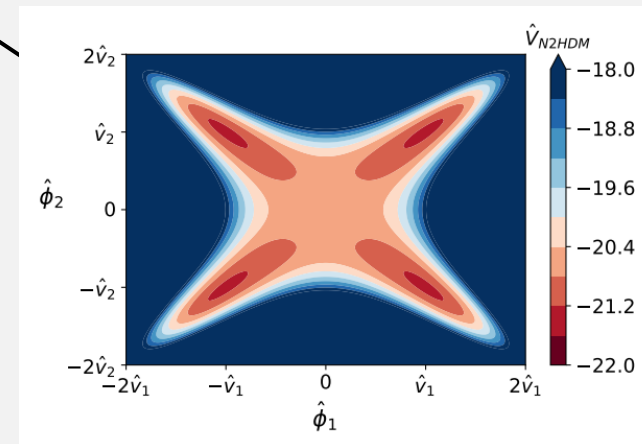
### Potential at $-\infty$ ( $-v_s$ )



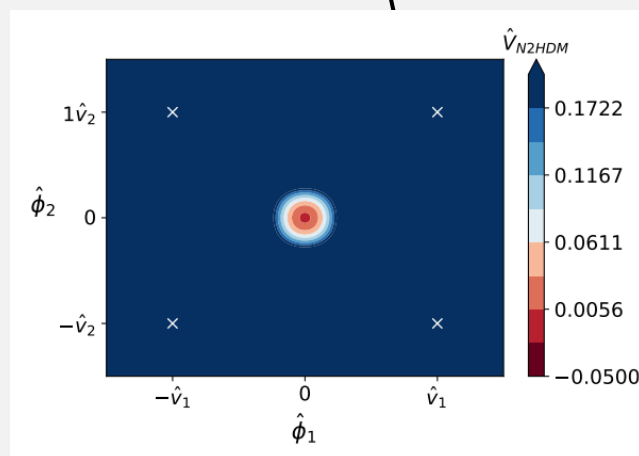
$\Phi_s / v_{sm}$



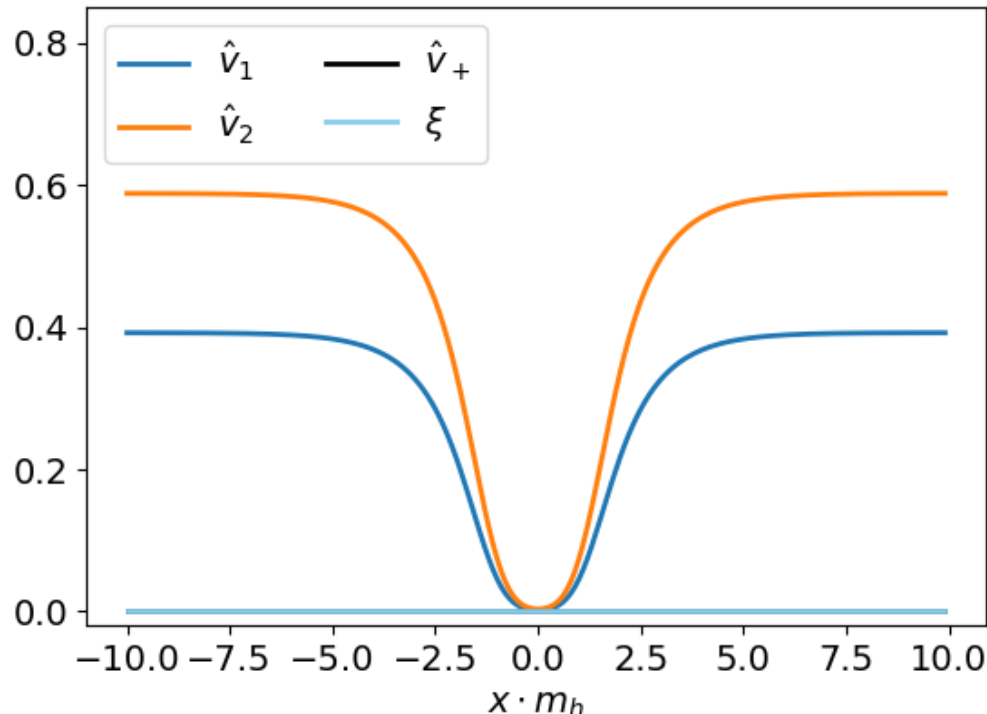
### Potential at $+\infty$ ( $v_s$ )



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



# Electroweak Symmetry Restoration in the N2HDM



$$\Gamma_{sph} \propto \exp(-E_{sph}/T)$$

$$E_{sph} \propto \sqrt{v_1^2 + v_2^2}$$

- The sphalerons are active **inside** the wall and inactive **outside**.
- Spatial separation of the sphaleron rate leads to **departure from thermal equilibrium**.

Electroweak symmetry is restored inside and in the vicinity of the wall

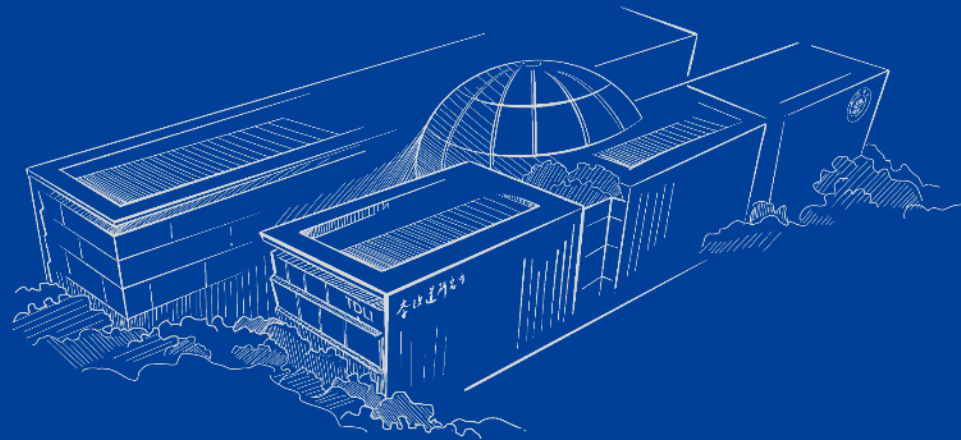
## ● Summary and Outlook

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- Domain walls provide lots of opportunities in the early universe **beyond their gravitational wave effects**:
  - **Electric charge violating domain walls** can lead to the **production of Sterile Neutrinos, Photon decay, electric charge genesis**, ect...
  - Domain walls can lead to **Electroweak symmetry restoration inside and in the vicinity of the wall**, making them useful for Electroweak Baryogenesis **without the need for a first order phase transition!**
- **Open Questions**:
  - **How efficient is the production of Sterile Neutrinos ?**
  - **Can the regions of electroweak symmetry restoration absorb and amplify primordial Hypermagnetic fields ? Is the chiral asymmetry caused by these Hypermagnetic fields inside the EW symmetric region useful for Baryogenesis ?**

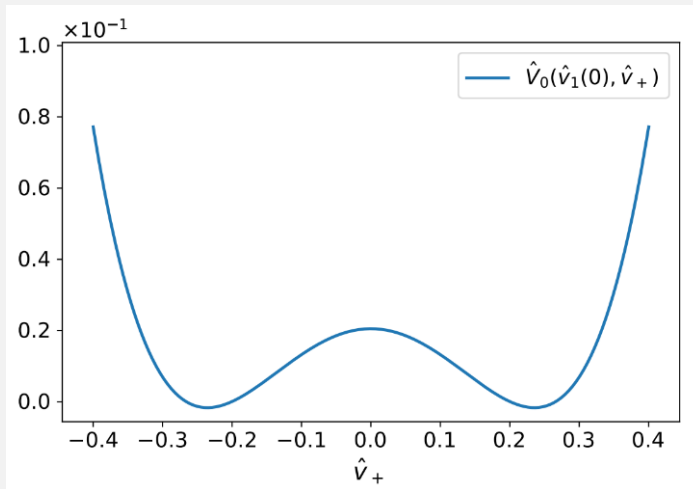
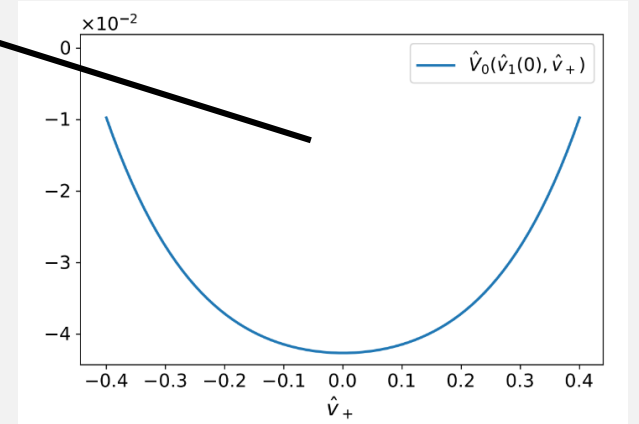
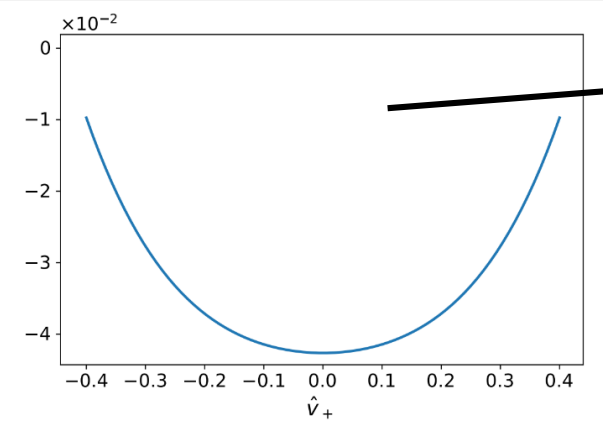
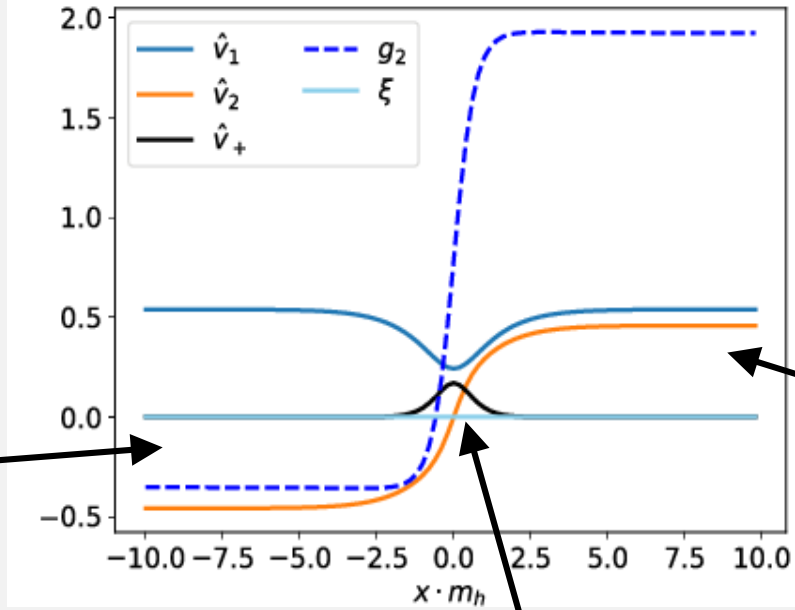


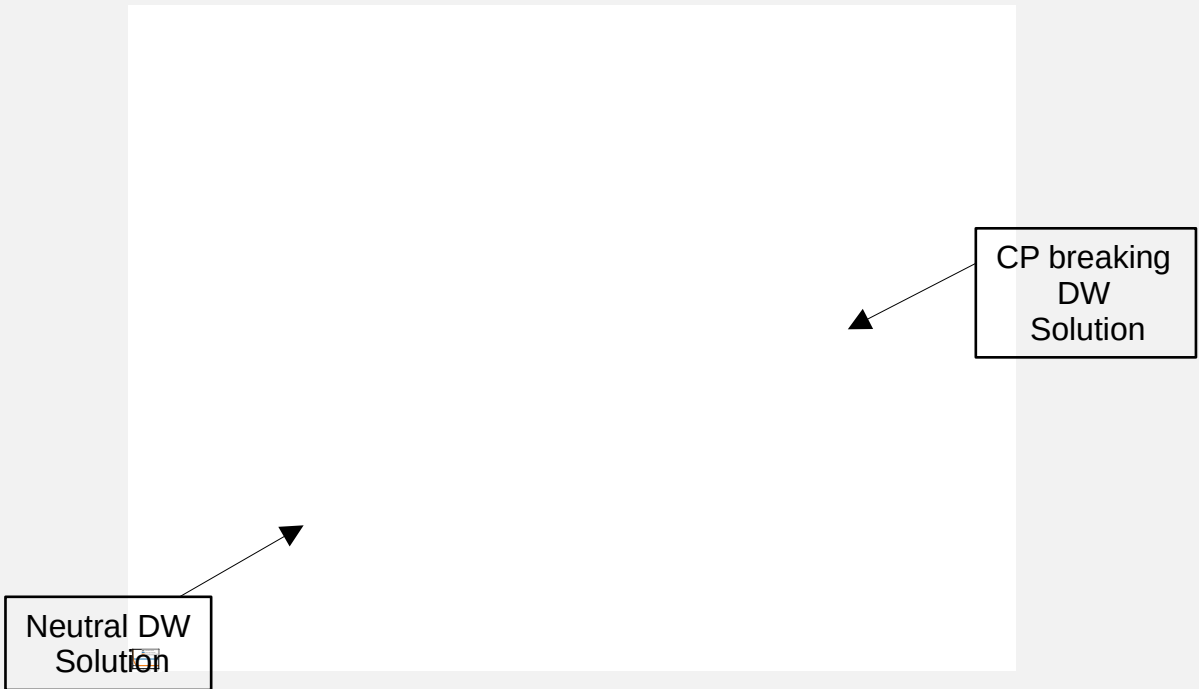
—— 谢谢! ——




— Backup —

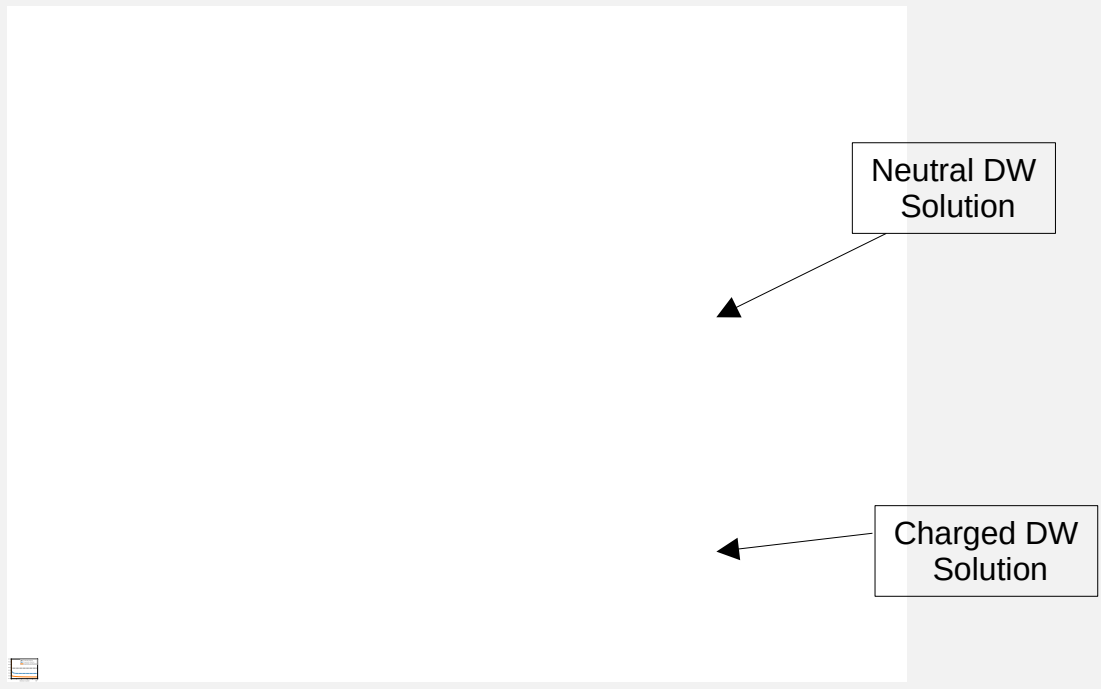
Inside the wall, the scalar potential in the  $v_+$  direction has a non zero minimum.





**CP-violating domain wall field configuration** 

Configuration has a higher energy than the “standard” DW configuration  
 → **unstable**



**Electric charge violating domain wall field configuration** 

Configuration has a lower energy than the “standard” DW configuration  
 → **stable**

# One explanation for the CP and electric charge breaking

A closer look at the E.O.M for  $\xi(x)$ :

$$\frac{d}{dx} \left( v_2^2(x) \frac{d\xi}{dx} \right) = -v_2^2(x) \frac{d^2\theta}{dx^2} - \frac{1}{2} v_1^2(x) v_2^2(x) \lambda_5 \sin(2\xi(x))$$

$$\frac{d^2\theta}{dx^2} \neq 0 \quad \longrightarrow \quad \xi(x) \text{ cannot be zero everywhere}$$

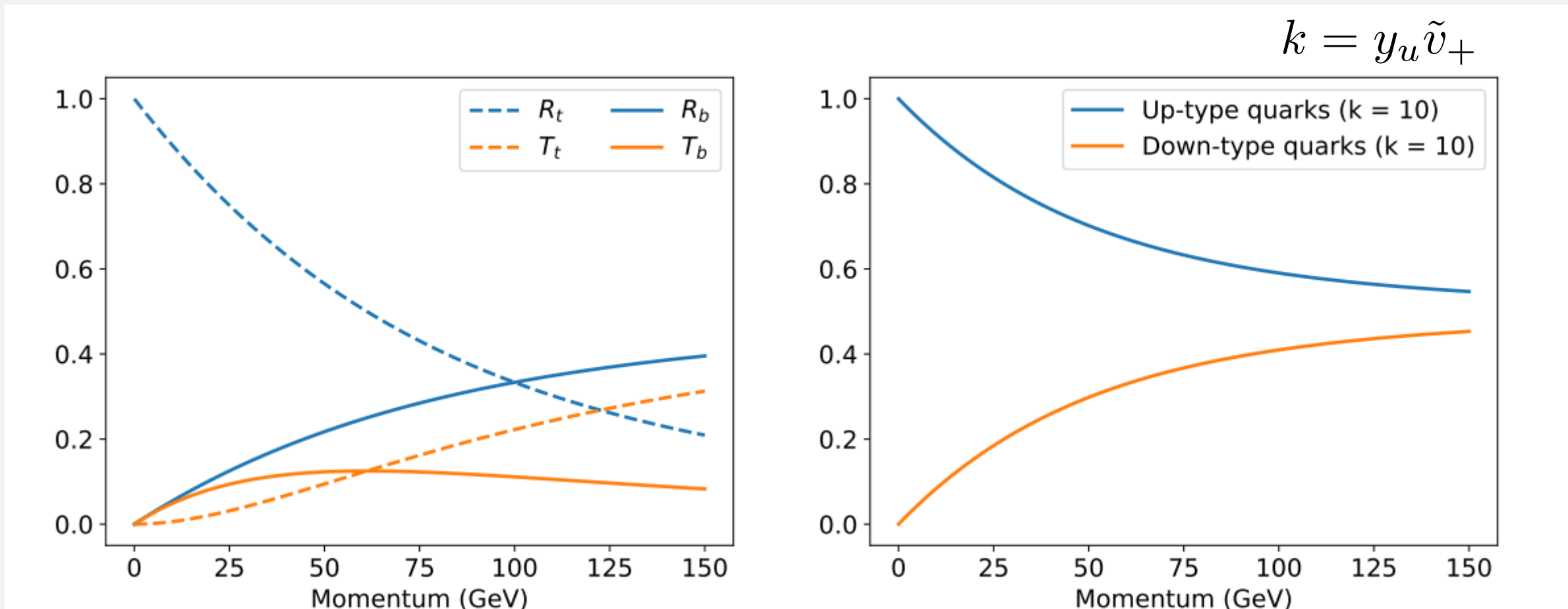
A closer look at the E.O.M for  $g_2(x)$ :

$$\frac{dg_2}{dx} = -\frac{2}{v_1^2(x) + v_2^2(x) + v_+^2(x)} \left( v_2(x) \frac{dv_+}{dx} - v_+(x) \frac{dv_2}{dx} \right)$$

$$\frac{dg_2}{dx} \neq 0 \quad \longrightarrow \quad v_+(x) \text{ cannot be zero everywhere}$$

# Electric charge scattering off the domain wall

## Interaction of top quarks with the electric charge breaking wall



# Interaction between hypermagnetic fields and the Electroweak symmetry restored wall

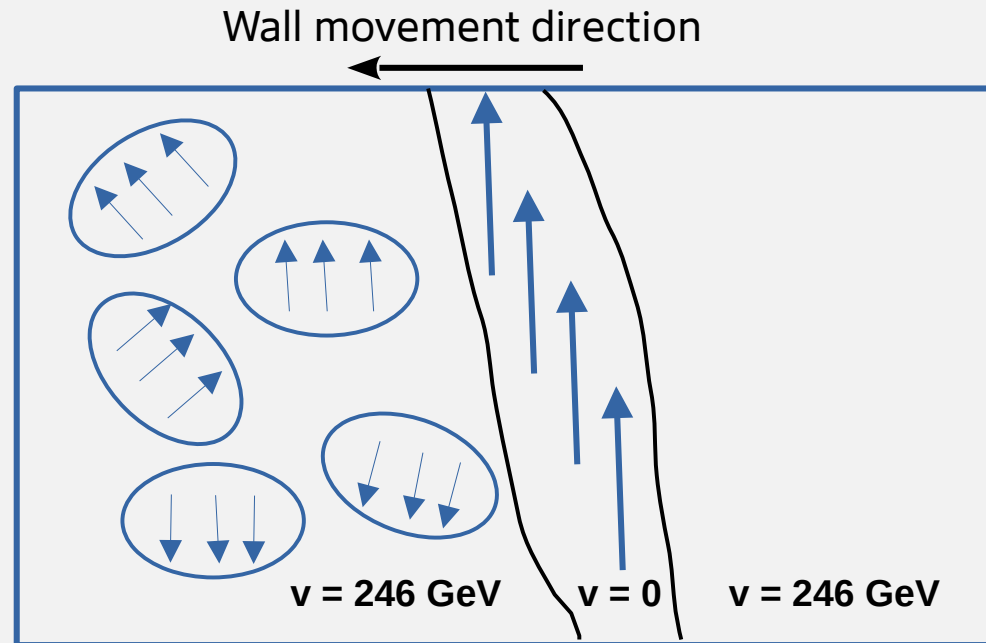
A primordial hypermagnetic field is **stuck** inside the symmetry restored region (energetically more favourable).

$$\mathcal{E}(x) = E_{kin}^{scalar}(x) + V_{scalar}(x) + \frac{1}{2} |B(x)|^2 (v_1^2(x) + v_2^2(x))$$

Small / vanishes inside the wall !

## Open question:

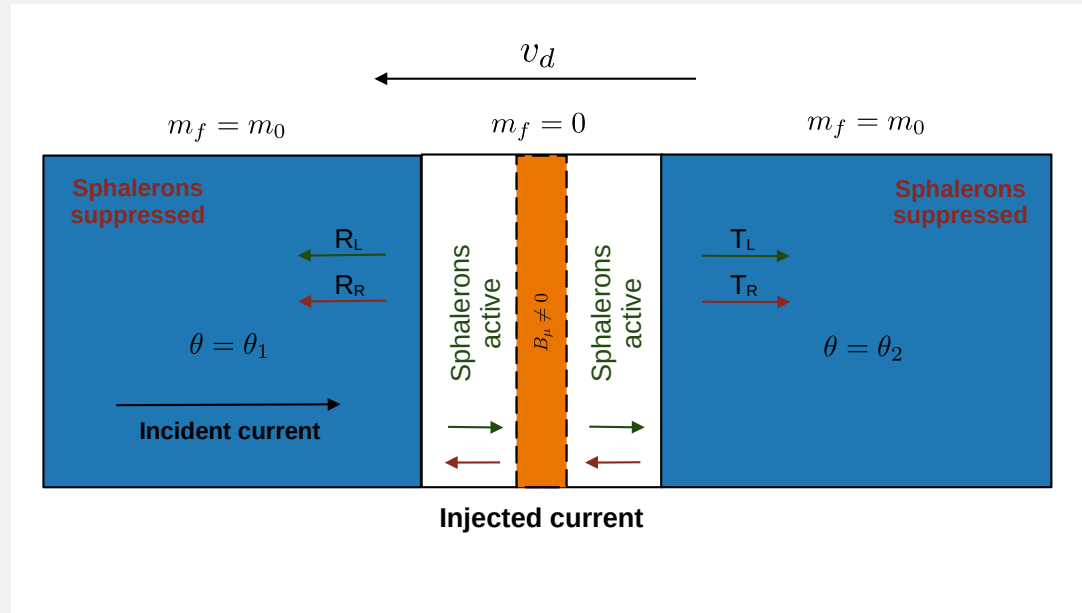
- Does the symmetry restoration wall act as a "sponge" for primordial hypermagnetic fields ?
- The field gets compressed and enhanced inside the wall to higher values. Can that cause a sizeable back-reaction on the domain wall ?



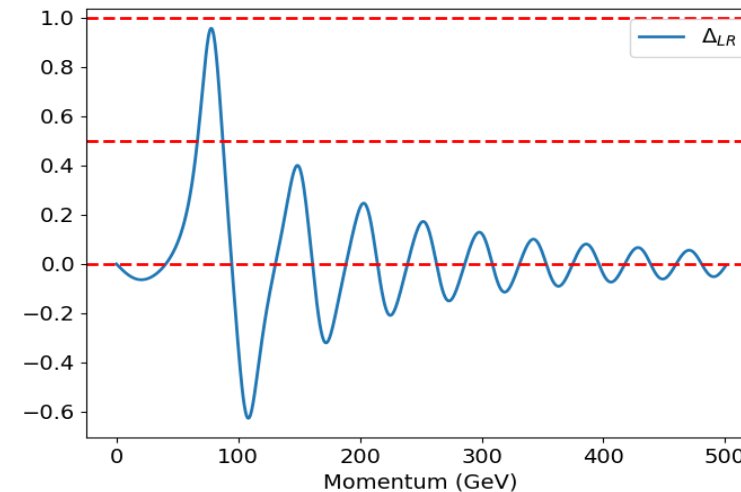
# Hypermagnetic fields, a source for CP-violation ?

The hypermagnetic field inside the wall interacts differently with left-handed and right handed particles!

$$\mathcal{L} \supset iY_L \bar{\Psi}_L \gamma_\mu B^\mu \Psi_L + iY_R \bar{\Psi}_R \gamma_\mu B^\mu \Psi_R$$

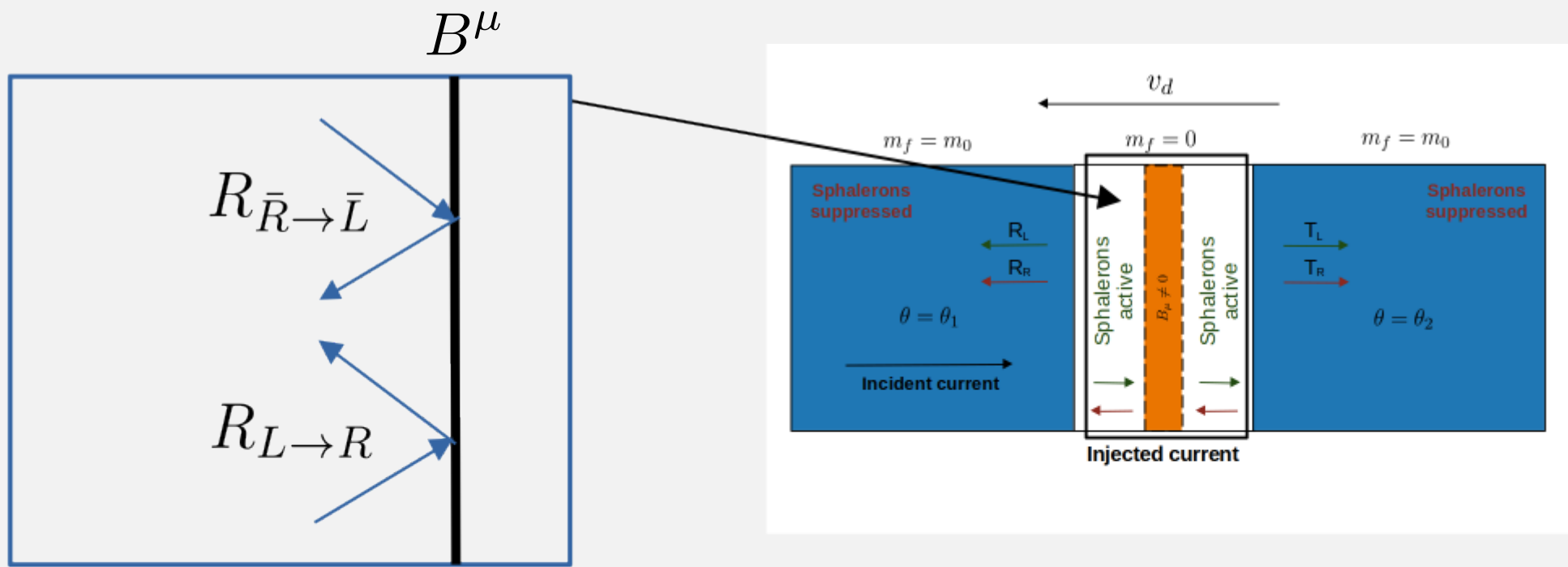


$\Delta_{LR} = \text{LH particle current} - \text{RH antiparticle current}$



$$J = \bar{\Psi} \gamma_0 \gamma_3 \Psi$$

Interference with incoming fermions makes the fermion's current inside the wall chirally asymmetric.



From CPT invariance:  $R_{L \rightarrow R} = R_{\bar{R} \rightarrow \bar{L}}$

So:  $R_{L \rightarrow R} \neq R_{R \rightarrow L} = R_{\bar{L} \rightarrow \bar{R}}$

CPT invariance

**This is a CP violating process!**