MANCHESTER 1824

The University of Manchester

Science & Technology Facilities Council

Domain Walls in Accidentally Symmetric Two Higgs Doublet Models

Dominic Viatic
Jodrell Bank Centre for Astrophysics
The University of Manchester, UK

2nd July 2019

D. G. Viatic, R. A. Battye & A. Pilaftsis (paper in prep.)

PASCOS 2019
XXV International Symposium

Introduction

- Motivation
  - Domain walls as cosmological probes
- The Two Higgs Doublet Model (2HDM)
  - Physical parameters
  - Possibile discrete symmetries
- Kink Solutions
  - Variation with parameters
- Domain Wall Networks
  - Neutral vacum condition
  - Scaling dynamics
- Interaction of Kinks
  - An analytical approach

Motivation

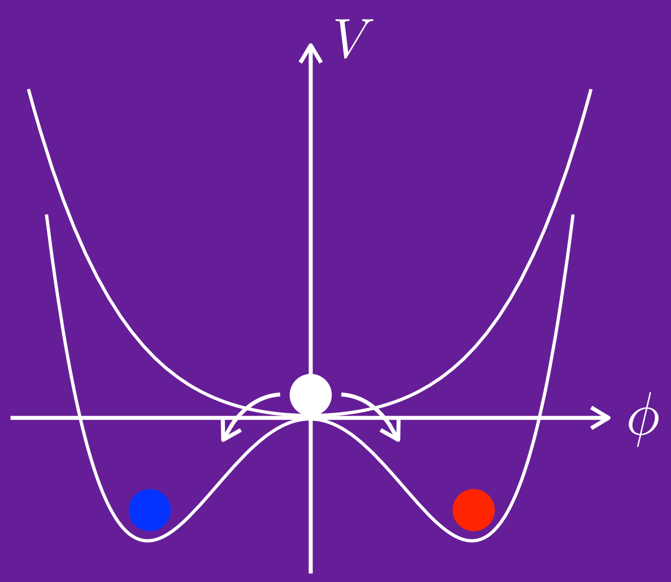
SM insufficient to describe observations in cosmology, e.g.

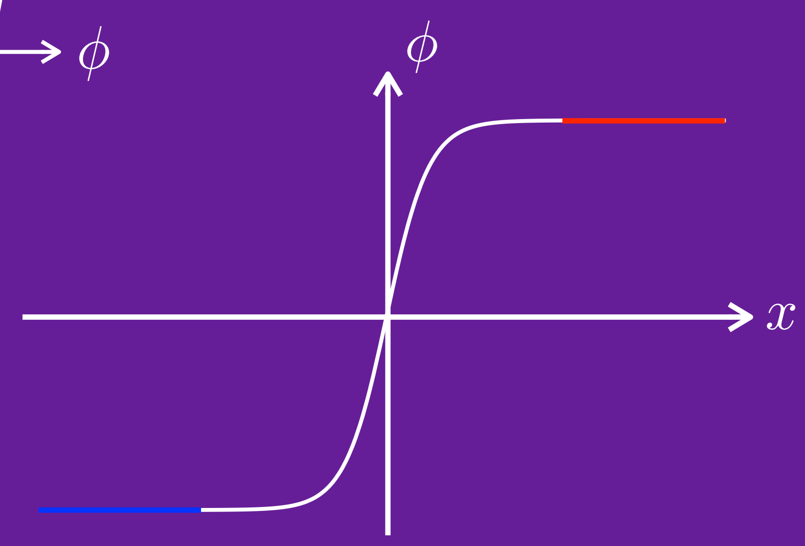
- Dark matter
- Baryon asymmetry
- Dark energy

2HDM is well-motivated but can also be topologically non-trivial

The Domain Wall Problem

- Radiation and matter scale like t^{-2}
- DWs scale like t^{-1}
- DWs dominate Universe at late times





The Two Higgs Doublet Model

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

$$\begin{aligned} V = & -\mu_1^2 \Phi_1^\dagger \Phi_1 - \mu_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 \\ & + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.} \right] \end{aligned}$$

3 accidental discrete symmetries:

Symmetry	μ_1^2	μ_2^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
Z_2	-	-	0	-	-	-	-	Real	0	0
CP1	-	-	Real	-	-	-	-	Real	Real	Real
CP2	-	μ_1^2	0	-	λ_1	-	-	-	-	$-\lambda_6$

Physical 2HDM Parameters

$h, \; H$ CP-even scalars - mixing angle, α

A CP-odd scalar - mixing angle, β

$H^{\pm}$ Charged scalars

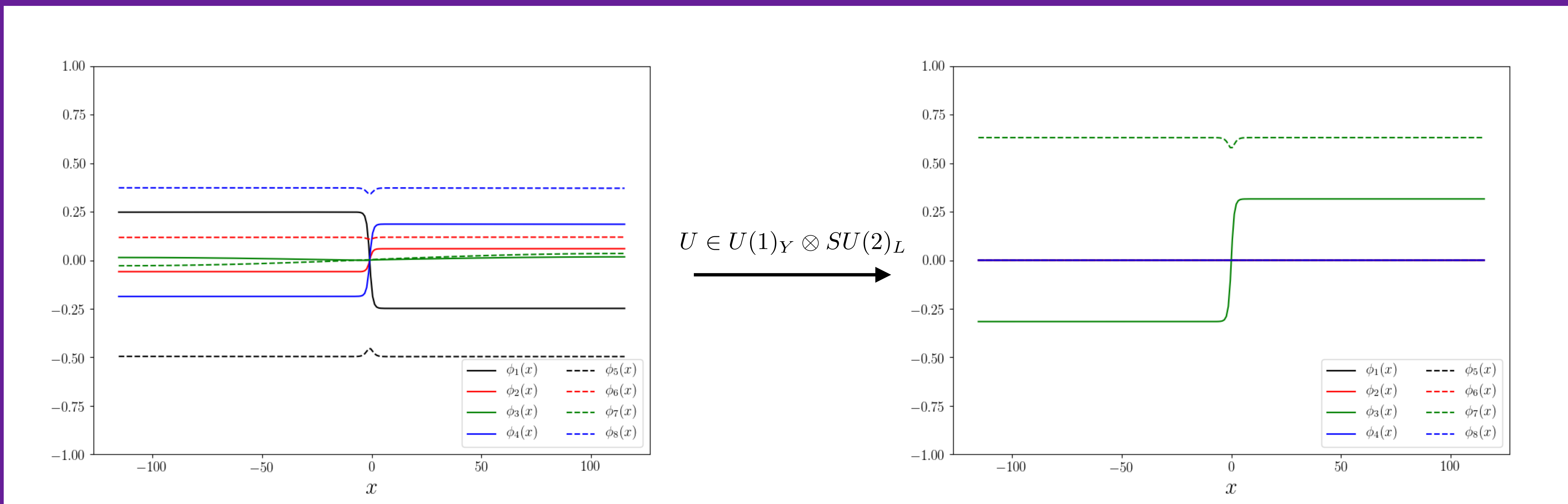
$$\left.\begin{aligned} M_h &= 125 \text{ GeV} \\ v_{\text{SM}} &= 246 \text{ GeV} \end{aligned}\right\} \text{ Fixed by experiment } \longrightarrow \hat{E} = \frac{M_h}{v_{\text{SM}}^2} E$$

$\cos(\alpha - \beta) = 1$ SM alignment

5 physical parameters: $M_H, \; M_A, \; M_{H^{\pm}}, \; \tan\beta, \; \cos(\alpha - \beta)$

Kink Solutions

Minimum energy solutions via gradient flow



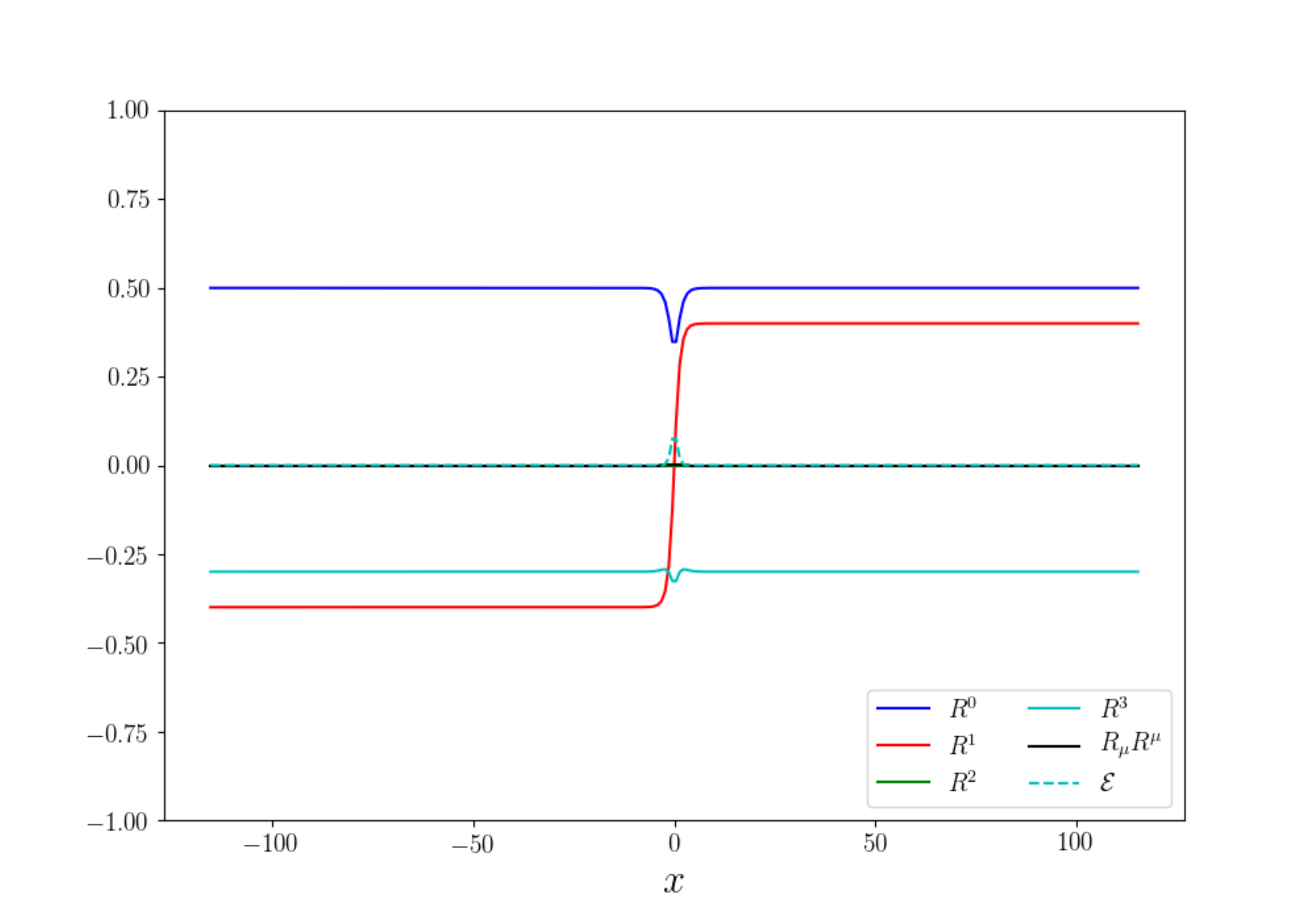
Field configuration interpolates between the VEVs,

$v_1 = v_{\mathrm{SM}} \cos\beta$

$v_2 = v_{\mathrm{SM}} \sin\beta$

$$\Phi_1^0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \Phi_2^0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

R-Space Profiles



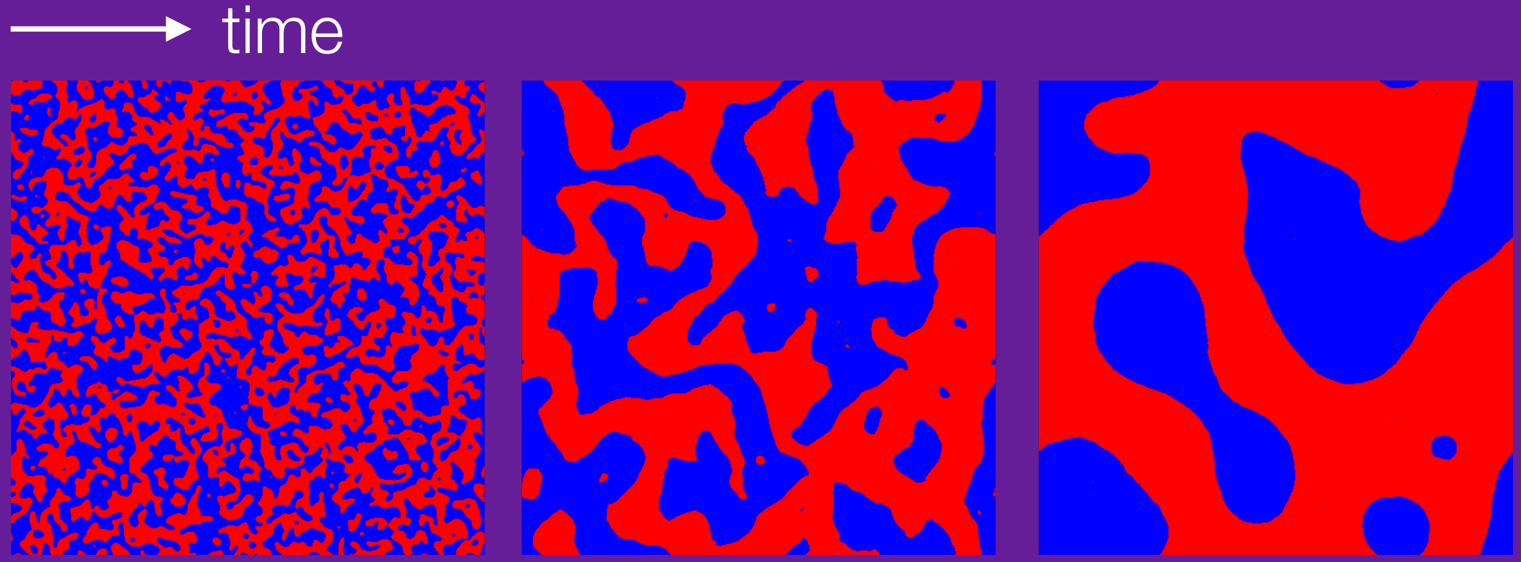
Bilinear scalar field formalism:

$$V = -\frac{1}{2} M_\mu R^\mu + \frac{1}{4} L_{\mu\nu} R^\mu R^\nu$$

$$R^\mu = \begin{pmatrix} \Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 \\ \Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \\ -i \left[\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1 \right] \\ \Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2 \end{pmatrix}$$

Neutral vacuum condition: $R^\mu R_\mu = 0$

Domain Wall Networks



Time evolution of Z_2 2HDM domains

Walls/condensates form in R^μ

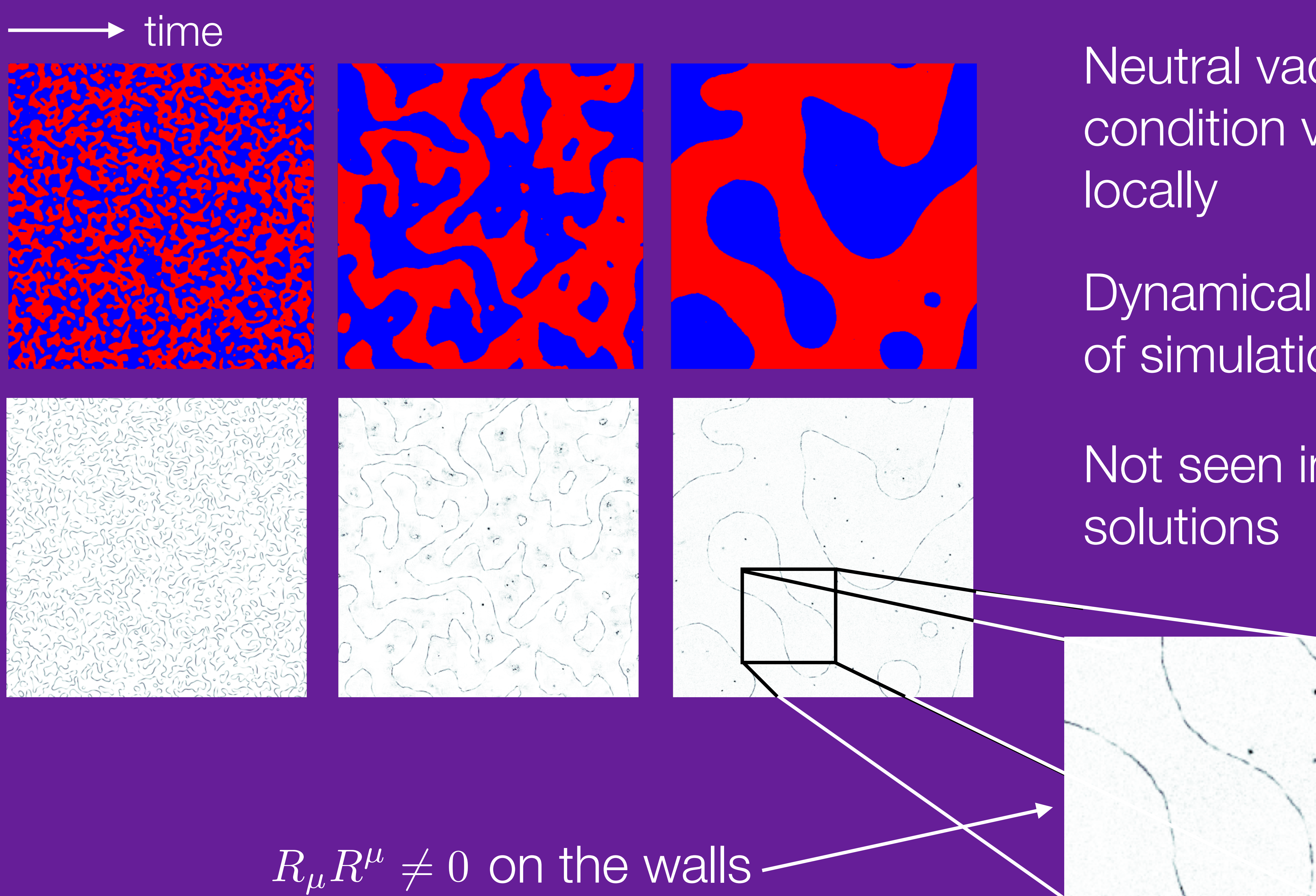
- Walls in R^1 in Z2 and CP2
- Walls in R^2 in CP1

Numerically solve EoMs for 2HDM

$$\partial_\mu \partial^\mu \Phi_i + \frac{\partial V}{\partial \Phi_i^\dagger} = 0$$

$$R^\mu = \begin{pmatrix} \Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 \\ \Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \\ -i \left[\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1 \right] \\ \Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2 \end{pmatrix}$$

Neutral Vacuum Condition

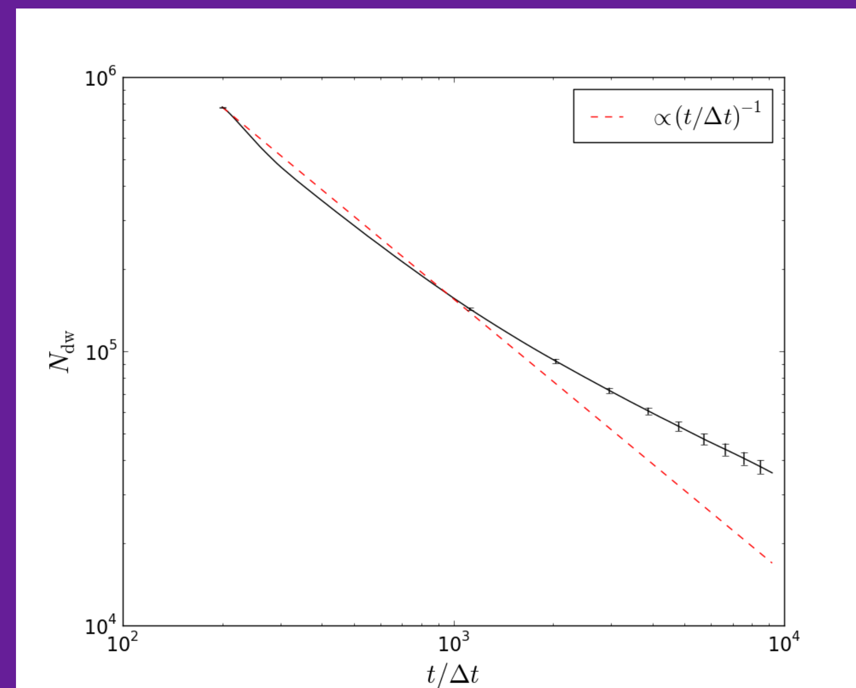


Neutral vacuum condition violated locally

Dynamical feature of simulations

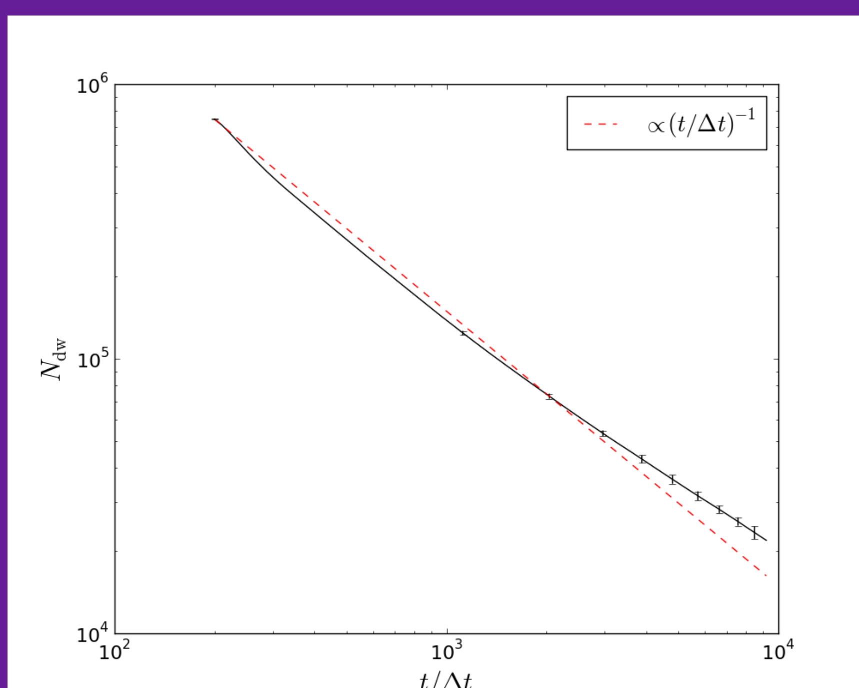
Not seen in kink solutions

Network Scaling

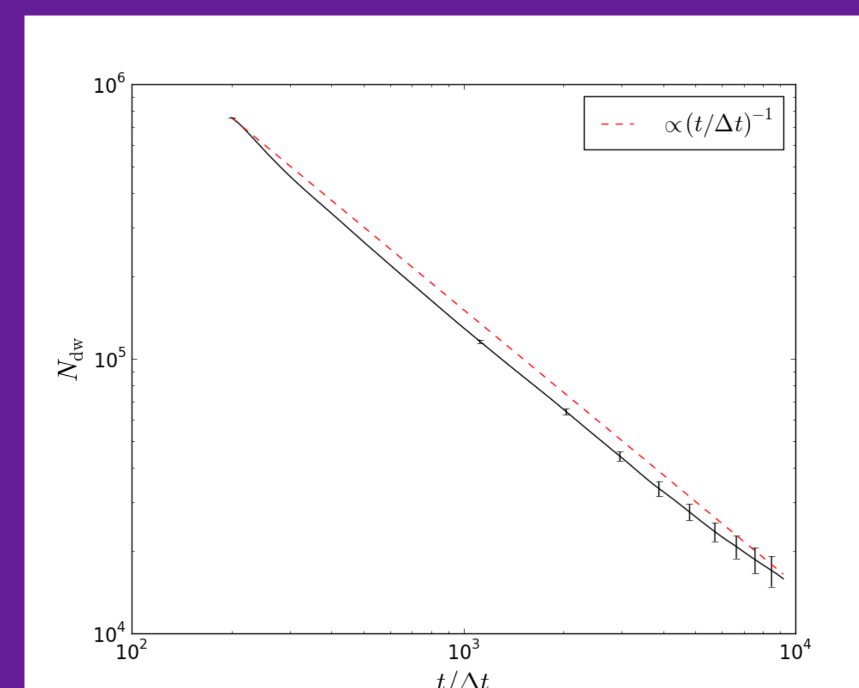


Minkowski

Radiation era



Matter era

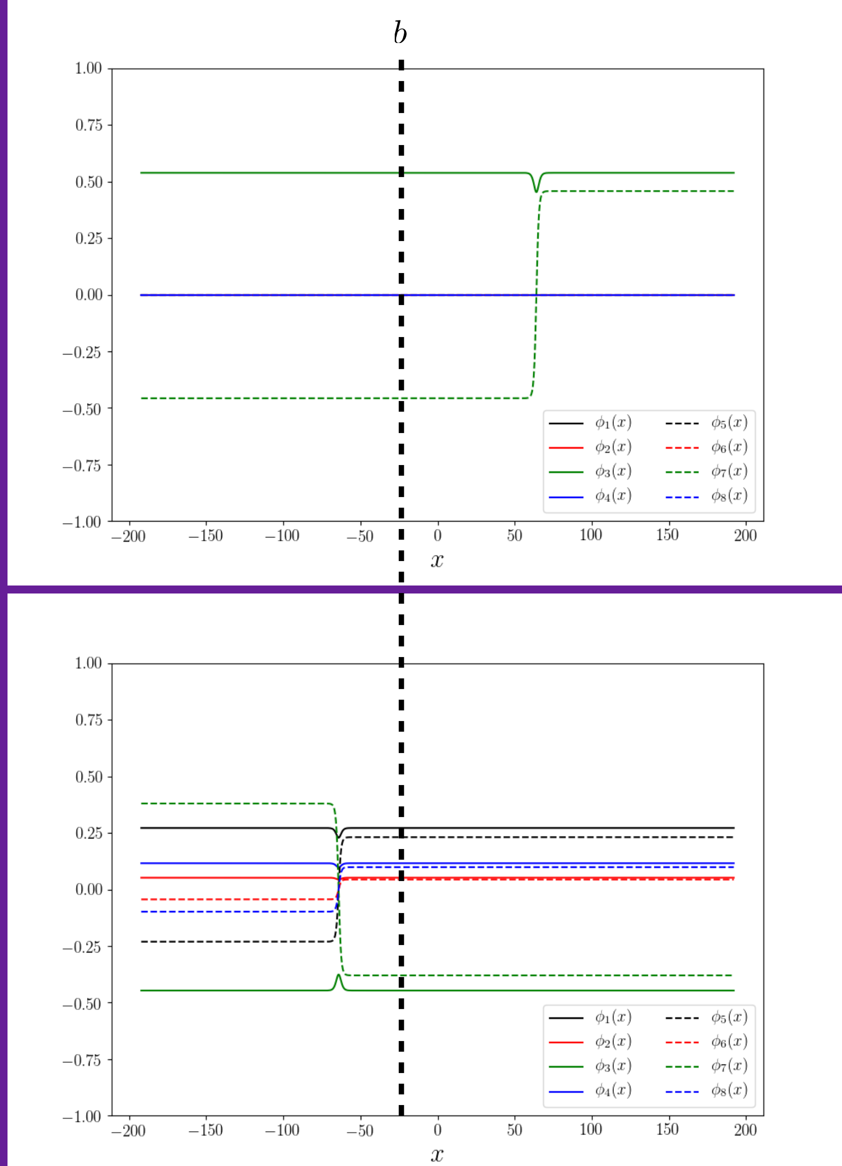


Kink Interaction Energy

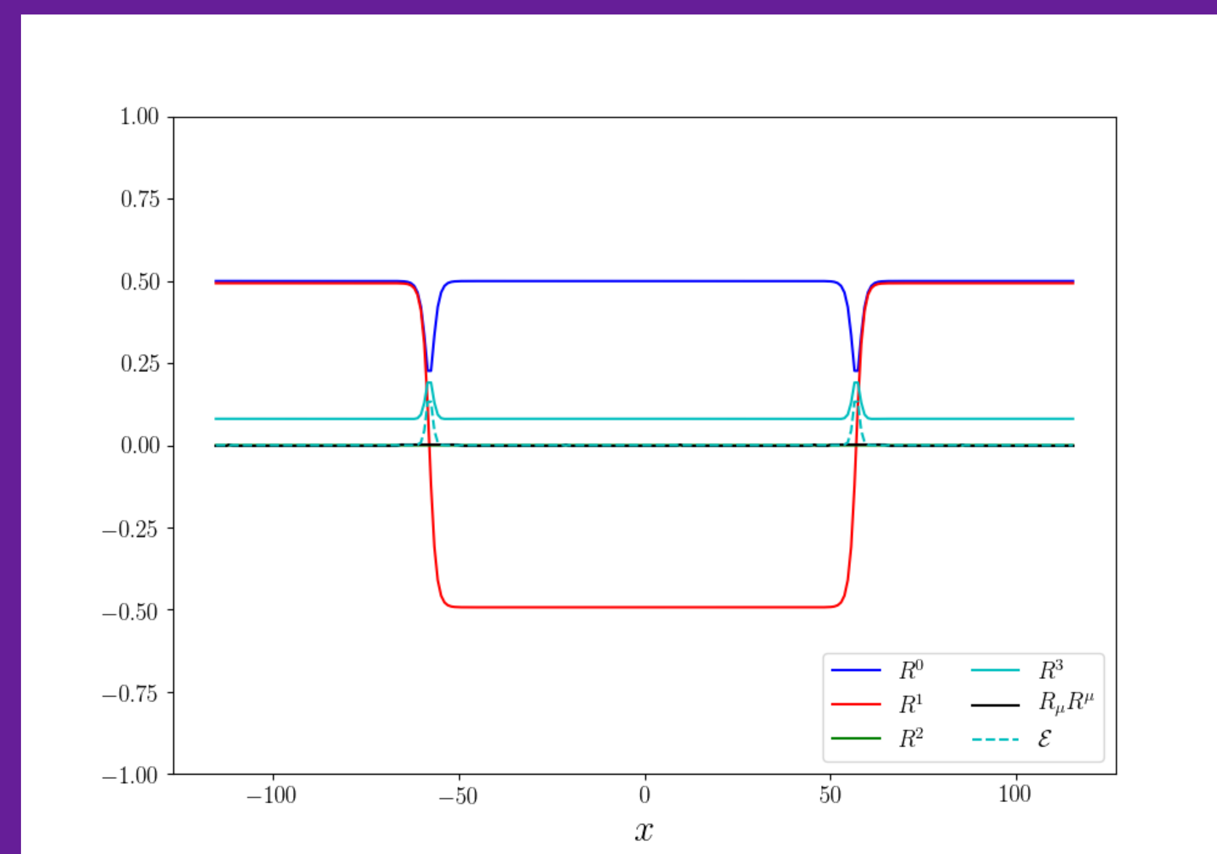
$$\Phi_1(x) = \hat{\Phi}_1(x-a) + U\left[\hat{\Phi}_1(x+a) - \Phi_1^0\right]$$

$$\Phi_2(x) = \hat{\Phi}_2(x-a) - U\left[\hat{\Phi}_2(x+a) - \Phi_2^0\right]$$

$$U = e^{i\theta}\begin{pmatrix} \bar{A} & B \\ -\bar{B} & A \end{pmatrix}$$



$$F = \left[-\Phi_1^{\dagger\prime}\Phi_1' - \Phi_2^{\dagger\prime}\Phi_2' + V(\Phi_1, \Phi_2)\right]_b^\infty$$



Kink Interaction Energy

$$\Phi_1(x) = \hat{\Phi}_1(x-a) + U\left[\hat{\Phi}_1(x+a) - \Phi_1^0\right]$$

$$\Phi_2(x) = \hat{\Phi}_2(x-a) - U\left[\hat{\Phi}_2(x+a) - \Phi_2^0\right]$$

$$U = e^{i\theta}\begin{pmatrix} \bar{A} & B \\ -\bar{B} & A \end{pmatrix}$$

$$F = \left[-\Phi_1^{\dagger\prime}\Phi_1' - \Phi_2^{\dagger\prime}\Phi_2' + V(\Phi_1, \Phi_2)\right]_b^\infty$$

Well-separated kinks: $-a \ll b \ll a$

Linearize in $\hat{\Phi}_i(x+a)$:

$$F = \frac{dE_{\rm int}}{dR} = -(e^{i\theta}A + e^{-i\theta}\bar{A})\left(\rho^2\mu^2 e^{-\mu R} + \sigma^2\nu^2 e^{-\nu R}\right)$$

$$E_{\rm int} = (e^{i\theta}A + e^{-i\theta}\bar{A})\left(\rho^2\mu e^{-\mu R} + \sigma^2\nu e^{-\nu R}\right)$$

Kink separation , $R = 2a$

Summary and Outlook

- 2HDM can admit topological defects
  - 3 accidental symmetries produce DWs
  - Domain wall problem
- Kink Solutions
  - Energy of kinks sets DW domination time
  - Physical parametrisation needed for CP1/2
- Domain Wall Networks
  - Dynamical features not found in kinks
  - Non-standard scaling of DWs
  - Local violation of neutral vacuum condition
- Interaction of Kinks
  - Falls exponentially with kink separation
  - Kinks in different fields can attract/repel

Thanks for listening.

Gauge Fields

$$\partial_\mu F^{\mu\nu,a} + g\varepsilon^{abc} W^b_\mu F^{\mu\nu,c} = -\frac{ig}{2}\left(\Phi_i^\dagger \sigma^a D^\nu \Phi_i - (D^\nu \Phi_i)^\dagger \sigma^a \Phi_i\right)$$

$$\partial_\mu f^{\mu\nu} = -\frac{ig'}{2} Y \left(\Phi_i^\dagger D^\nu \Phi_i - (D^\nu \Phi_i)^\dagger \Phi_i\right)$$

$$f_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g\varepsilon^{abc} W^b_\mu W^c_\nu$$

$$D_\mu = \partial_\mu - \frac{ig}{2}\sigma^a W^a_\mu - \frac{ig'}{2} Y B_\mu$$

U(1) Charge?

$$\Phi_1^0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$$

$$\Phi_2^0 = \frac{1}{\sqrt{2}} \begin{pmatrix} v_+ \\ v_2 e^{i\xi} \end{pmatrix}$$

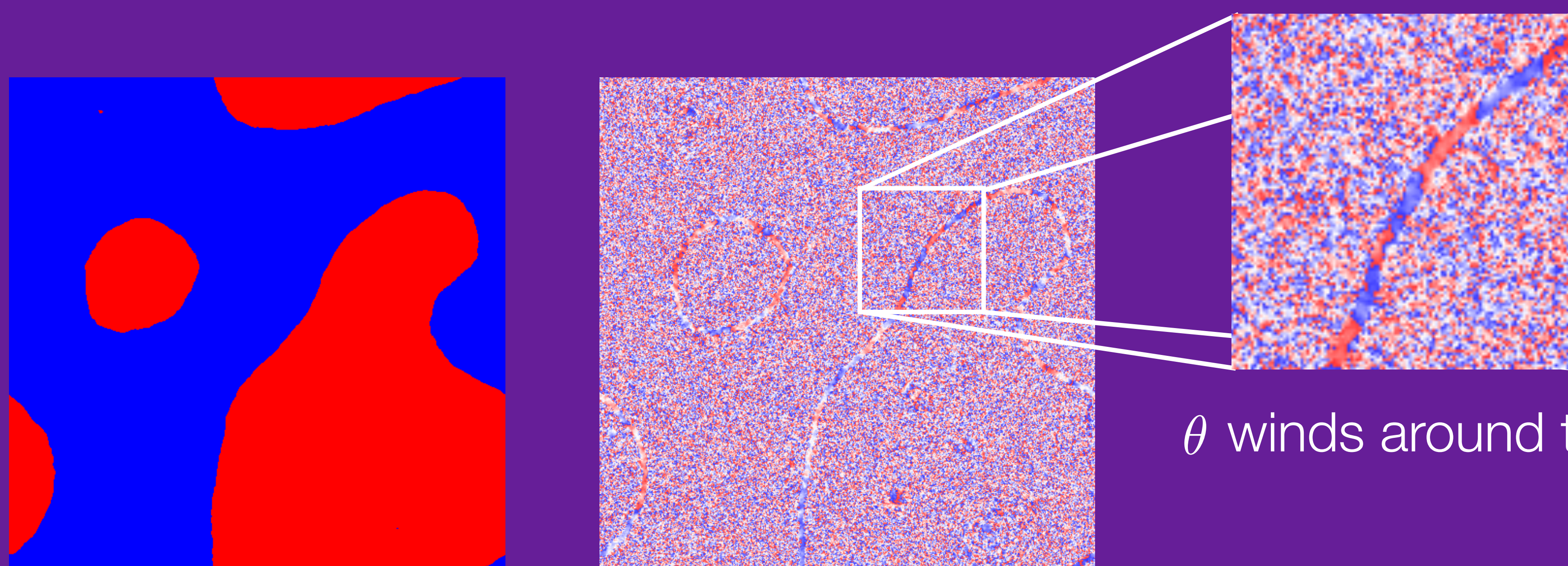
$$\Phi_i = U \Phi_i^0$$

$$U = e^{i\theta} \begin{pmatrix} \bar{A} & B \\ -\bar{B} & A \end{pmatrix}$$

$$R^\mu \to R^A, \; A = 0, 1, ..., 5$$

$$R^4 = \Phi_1^T i\sigma^2 \Phi_2 - \Phi_2^\dagger i\sigma^2 \Phi_1^*$$

$$R^5 = -i \left(\Phi_1^T i\sigma^2 \Phi_2 + \Phi_2^\dagger i\sigma^2 \Phi_1^* \right)$$



θ winds around the wall