Topological Nambu monopole in two Higgs doublet models

Yu Hamada (Kyoto Univ.)

[arXiv:1904.09269] PLB 802 (2020) 135220

[arXiv:2003.08772] JHEP 07 (2020) 004

[arXiv:2007.15587] PRD 102 (2020) 105018

and work in progress...

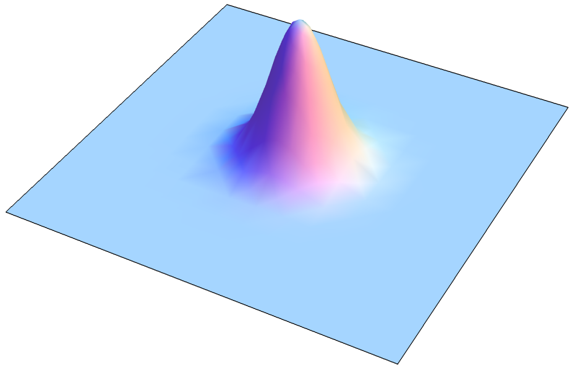
in collaboration with **Minoru Eto (Yamagata U. & Keio U.), Masafumi Kurachi (ICRR), Muneto Nitta (Keio U.)**

素粒子現象論研究会2020 (27th Nov. 2020) @ 大阪市立大学

Introduction

Topological soliton

- **topologically stable excitations in field theories.**



- **Non-perturbative aspects of field theory** that we cannot see in perturbation theory.

Eg.) QCD instanton, …

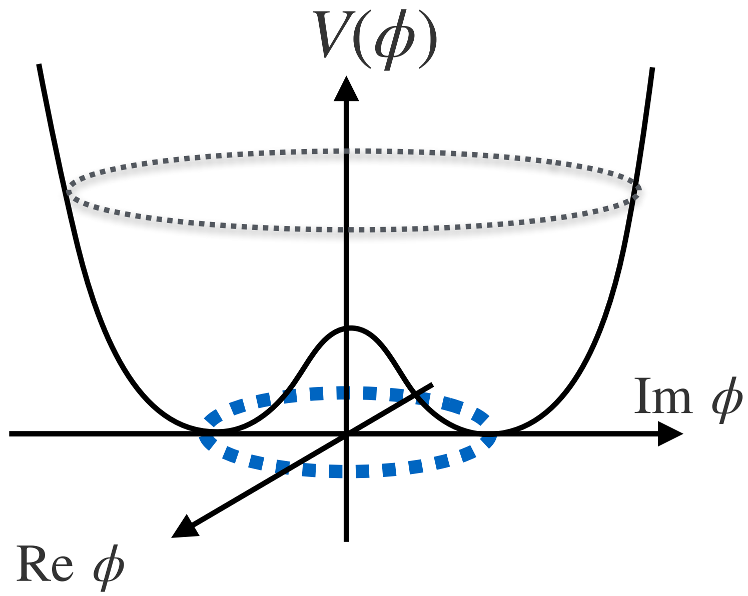
- **Such solitons (or their remnants) are useful to explore New Physics !**

Eg.) Axion string, GUT monopole, domain wall

Eg.) ANO Vortex string

[Abrikosov '58]
[Nielsen-Olesen '73]

- Vortex string is a topological soliton associated with a spontaneously broken U(1) symmetry.

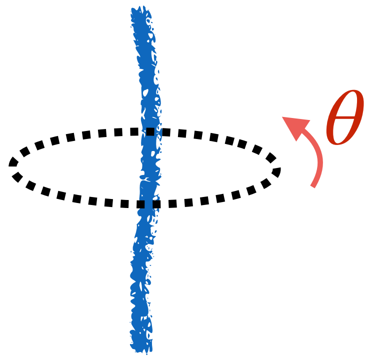


eg.) Abelian-Higgs model:

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$

Vac.: S^1 $\quad (\pi_1(\text{Vac.}) = \mathbb{Z} \neq 0)$

- asymptotic forms: $\begin{cases} \phi(x) \sim ve^{i\theta} \\ A_i(x) \sim i\partial_i\theta \end{cases} \quad (r \to \infty)$



winding # $= 1$ ➧ **topologically stable**

- Magnetic flux tube: $\Phi_B \equiv \int dxdy\, F_{xy} = 2\pi/g$

Eg.) Global string

- If U(1) symmetry is global, a fat string appears **(global string)**.

eg.) Abelian-Higgs model:

$$\mathscr{L} = -\cancel{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + |D_\mu\phi|^2 - V(\phi)$$

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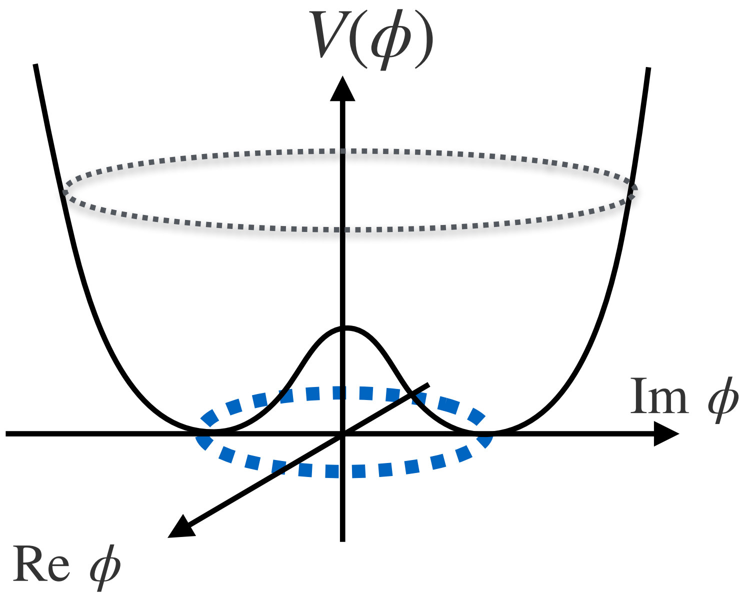

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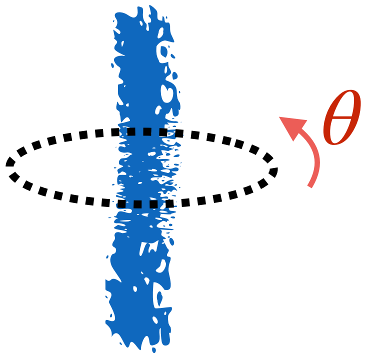

winding # $= 1$ ➡ **topologically stable**

- This is the case of the **axion string.**

Embedding of ANO vortex in SM

[Nambu, '77]

[Vachaspati, '92]

$$D_\mu \Phi = (\partial_\mu - i\frac{g}{2}W_\mu^a \sigma^a - i\frac{g'}{2}Y_\mu)\Phi$$

- **Embed ANO vortex in** $U(1)_Z \subset SU(2)_W \times U(1)_Y$

$$D_\mu \Phi = \begin{pmatrix} 0 & 0 \\ 0 & \underbrace{\partial_\mu + i\frac{g}{2}W_\mu^3 - i\frac{g'}{2}Y_\mu}_{= i\frac{g_Z}{2}Z_\mu} \end{pmatrix} \begin{pmatrix} 0 \\ \Phi_2 \end{pmatrix}$$

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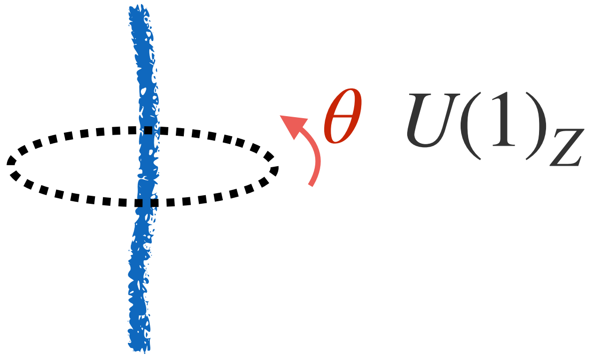
$$\begin{cases} \Phi_2(x) \sim v e^{i\theta} \\ Z_\mu(x) \sim i\partial_\mu \theta \end{cases} \qquad (r \to \infty)$$



embedding ANO vortex in $U(1)_Z$ **part in SM**

- Z-flux tube: $\Phi_Z \equiv \int dxdy\, Z_{xy} = 4\pi/g_Z$ ➡ **called the Z-string**

Nambu monopole in SM

[Nambu, '77]
[Vachaspati, '92]

- The Z string can terminate.

➧ Nambu monopole

- EM magnetic flux : $\Phi_B = 4\pi \sin\theta_W / g$

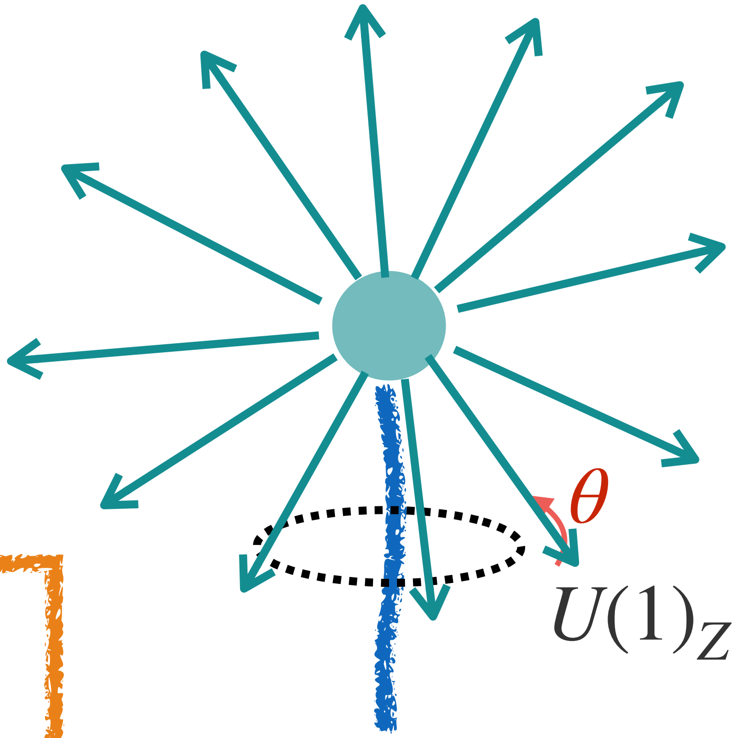
Nambu monopole

||

magnetic monopole + Z string (flux tube)

- However, this is **unstable** because of the string tension.

EM-magnetic flux



Two Higgs doublet model (2HDM)

SM

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \longrightarrow$$

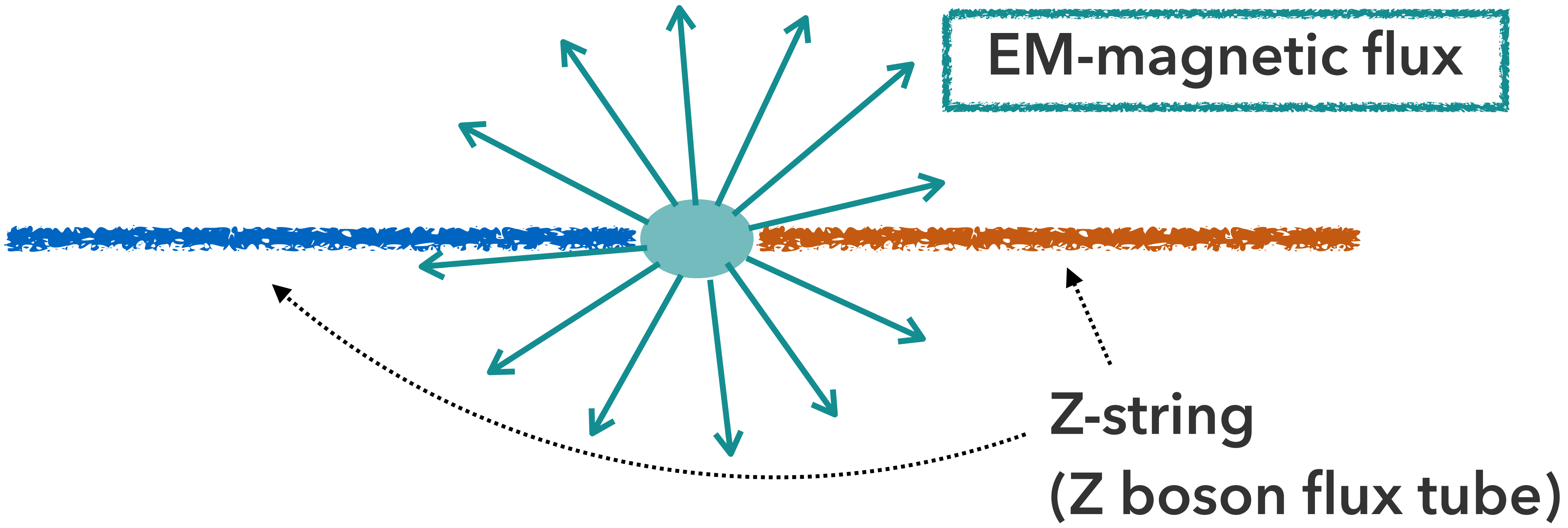
2HDM

$$\Phi_1 = \begin{pmatrix} \phi_{1,1} \\ \phi_{1,2} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_{2,1} \\ \phi_{2,2} \end{pmatrix}$$

- **2HDM is one of popular extensions of SM because of**
  - simple extension of the SM Higgs sector
  - EW baryogenesis
  - SUSY

How about Nambu monopole in 2HDM?

In 2HDM, we will show:



Nambu monopole in 2HDM

=

magnetic monopole + two Z strings

- **topologically stable** when the Higgs potential has two global symmetries (explained later).

Plan of talk

- Introduction ←Done
- Vortex string in 2HDM
- Nambu monopole in 2HDM
- Nambu monopole and EW baryogenesis
- Summary

Vortex string in 2HDM

[Dvali, Senjanovic '93]

[Eto, Kurachi, Nitta '18]

Higgs Potential in 2HDM

$$
\begin{aligned}
V(\Phi_1, \Phi_2) = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right) + \frac{\beta_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\beta_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\
& + \beta_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \beta_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left\{ \frac{\beta_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \mathrm{h.c.} \right\} \\
& + \left\{ \beta_6 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_1^\dagger \Phi_1 \right) + \beta_7 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \mathrm{h.c.} \right\}
\end{aligned}
$$

- We also assume both of the two doublets acquire real VEVs.

$$
\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad v_{EW}^2 = 2(v_1^2 + v_2^2) \simeq (246 \ \mathrm{GeV})^2
$$

- Besides the SM Higgs, there are four additional Higgs bosons.

charged $H^\pm$, CP even neutral H, CP odd neutral A

Higgs Potential in 2HDM

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right) + \frac{\beta_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\beta_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$

$$+\beta_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \beta_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left\{\frac{\beta_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \mathrm{h.c.}\right\}$$

$$+\left\{\beta_6\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_1\right) + \beta_7\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_2\right) + \mathrm{h.c.}\right\}$$

- **Impose two global symmetries :**

Higgs Potential in 2HDM

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$$+\beta_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \beta_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left\{\cancel{\frac{\beta_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \mathrm{h.c.}}\right\}$$

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- **Impose two global symmetries :**

- $U(1)_a$ sym. : $\Phi_1 \to e^{-i\alpha}\Phi_1, \;\; \Phi_2 \to e^{i\alpha}\Phi_2$

(relative phase rotation)

This symmetry is spontaneously broken in the vacuum.

→ The vacuum has a non-trivial topology ($\mathrm{Vac.} \simeq S^3 \times \underline{S^1}$) and **vortex string can exist.**

note: **massless NG boson** (CP-even Higgs) appers

Higgs Potential in 2HDM

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = {}& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(\cancel{m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}} \right) + \frac{\beta_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\beta_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 \\
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\end{aligned}
$$

- **Impose two global symmetries :**

- $(\mathbb{Z}_2)_C$ **sym.** : $\begin{cases} \Phi_1 \to \Phi_2^* \\ \Phi_2 \to \Phi_1^* \end{cases}$ $\simeq$ exchange of two doublets

(not broken in vacuum)

$\longrightarrow$ We obtain $m_{11} = m_{22}\,,\ \beta_1 = \beta_2$ $\longrightarrow$ $\tan\beta \equiv v_2/v_1 = 1$

Higgs Potential in 2HDM

- For later use, we introduce 2 x 2 matrix notation: $|H|^2 \equiv H^\dagger H$

$$H \equiv \left(i\sigma_2 \Phi_1^*,\ \Phi_2 \right) = \begin{pmatrix} \Phi_{1,2}^* & \Phi_{2,1} \\ -\Phi_{1,1}^* & \Phi_{2,2} \end{pmatrix}$$

- We can rewrite the potential as

$$\boxed{V = -m_1^2 \,\mathrm{Tr}|H|^2 + \alpha_1 \,\mathrm{Tr}|H|^4 + \alpha_2 \left(\mathrm{Tr}|H|^2\right)^2 + \alpha_3 \,\mathrm{Tr}\left(|H|^2\sigma_3|H|^2\sigma_3\right)}$$

- **Two global symmetries :**

- $U(1)_a$ sym : $H \to e^{i\alpha} H$

- $(\mathbb{Z}_2)_C$ **sym.** : $H \to (i\sigma^1) H (i\sigma^1)^\dagger$

- $SU(2)_W \times U(1)_Y$ gauge trsf. $H \to \underbrace{e^{i\theta_a\sigma_a}}_{SU(2)_W} H \underbrace{e^{i\theta_Y\sigma_3}}_{U(1)_Y}$

Topological Z-string

[Dvali, Senjanovic '93]

[Eto, Kurachi, Nitta '18]

- Topologically stable vortex solution

(0,1)-string

$$H^{(0,1)} = v \begin{pmatrix} f(\rho) & 0 \\ 0 & h(\rho)e^{i\theta} \end{pmatrix} = v\, e^{i\frac{\theta}{2}}\, e^{-i\frac{\theta}{2}\sigma_3} \begin{pmatrix} f(\rho) & 0 \\ 0 & h(\rho) \end{pmatrix}$$

$$Z_i^{(0,1)} = \frac{\cos\theta_W}{g} \frac{\epsilon_{3ij}\ x^j}{\rho^2} \left(1 - w(\rho)\right)$$

$$H \equiv \left(i\sigma_2\Phi_1^*,\ \Phi_2\right)$$

Topological Z-string

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(0,1)-string

$U(1)_a$ **phase :** $-\pi/2 \sim \pi/2$

$$H^{(0,1)} = v\begin{pmatrix} f(\rho) & 0 \\ 0 & h(\rho)e^{i\theta} \end{pmatrix} = v\,\boxed{e^{i\frac{\theta}{2}}}\,\boxed{e^{-i\frac{\theta}{2}\sigma_3}}\begin{pmatrix} f(\rho) & 0 \\ 0 & h(\rho) \end{pmatrix}$$

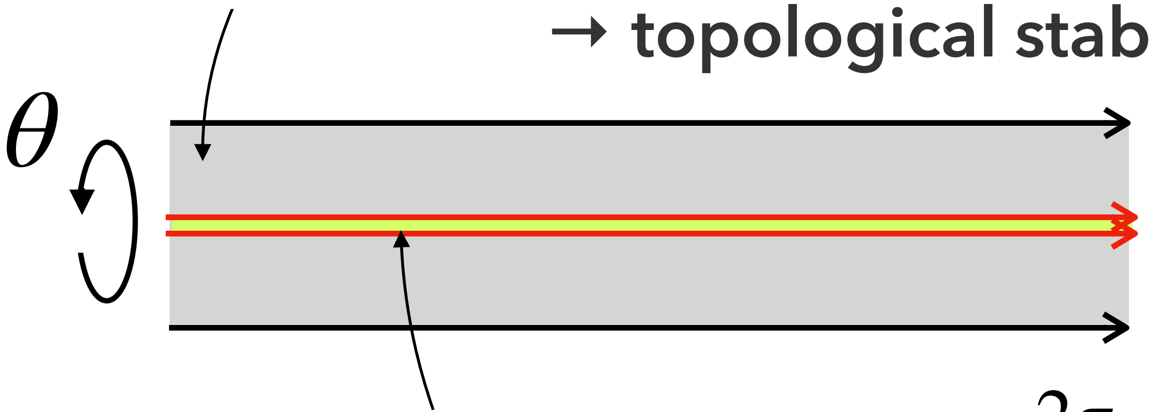
contribute to Z flux

$$Z_i^{(0,1)} = \frac{\cos\theta_W}{g}\frac{\epsilon_{3ij}\ x^j}{\rho^2}\left(1 - w(\rho)\right)$$

$$H \equiv \left(i\sigma_2\Phi_1^*,\ \Phi_2\right)$$

global $U(1)_a$ part (fat)

→ topological stability



confined Z flux $\Phi_Z = \dfrac{2\pi}{g_Z}$

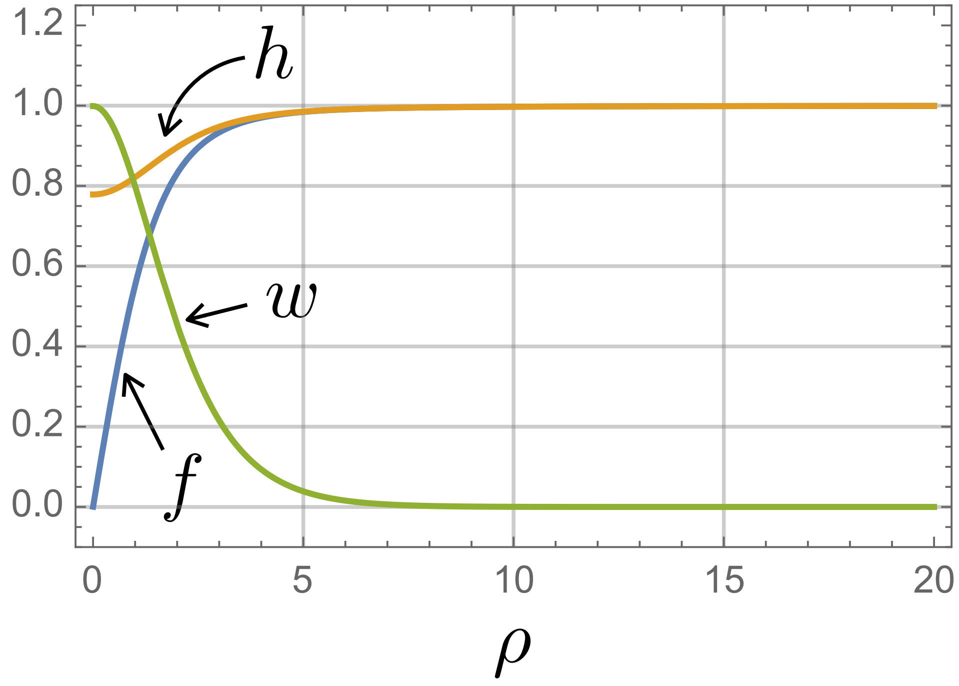


Fig. from arXiv:1805.07015

Two Z-strings

[Eto, Kurachi, Nitta '18]

$$H \equiv \left(i\sigma_2 \Phi_1^*,\ \Phi_2 \right)$$

- **Recall that $(\mathbb{Z}_2)_C$ symmetry is exchange of doublets:**

$$H \to (i\sigma^1) H (i\sigma^1)^\dagger \quad \xleftrightarrow{\text{equivalent}} \quad \begin{cases} \Phi_1 \to \Phi_2^* \\ \Phi_2 \to \Phi_1^* \end{cases}$$

- Due to this symmetry, we have another Z string.

- **(0,1)-string**

$$H^{(0,1)} \sim v \begin{pmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{pmatrix}$$

- **Z-flux:** $\Phi_Z = 2\pi / g_Z$

$(\mathbb{Z}_2)_C$ **trsf.**

$$\Longleftrightarrow$$

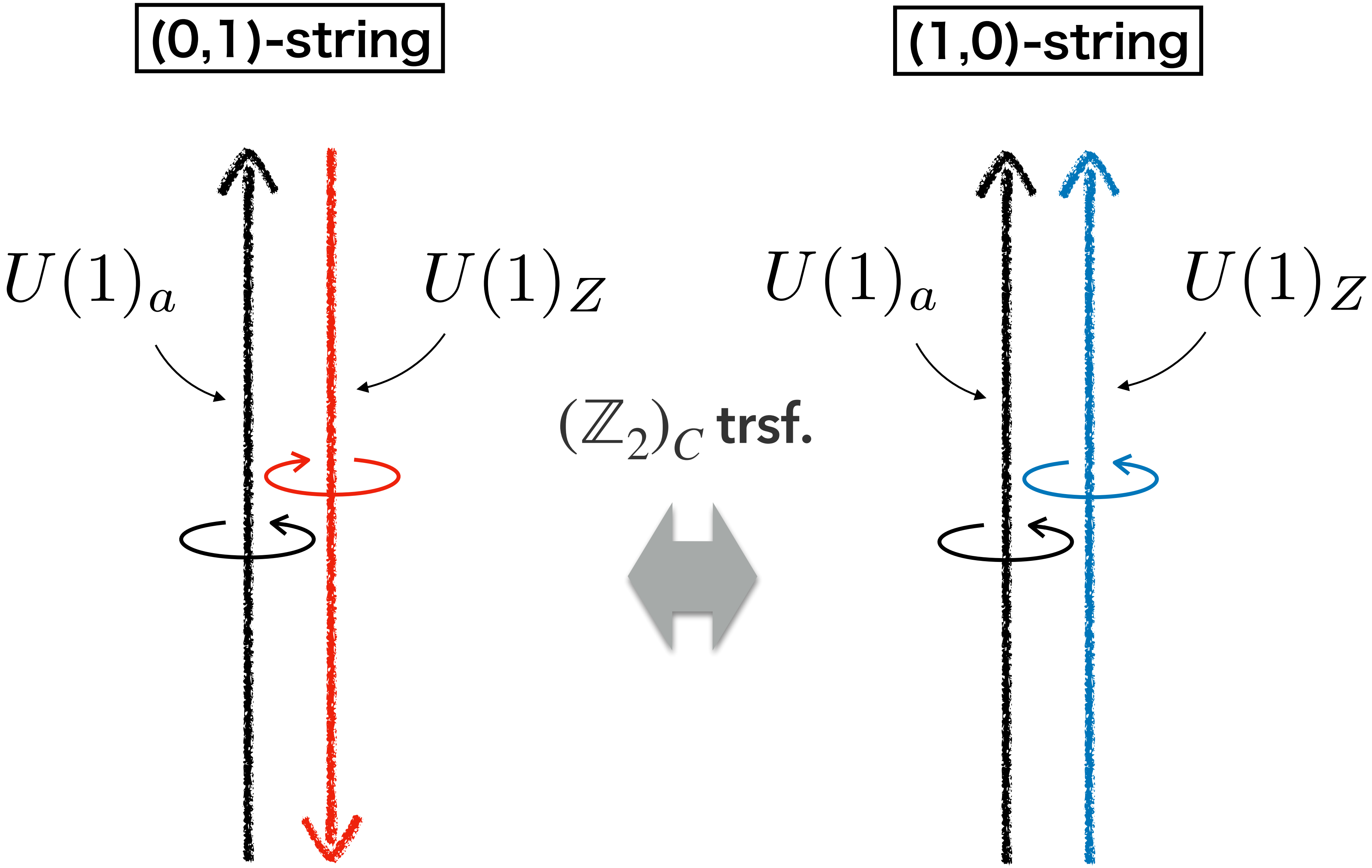
- **(1,0)-string**

$$H^{(1,0)} \sim v \begin{pmatrix} e^{i\theta} & 0 \\ 0 & 1 \end{pmatrix}$$

- **Z-flux:** $\Phi_Z = -2\pi / g_Z$

Tensions of the strings are exactly same.

Two Z-strings



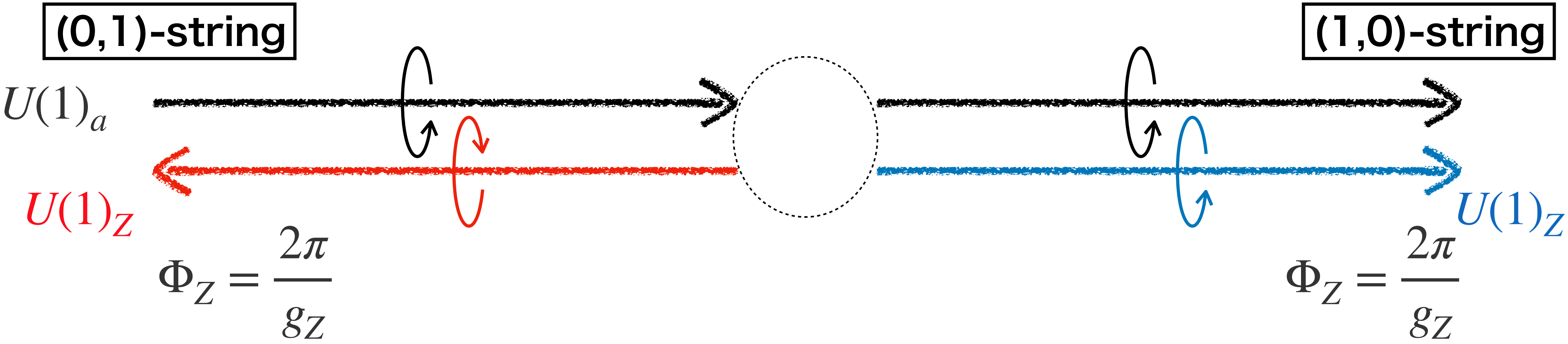
- $U(1)_a$ windings are the same
- Z fluxes are in opposite directions

Nambu monopole in 2HDM

[Eto, **YH**, Kurachi, Nitta 1904.09269, 2003.08772]

[Eto, **YH**, Nitta 2007.15587]

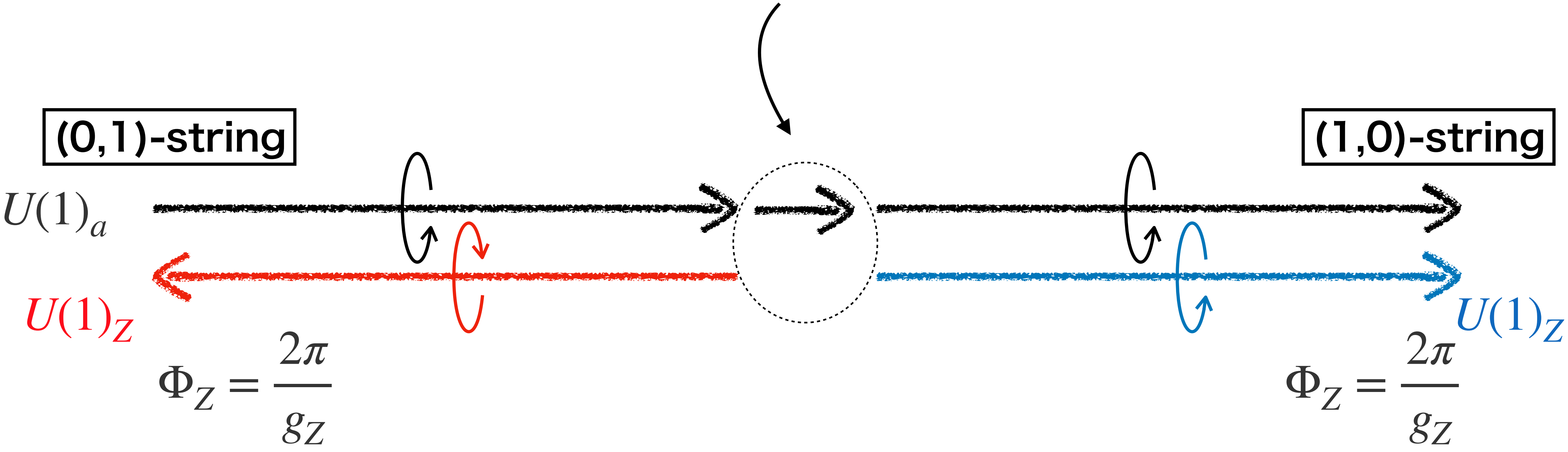
Connect two Z strings



Connect two Z strings

$U(1)_a$ **winding must be smoothly connected**

(topological charge)



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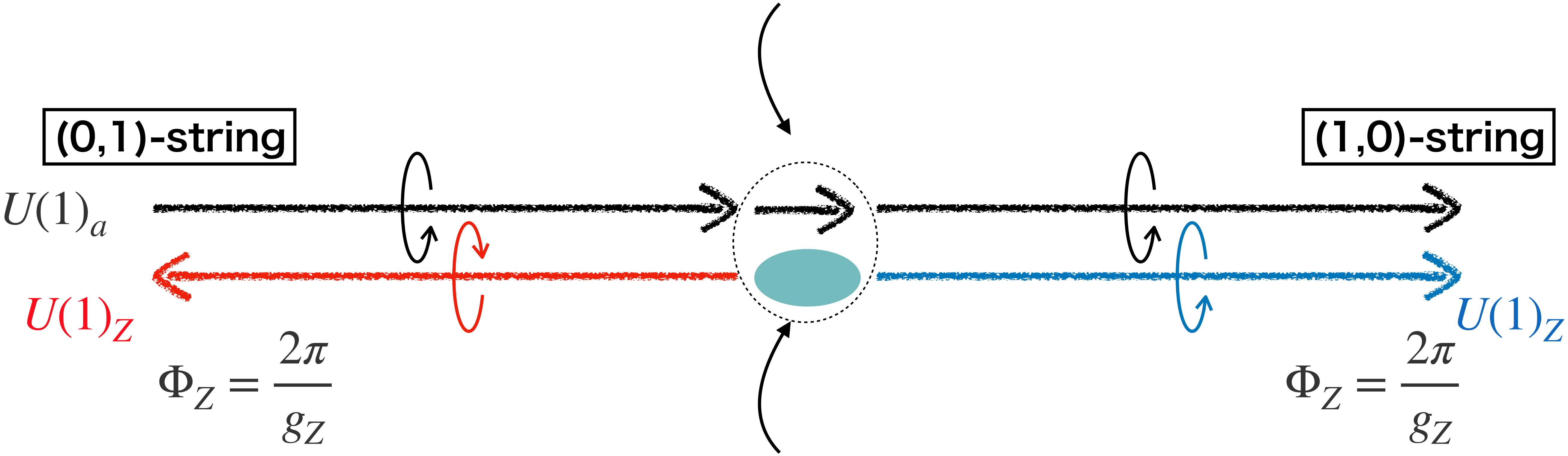
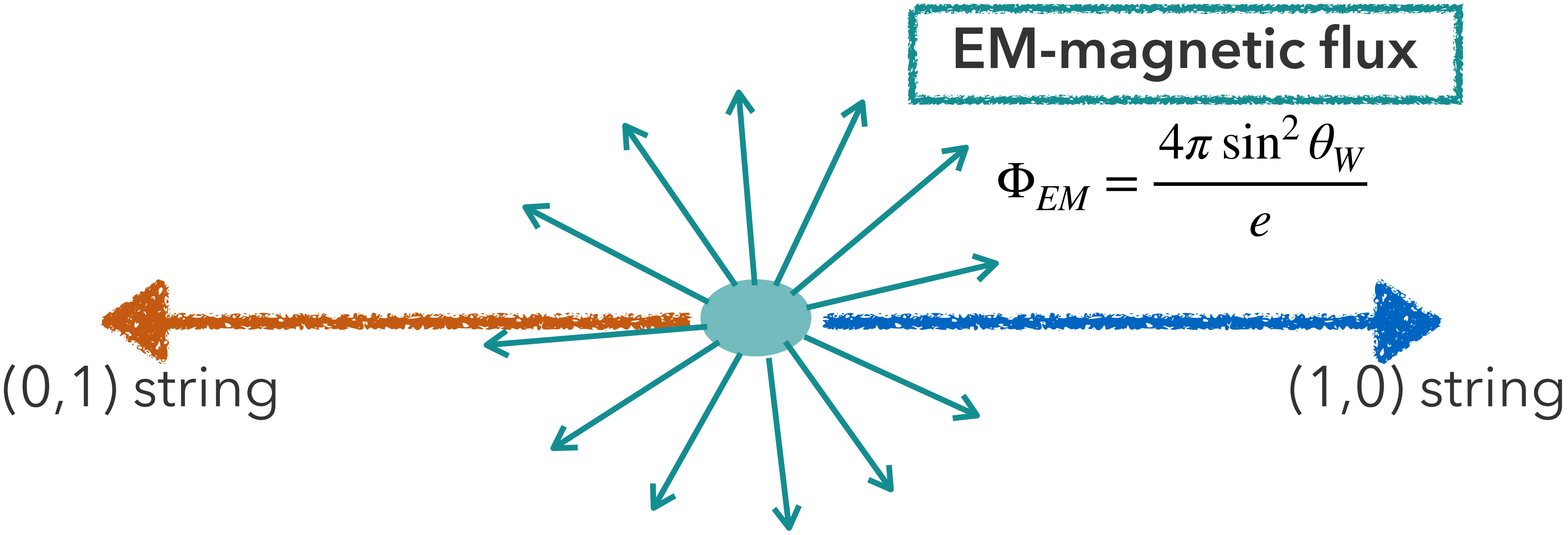


We need a source for Z fluxes

Picture of Nambu Monopole in 2HDM

- This connection behaves as a magnetic monopole
  = **Nambu monopole**



$$\Phi_{EM} = \frac{4\pi \sin^2 \theta_W}{e}$$

- It can be regarded as a $(\mathbb{Z}_2)_C$ **sym kink.**

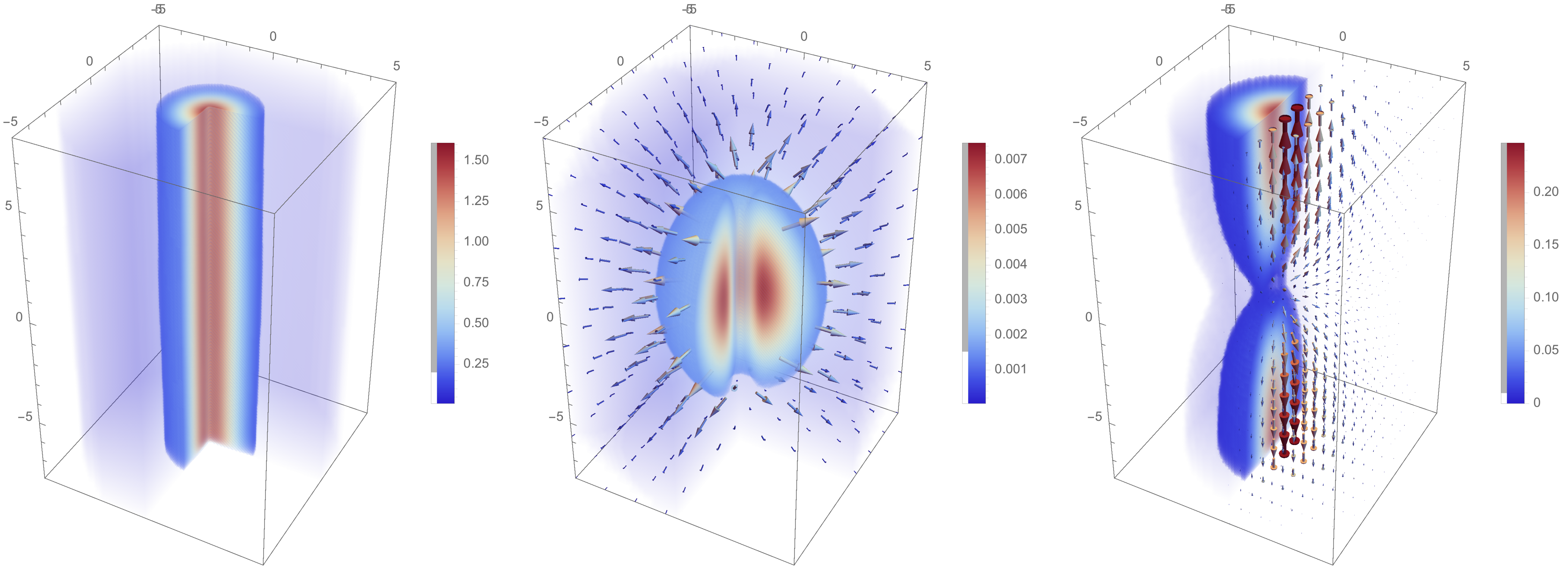
($\alpha_3 \lesssim 0$ is necessary)

→ **topological stability**

- In other words, **the tensions of the strings are balanced.**

Numerical Result

- Numerical solution to EOMs



(a) energy density (b) magnetic flux (c) Z flux

with $\sin^2\theta_W = 0.23,\ m_W = 80\ \text{GeV},\ v_{\text{EW}} = 246\ \text{GeV},\ \tan\beta = 1$

$$m_h = 125\ \text{GeV},\ m_A = m_{H^\pm} = 400\ \text{GeV},\ m_H = 0$$

- imposed $\mathbb{Z}_2$ symmetry: $\Phi_1 \to +\Phi_1 \quad \Phi_2 \to -\Phi_2$

よく聞かれる質問：

$U(1)_a$を課すとNG bosonが出て実験的に死んでるのでは？

よく聞かれる質問：

$U(1)_a$を課すとNG bosonが出て実験的に死んでるのでは？

A: そのとおりです

Two options to avoid constraint

1. singlet extension

2HDM

$U(1)_a$ sym:

$\longrightarrow$

add singlet S

DFSZ axion model

$U(1)_{PQ}$ sym:

NG boson = axion

DFSZ vortex string → 阿部君のトーク

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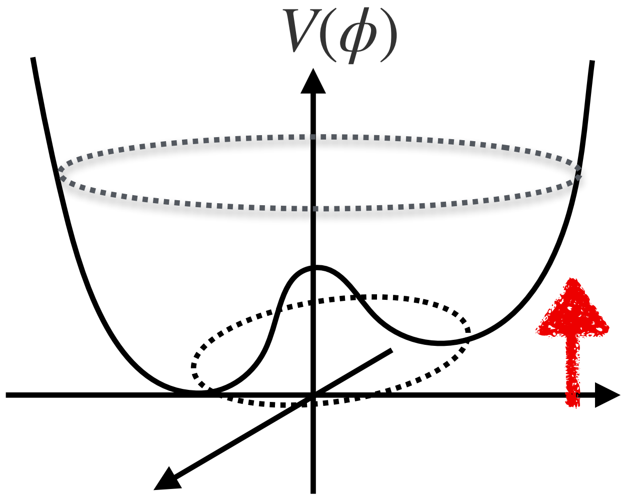
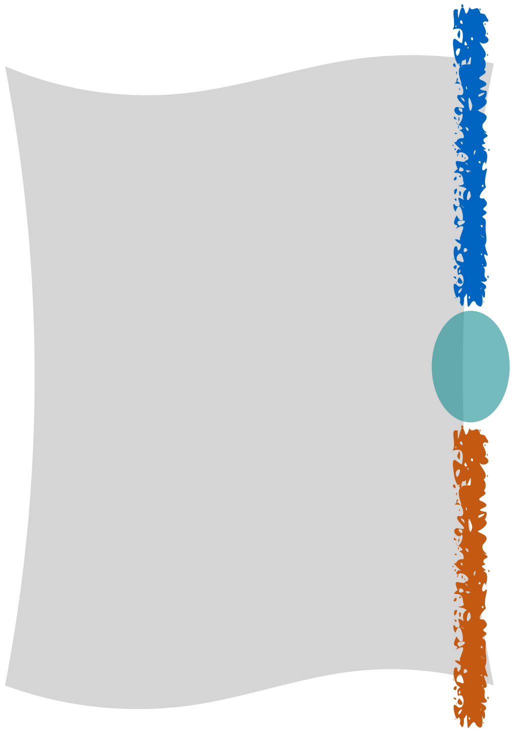
2. **explicit breaking :** $\cancel{U(1)}_a$ (mass of CP even Higgs: $m_H \neq 0$)

$\longrightarrow$ **wall (membrane) attaches**





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$\xrightarrow{\text{add singlet } S}$

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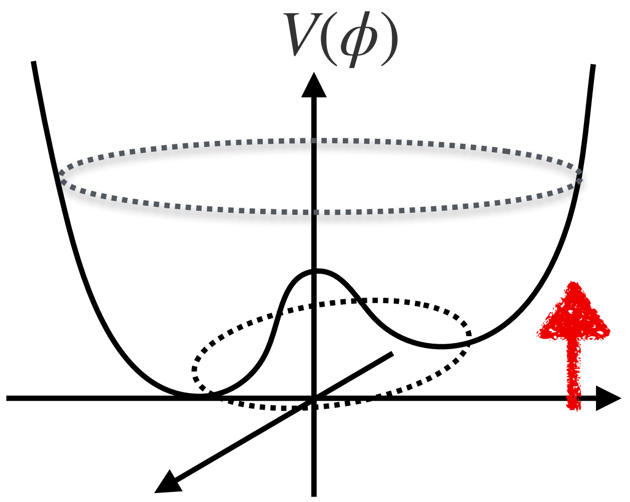
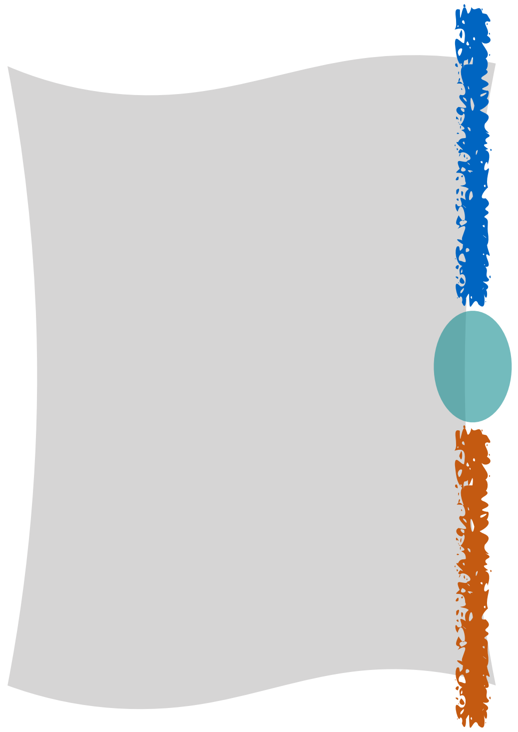


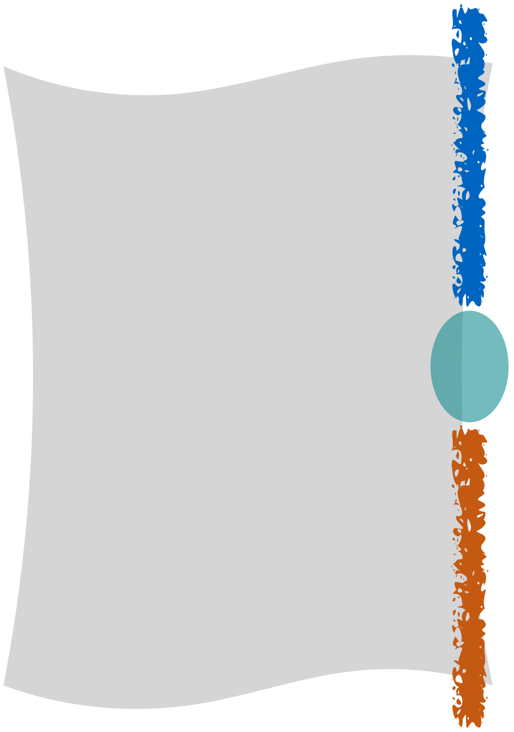


Wall stability

- NG boson becomes massive CP even Higgs: $m_H \neq 0$

case1) $0 < m_H \lesssim m_h \simeq 125\,\mathrm{GeV}$

case 2) $m_H \gtrsim m_h$



$$H \sim \underbrace{e^{i\frac{\theta}{2}}}_{U(1)_a} \underbrace{e^{-i\frac{\theta}{2}\sigma_3}}_{U(1)_Z} v\,\mathbf{1}$$

metastable wall

$$H \sim \underbrace{e^{-i\theta\sigma_3}}_{U(1)_Z} v\,\mathbf{1}$$

wall vanish

Wall stability

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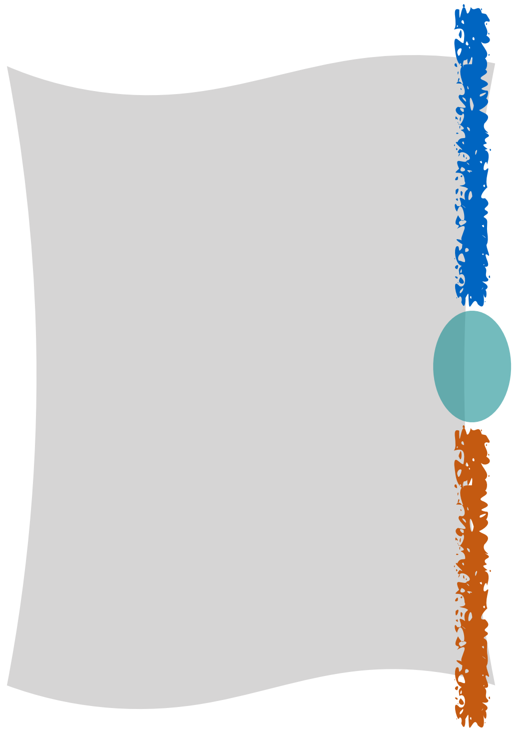
case 2) $m_H \gtrsim m_h$

monopole is not stable (not static)



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metastable wall

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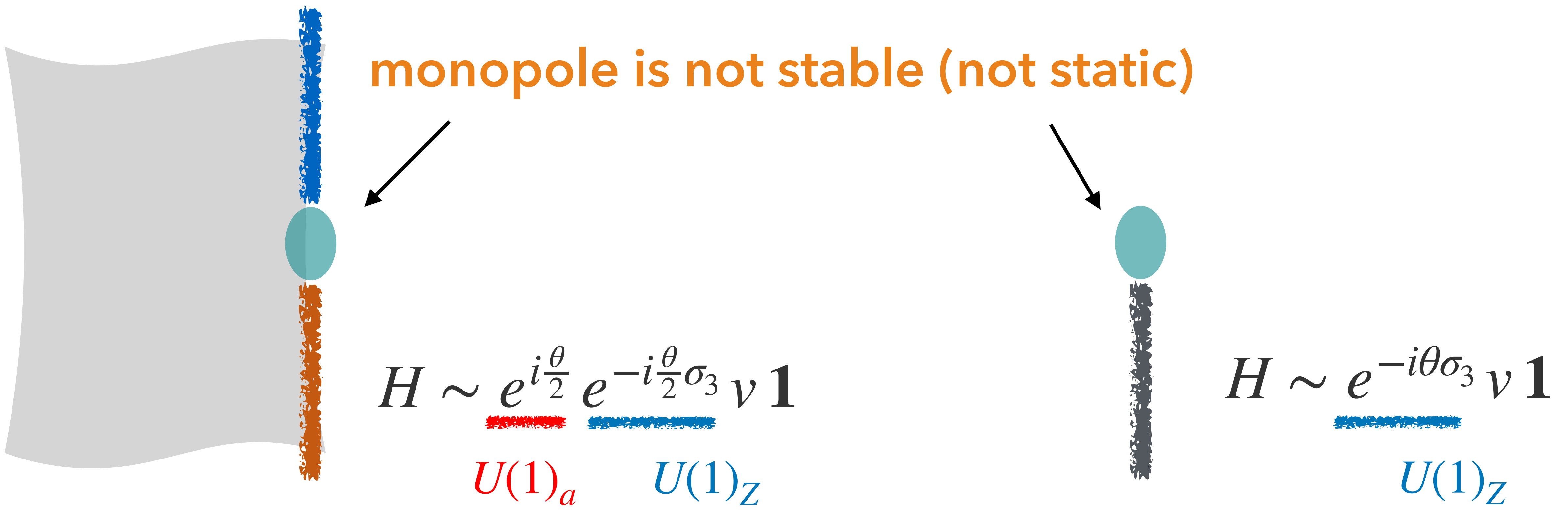
case1) $0 < m_H \lesssim m_h \simeq 125\,\mathrm{GeV}$

case 2) $m_H \gtrsim m_h$



monopole is not stable (not static)

$$H \sim \underbrace{e^{i\frac{\theta}{2}}}_{U(1)_a}\,\underbrace{e^{-i\frac{\theta}{2}\sigma_3}}_{U(1)_Z}\,v\,\mathbf{1}$$

$$H \sim \underbrace{e^{-i\theta\sigma_3}}_{U(1)_Z}\,v\,\mathbf{1}$$

metastable wall

wall vanish

↓

same as Nambu monopole in SM

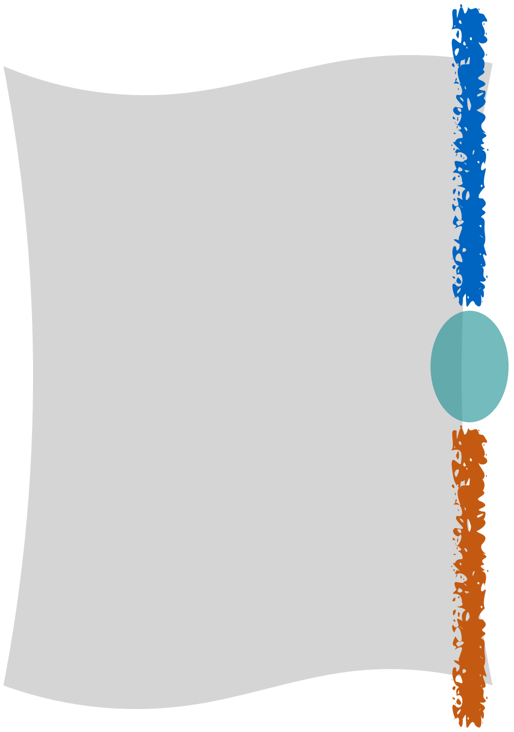
Wall stability

- NG boson becomes massive CP even Higgs: $m_H \neq 0$

case1) $0 < m_H \lesssim m_h \simeq 125\,\mathrm{GeV}$

case 2) $m_H \gtrsim m_h$

monopole is not stable (not static)



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metastable wall

$$H \sim \underbrace{e^{-i\theta\sigma_3}}_{U(1)_Z}\,v\,\mathbf{1}$$

wall vanish

↓

same as Nambu monopole in SM

- **case 2 reduces to the SM case** 😭

Nambu monopole and Electroweak baryogenesis

[Eto, **YH**, Nitta, work in progress]

Summary

- Nambu monopole = magnetic monopole + two Z-strings
- Key symmetries for the stability: $U(1)_a$ & $(\mathbb{Z}_2)_C$
- explicit breaking of $U(1)_a$: CP even Higgs is massive $m_H \neq 0$
- For the scenario $m_H \gtrsim m_h$, the Nambu monopole reduces in the SM case and is unstable.
- For $m_H \gtrsim m_h$, Nambu monopole washes out baryon # produced by EW baryogenesis.

Backup

Note on CP symmetry

- $(\mathbb{Z}_2)_C$ **sym.** : $\begin{cases} \Phi_1 \to \Phi_2^* \\ \Phi_2 \to \Phi_1^* \end{cases}$ $\simeq$ exchange of two doublets

- Although this symmetry looks different from the ordinary CP, **they are completely equivalent.**

- In 2HDM, one can freely change the basis of the doublets.

$$\Phi_i \to \Phi_i' = \sum_{j=1,2} U_{ij}\Phi_j \qquad U \in U(2)$$

- For $U = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ -i & i \end{pmatrix}$, **CP** : $\begin{cases} \Phi_1' \to \Phi_1'^* \\ \Phi_2' \to \Phi_2'^* \end{cases}$

ordinary CP!

Be more realistic!

- Unfortunately, the symmetries we have imposed should be **explicitly broken for realistic models.**
  - **Mass for NG boson (CP-even Higgs)**

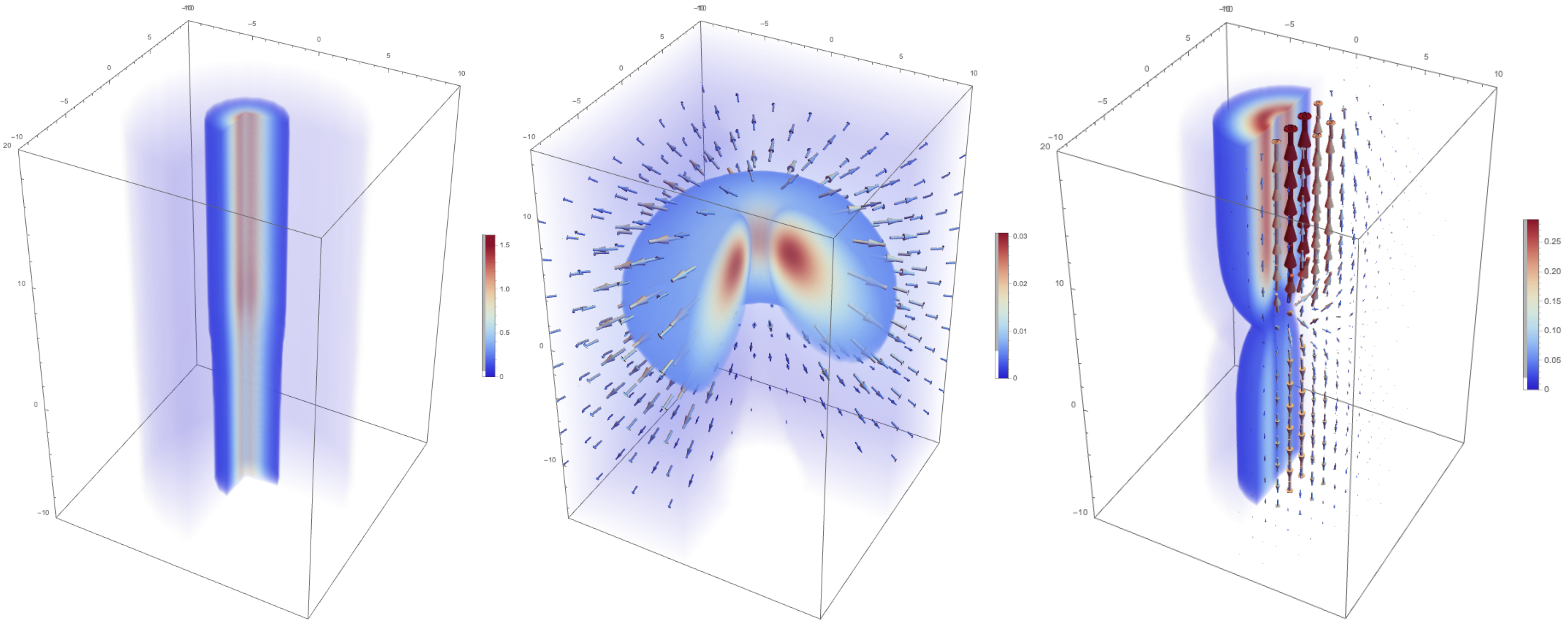
$$\longrightarrow \quad ✗ \qquad U(1)_a \text{ sym. : } \Phi_1 \to e^{-i\alpha}\Phi_1, \quad \Phi_2 \to e^{i\alpha}\Phi_2$$

  - **Yukawa couplings breaks CP sym.**

$$\longrightarrow \quad ✗ \qquad \textbf{CP sym. : } \begin{cases} \Phi_1 \to \Phi_2^* \\ \Phi_2 \to \Phi_1^* \end{cases}$$

Let us consider CP-broken case ! (keep $U(1)_a$ sym.)

Numerical result for $(\mathbb{Z}_2)_C$ -broken case



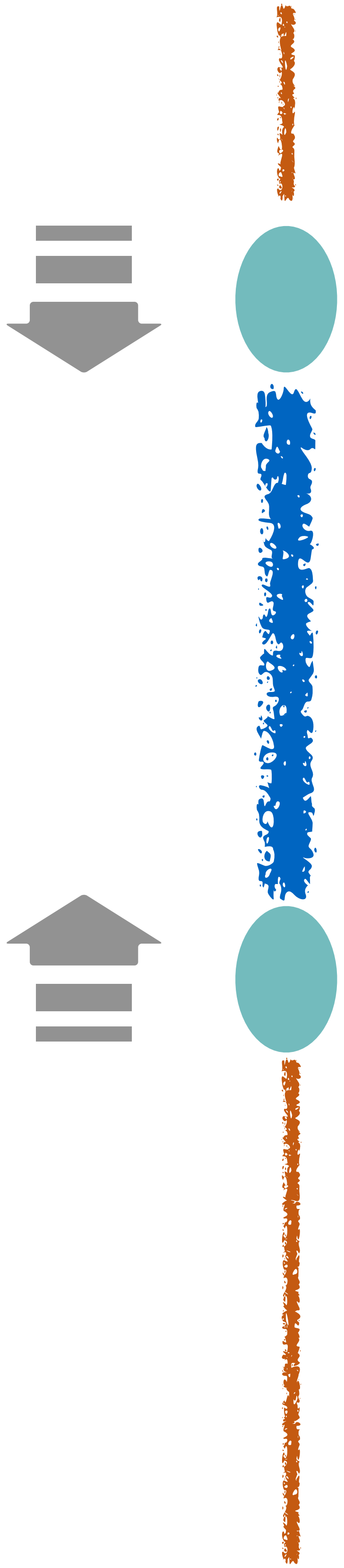
energy magnetic flux Z-flux

- **One Z string becomes heavier and fatter.**

$$\sin^2\theta_W = 0.23,\ m_W = 80\ \text{GeV},\ v_{\text{EW}} = 246\ \text{GeV},\ \tan\beta = 1.3$$

$$m_h = 125\ \text{GeV},\ m_H = 400\ \text{GeV},\ m_{H^\pm} = 800\ \text{GeV}$$

Dynamics of Nambu monopole



- The monopole is pulled by the heavier string

  → **accelerates and emits EM radiation!**

- After the acceleration, **the monopole collides to the anti-monopole on the string.**

  → **unstable**

- Such collision events can occur in the early universe, and the max kinetic energy is

$$K_{max} \sim (\cos 2\beta)^{1/4}\, 10^{11}\,\mathrm{GeV} \qquad \tan\beta \equiv v_2/v_1$$

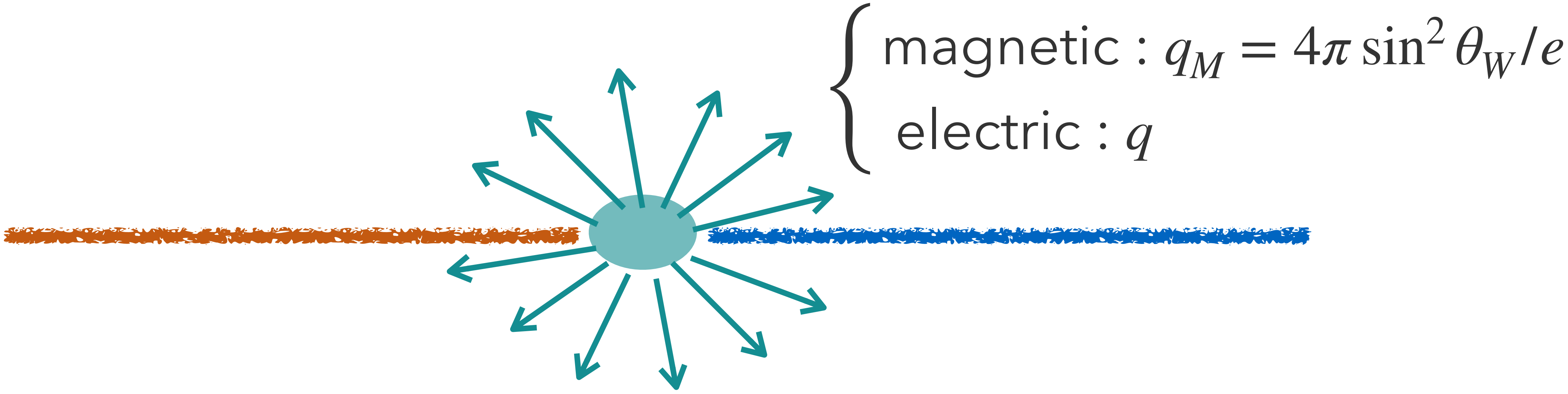
$\Rightarrow$ **``Cosmological Monopole Collider''**

The remnants could be observed by astrophysical sources.

Dyon in 2HDM

- **Dyon : solitons with magnetic and electric charges**
  - give stationary time-dependence to the monopole

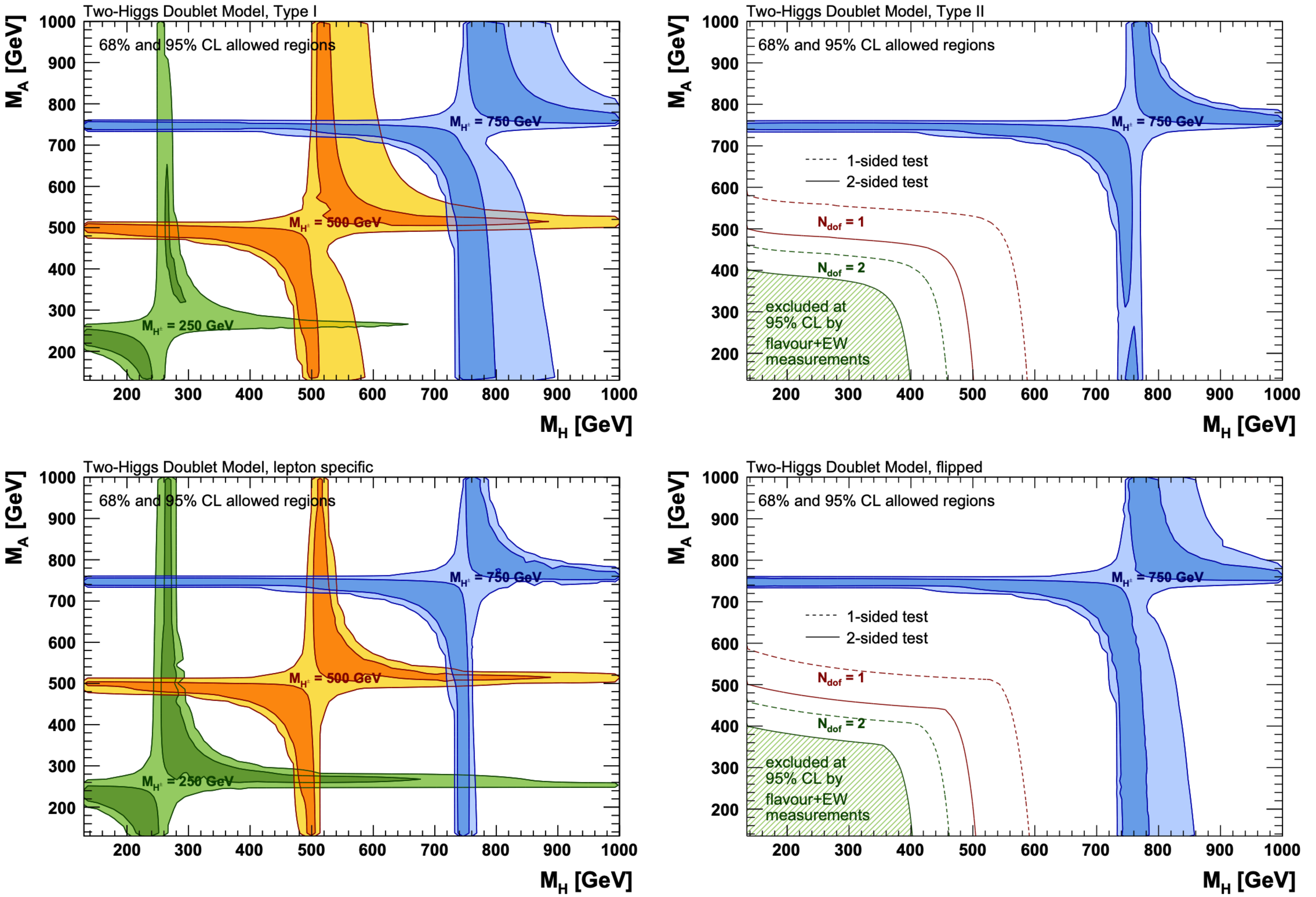
$$\longrightarrow \boxed{\text{electric: } q = ne} \qquad n \in \mathbb{Z}$$



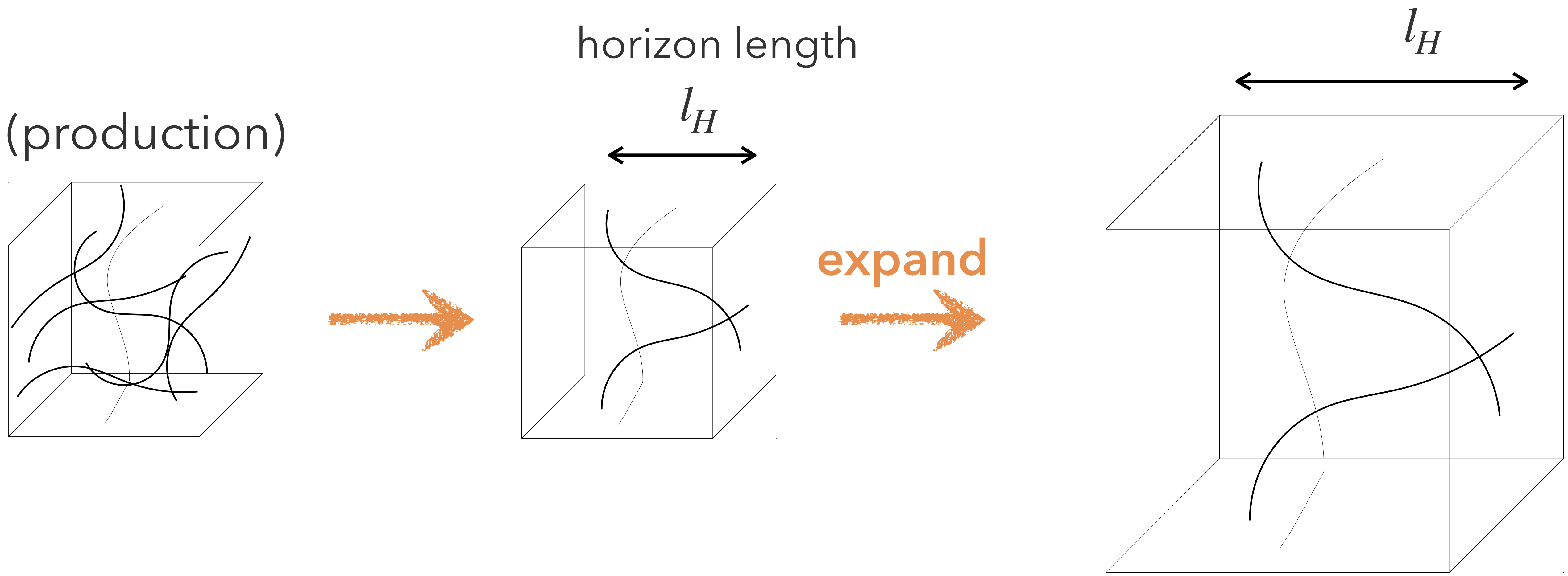
Dyon with two Z strings

Global fit for Higgs masses

[arXiv:1803.01853]



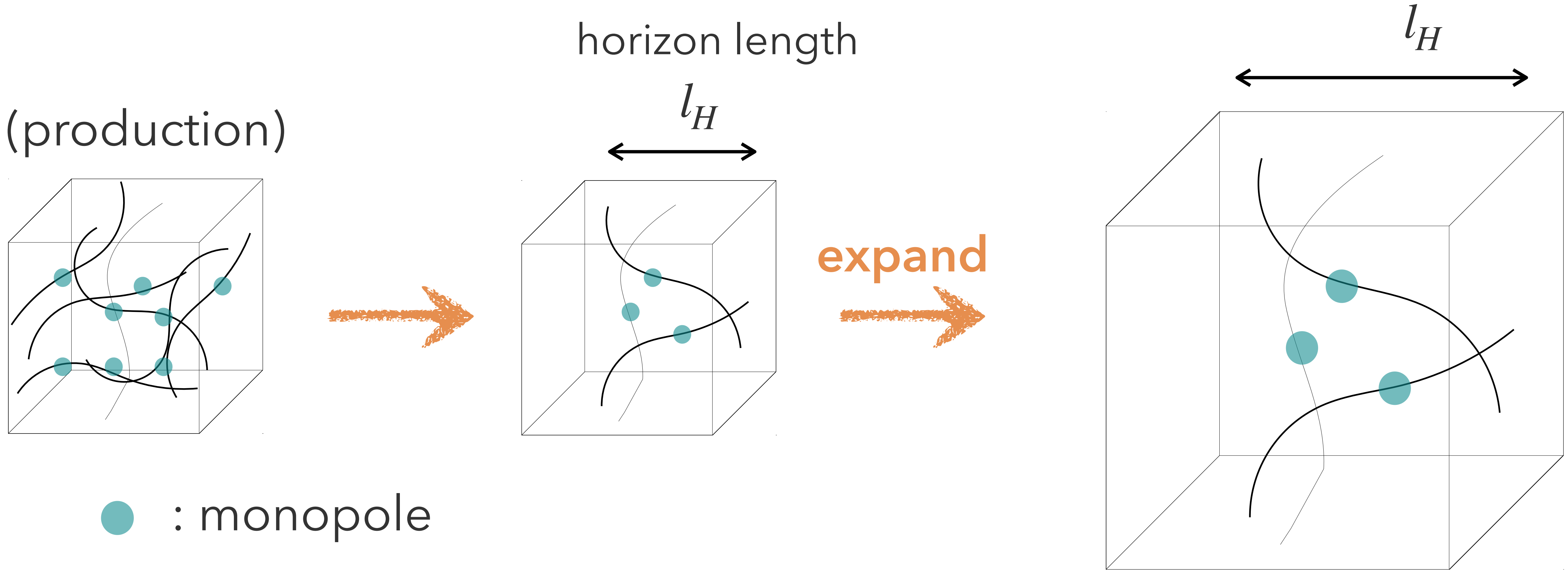
Cosmological history of monopoles



- In simple modes like axion strings, cosmic string network is produced during the phase transition, and then immediately reaches to ``scaling region''.

typical length $\sim l_H$

Cosmological history of monopoles

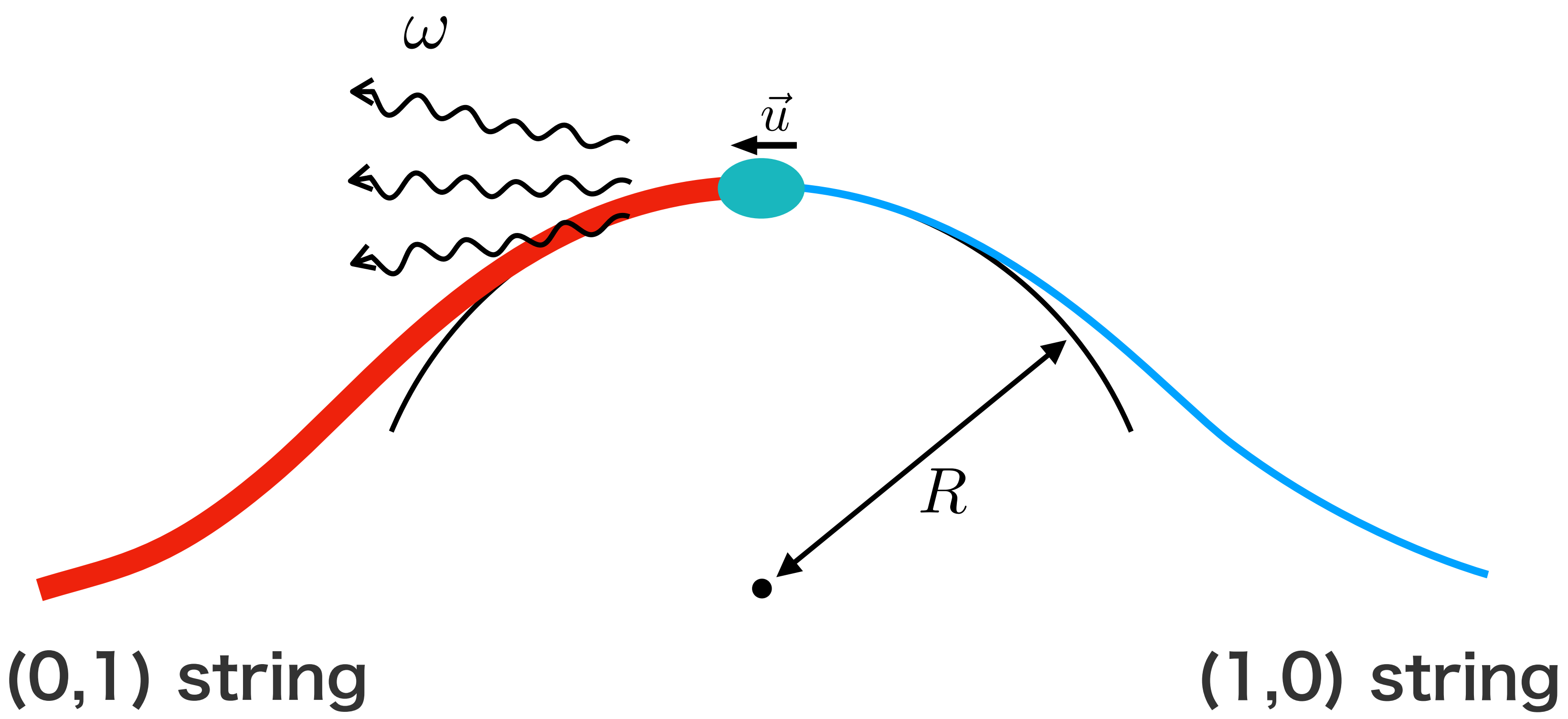


- In simple modes like axion strings, cosmic string network is produced during the phase transition, and then immediately reaches to ``scaling region''.

typical length $\sim l_H$

- We simply assume that this is also true for our case of **the Z strings with the monopole.**

Cosmological Monopole Collider



- The monopole emits radiations depending on the radius of the curvature R like a charged particle.
- From the assumption, R is naturally taken as the horizon scale l_H .

Synchrotron accelerator with the horizon size!

Cosmological Monopole Collider

- The accelerated monopole collides to the anti monopole with the kinetic energy K :

$$K = \gamma M_{mon.} \sim (R^2 \Delta T / q_M^2)^{1/4} \, M_{mon.}$$

$$\sim \boxed{(\cos 2\beta)^{1/4} \; 10^{11} \; \mathrm{GeV}}$$

$$\tan\beta \equiv v_2/v_1$$

$$q_M \sim 1$$

$$\Delta T \sim v_{EW}^2 \cos 2\beta$$

$$R \sim l_H \sim \frac{M_{pl}}{\sqrt{g_*} T_{th}^2}$$

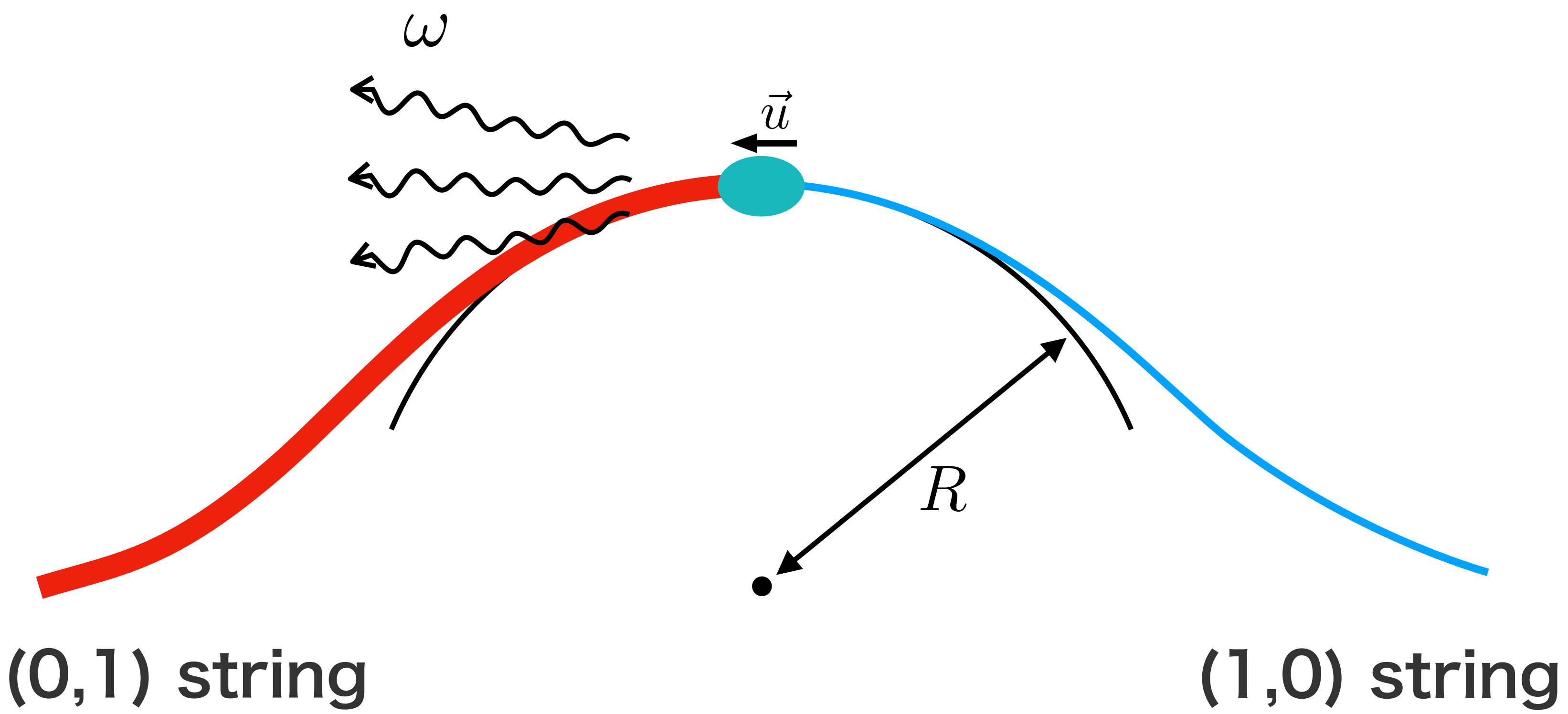
$$T_{th} \sim v_{EW}$$

$$M_{mon.} \sim 1 \; \mathrm{TeV}$$

- This high energy collision event **can produce heavy particles** in the early universe, and their remnants could be observed by astrophysical observations. (cf. ``cosmological collider'')

[Arkani-Hamed, Maldacena, '15]

Cosmological Monopole Collider



- We approximate the monopole to a point-like object and analyze it in the classical mechanics:

$$\boxed{\frac{d}{dt}K + P_{rad} = P_{string}}$$

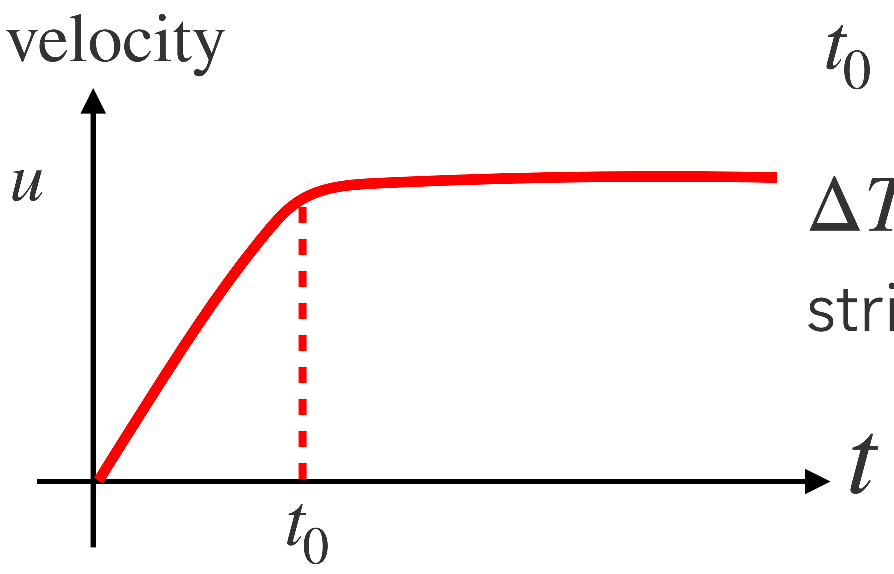
K: kinetic energy of monopole

P_{rad} : energy loss by radiation

P_{string} : energy gain from string

Cosmological Monopole Collider

- The monopole is immediately accelerated to u



$t_0 \sim 1/\Delta T$

ΔT : difference of string tension

The accelerated rapidity γ is determined by $P_{rad} = P_{string}$:

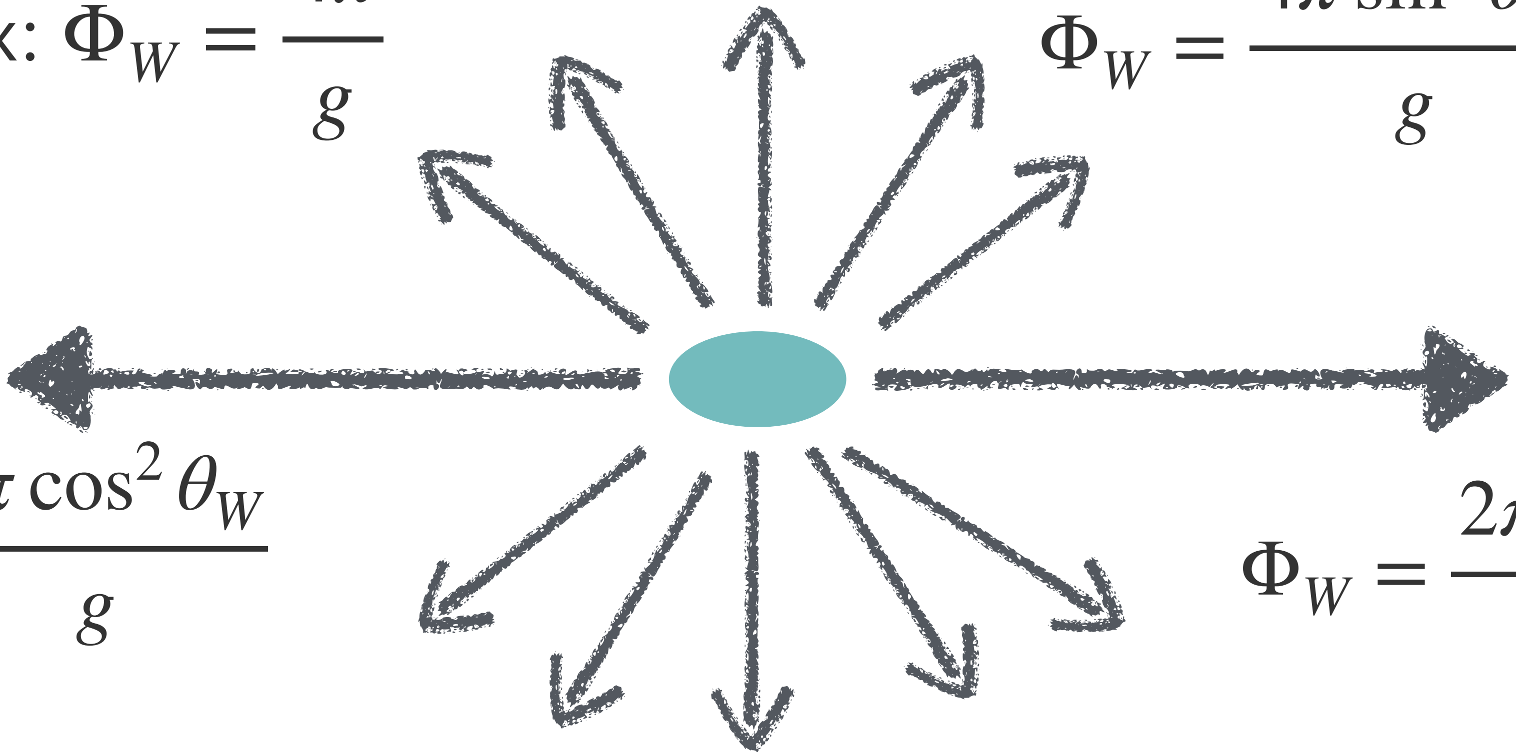
$$\Leftrightarrow \frac{q_M^2 u^4 \gamma^4}{R^2} \sim u\Delta T$$

$$\therefore \gamma = 1/(1-u^2)^{1/2} \sim (R^2 \Delta T/q_M)^{1/4} \sim (\cos 2\beta)^{1/4} \ 10^8$$

Flux matching

- $SU(2)_W$ flux: $\Phi_W = \dfrac{4\pi}{g}$

$$\Phi_W = \frac{4\pi \sin^2\theta_W}{g}$$

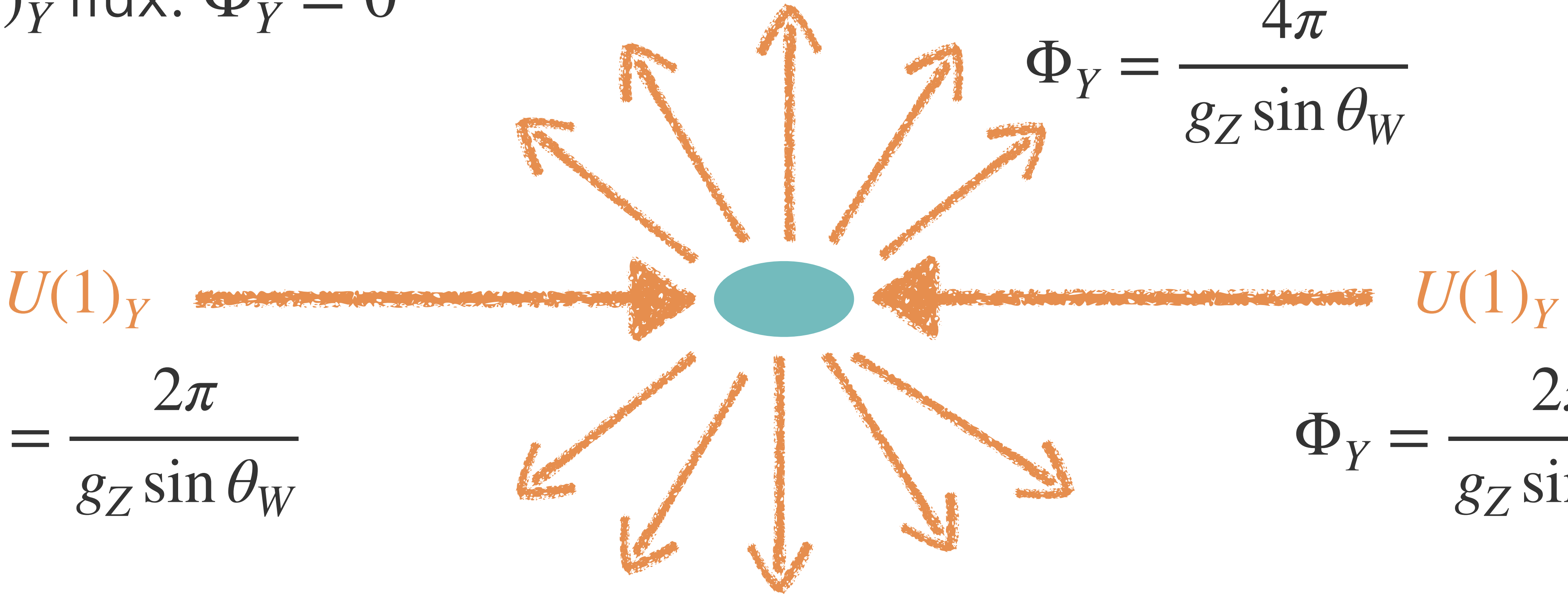


$$\Phi_W = \frac{2\pi \cos^2\theta_W}{g}$$

$$\Phi_W = \frac{2\pi \cos^2\theta_W}{g}$$

- $U(1)_Y$ flux: $\Phi_Y = 0$

$$\Phi_Y = \frac{4\pi}{g_Z \sin\theta_W}$$



$$\Phi_Y = \frac{2\pi}{g_Z \sin\theta_W}$$

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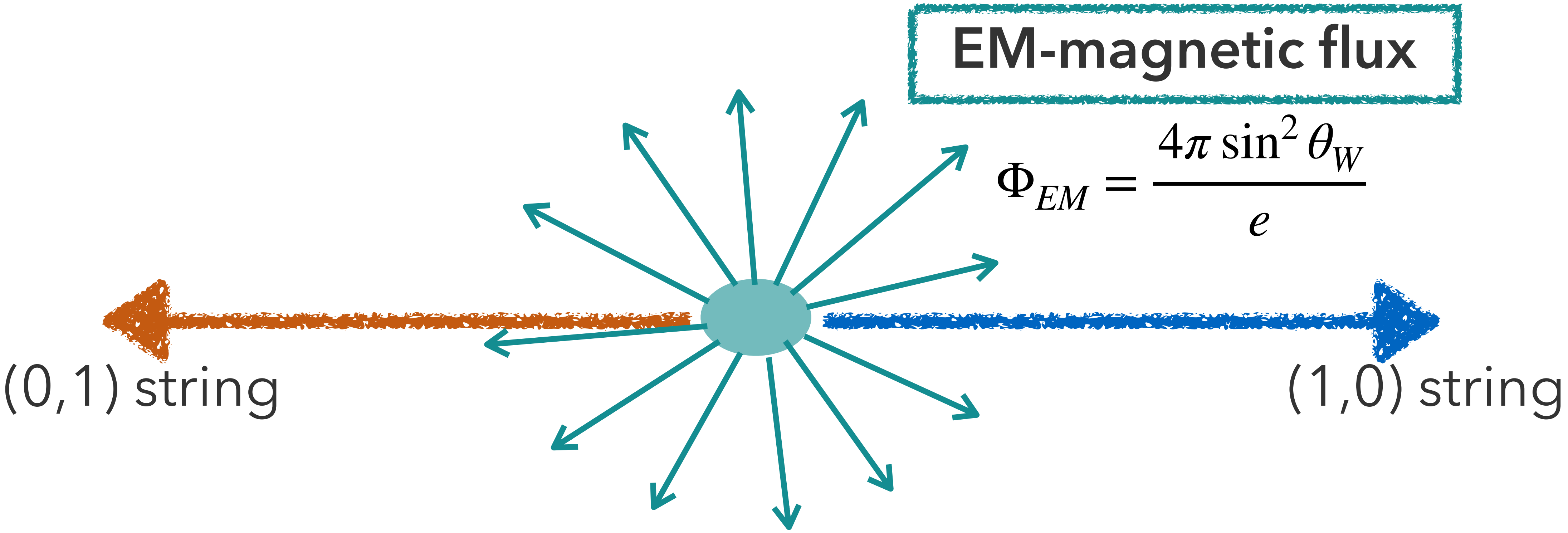
Flux matching



$$\Phi_{EM} = \frac{4\pi \sin^2 \theta_W}{e}$$

Z flux: $\Phi_Z = \dfrac{4\pi}{g_Z}$

EM flux: $\Phi_{EM} = \dfrac{4\pi \sin^2 \theta_W}{e}$

⇔

$SU(2)_W$ flux:

$$\Phi_W = \cos\theta_W \Phi_Z + \sin\theta_W \Phi_{EM} = \frac{4\pi}{g}$$

$U(1)_Y$ flux:

$$\Phi_Y = -\sin\theta_W \Phi_Z + \cos\theta_W \Phi_{EM} = 0$$

These fluxes satisfy the flux quantization conditions

Moduli Space of Strings

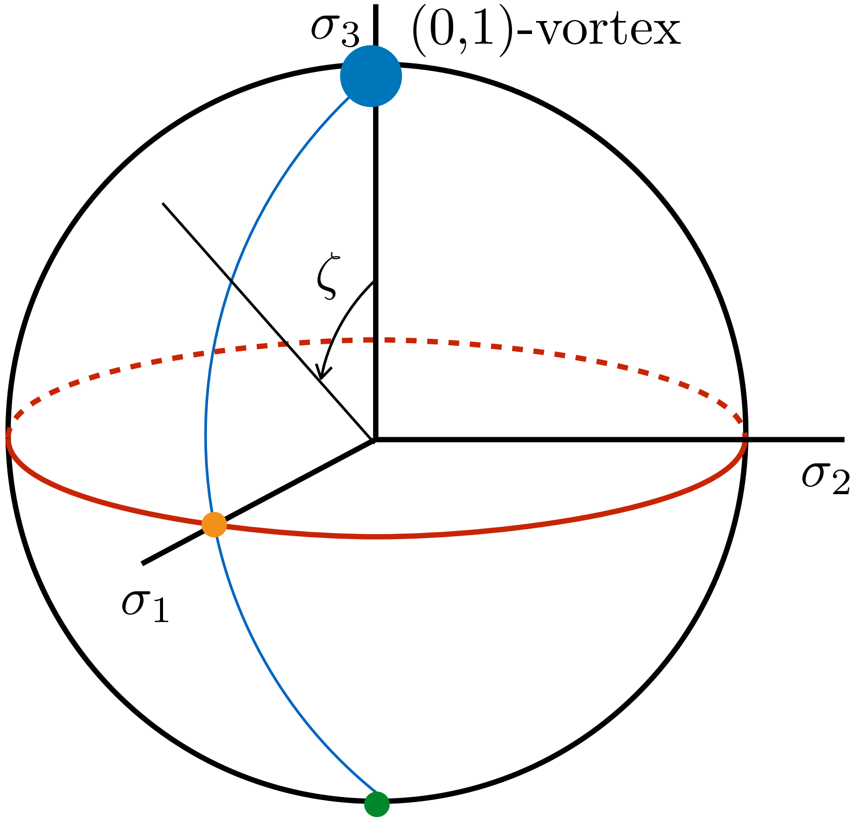
- Acting the $SU(2)$ transf. on (0,1)-string:

$$\begin{cases} H^{(0,1)} \to U^\dagger H^{(0,1)} U \\ W_i^{(0,1)} \to U^\dagger W_i^{(0,1)} U \end{cases} \qquad U \in SU(2)_C$$

we obtain other topological vortices.

- **Space of topological vortices**
= moduli space S^2

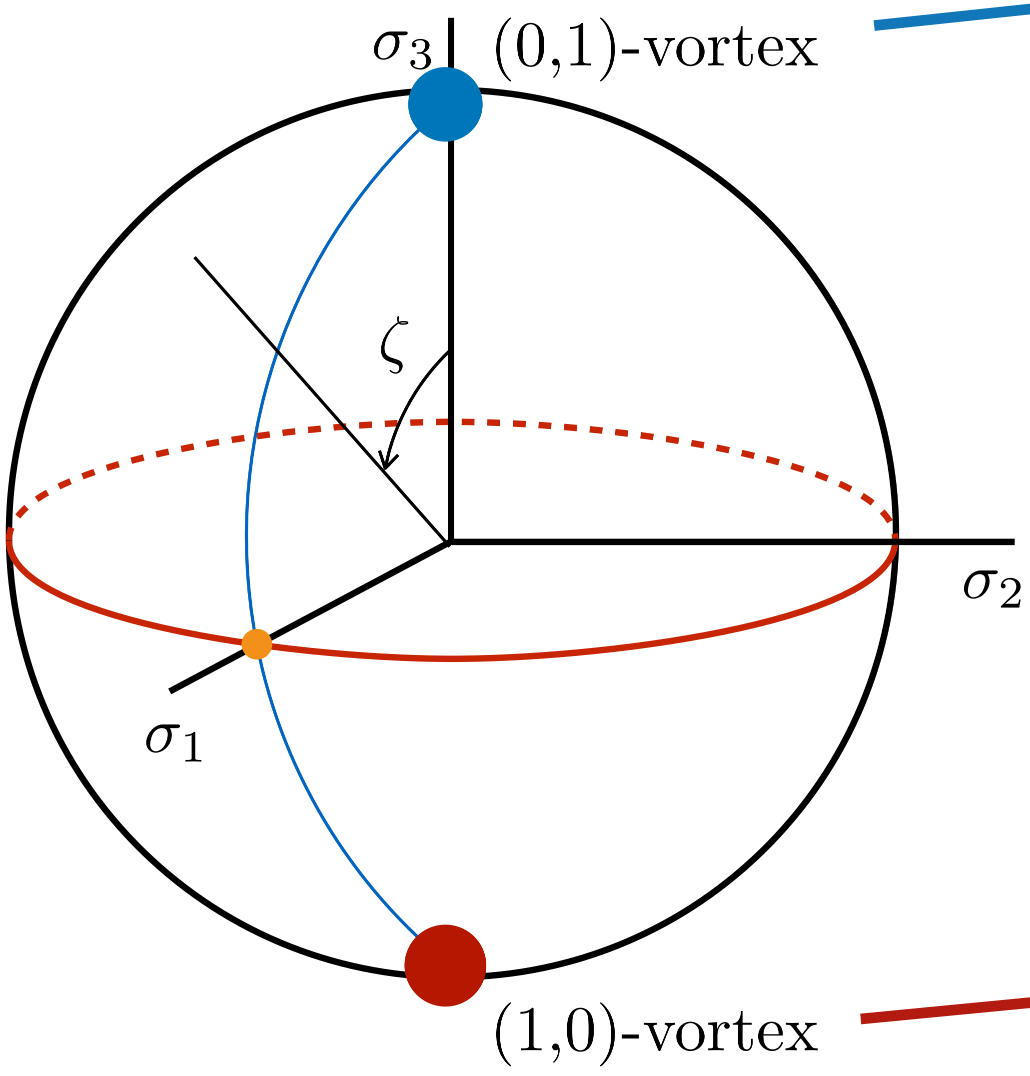
⇔ A point on the moduli space corresponds to one vortex configuration.



[1805.07015]

Moduli Space of Strings

There are two Z-strings.



[1805.07015]

- **(0,1) string :**

$$H^{(0,1)} \sim v \begin{pmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{pmatrix}$$

Φ_2 **has a winding #**

Z-flux : $\Phi_Z = \frac{2\pi}{g_Z}$

- **(1,0) string :**

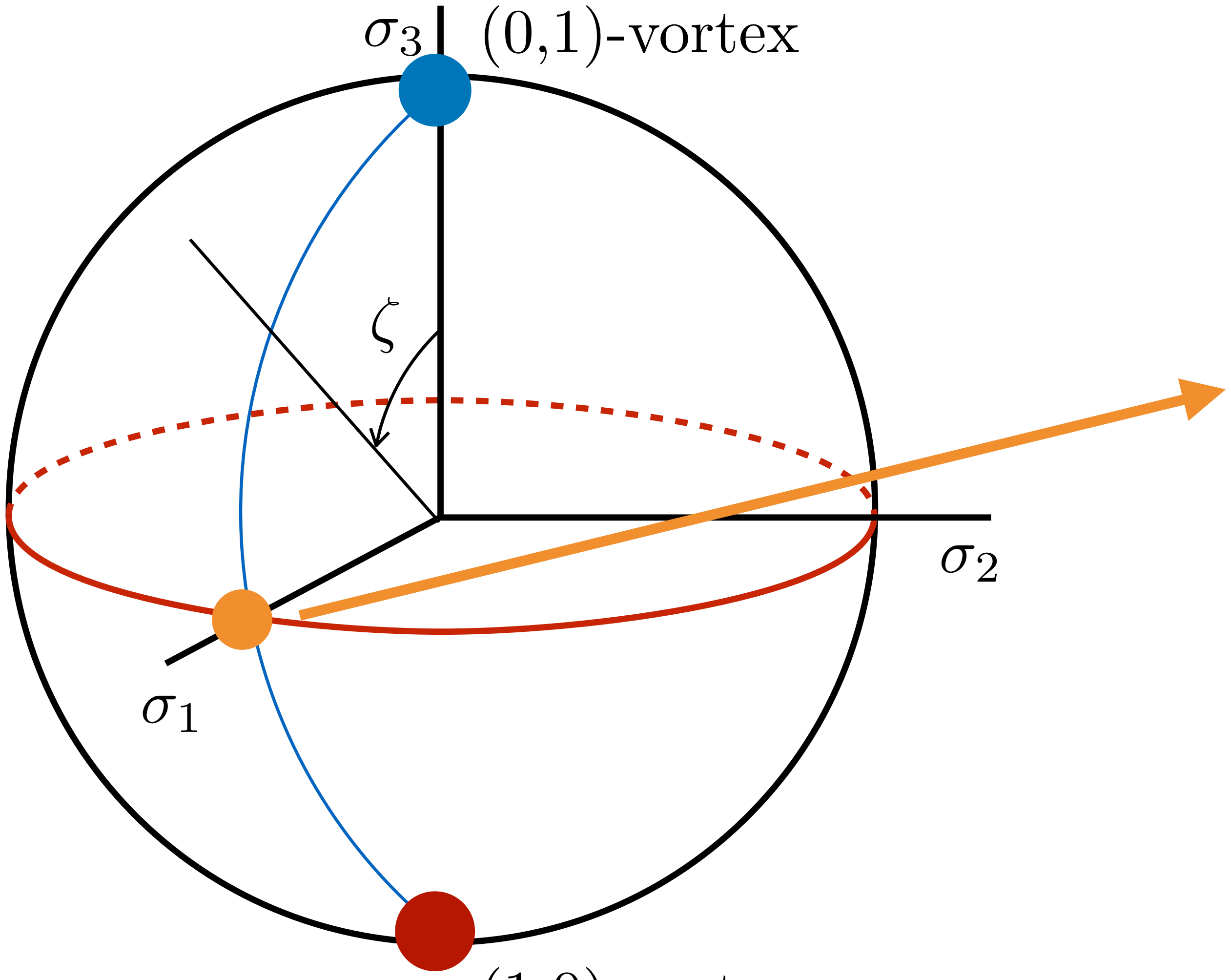
$$H^{(1,0)} \sim v \begin{pmatrix} e^{i\theta} & 0 \\ 0 & 1 \end{pmatrix}$$

Φ_1 **has a winding #**

Z-flux : $\Phi_Z = \frac{-2\pi}{g_Z}$

Moduli Space of Strings

There are also more general vortices.



[1805.07015]

W-string

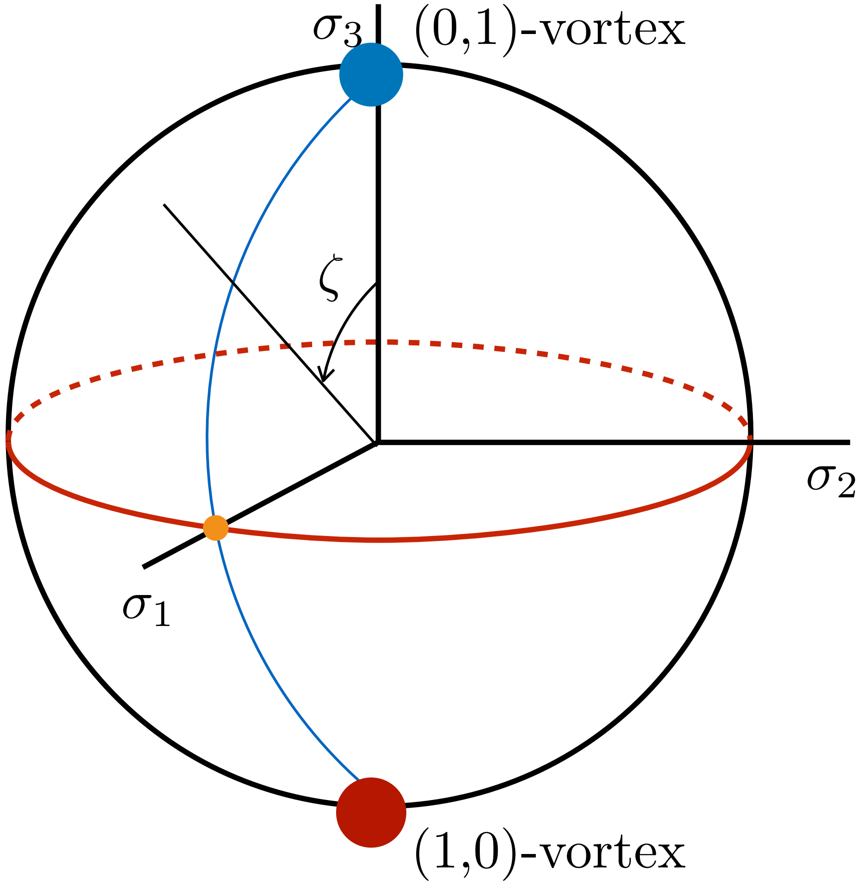
$$H \sim v\; e^{\frac{i\theta}{2}}\; e^{\frac{i\theta}{2}\sigma_1}$$

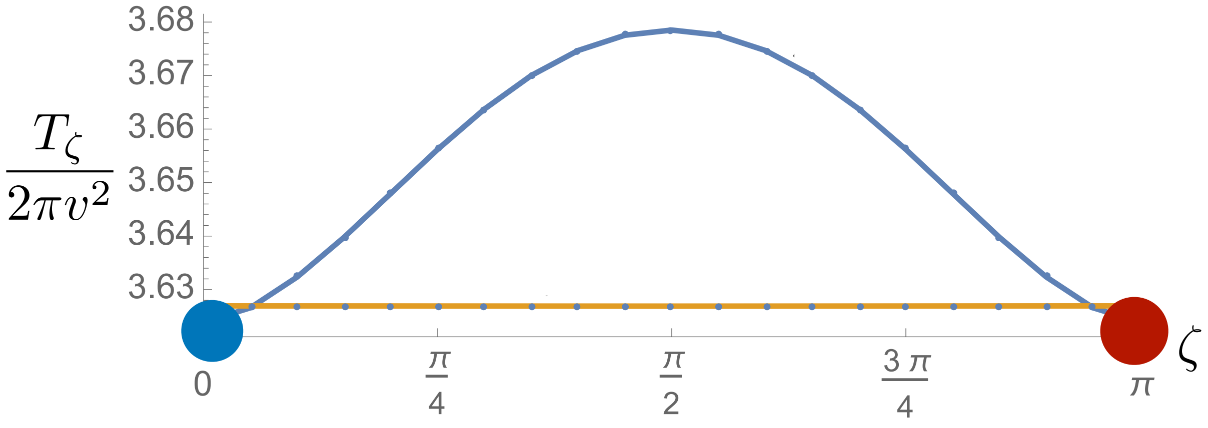
W flux: $\Phi_W = \dfrac{2\pi}{g}$

Magnetic Monopole as CP kink

- Z-stringが存在するとき、CP対称性は自発的に破れている

[redacted]





Magnetic Monopole as CP kink

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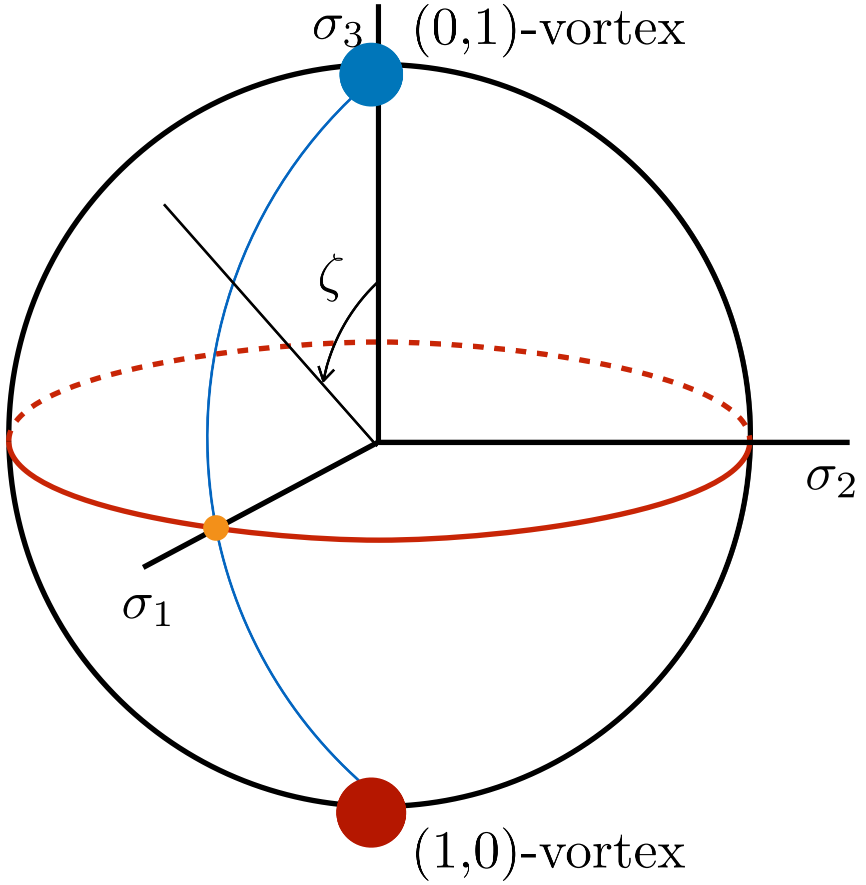

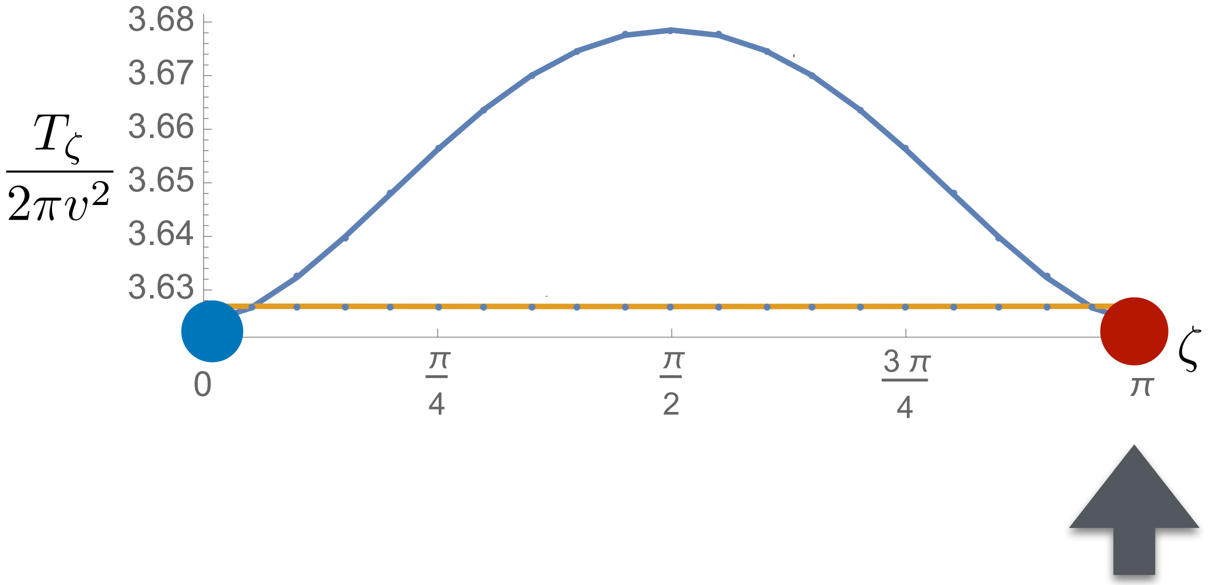

Magnetic Monopole as CP kink

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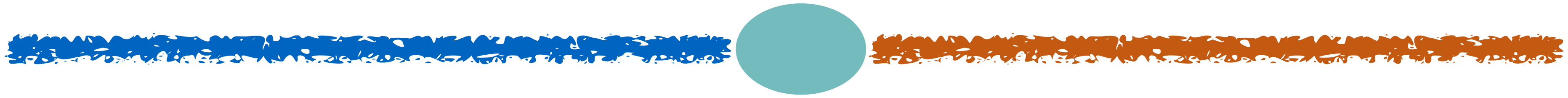
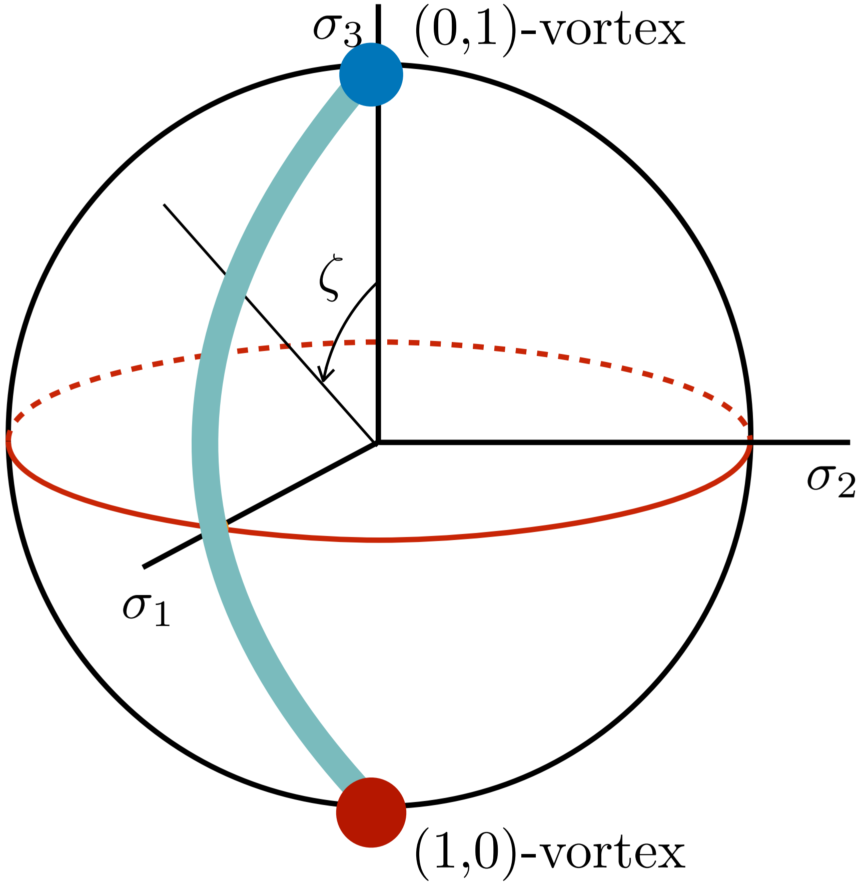
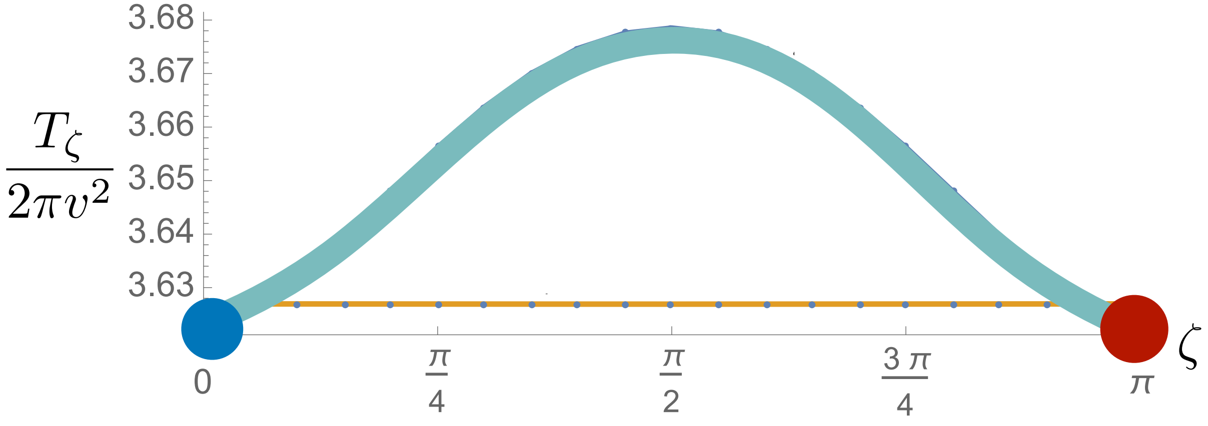


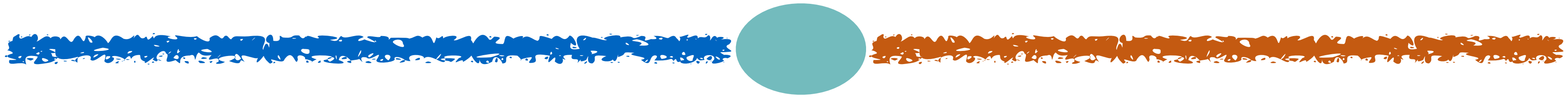
- このSSBに付随するtopological kinkが生じる





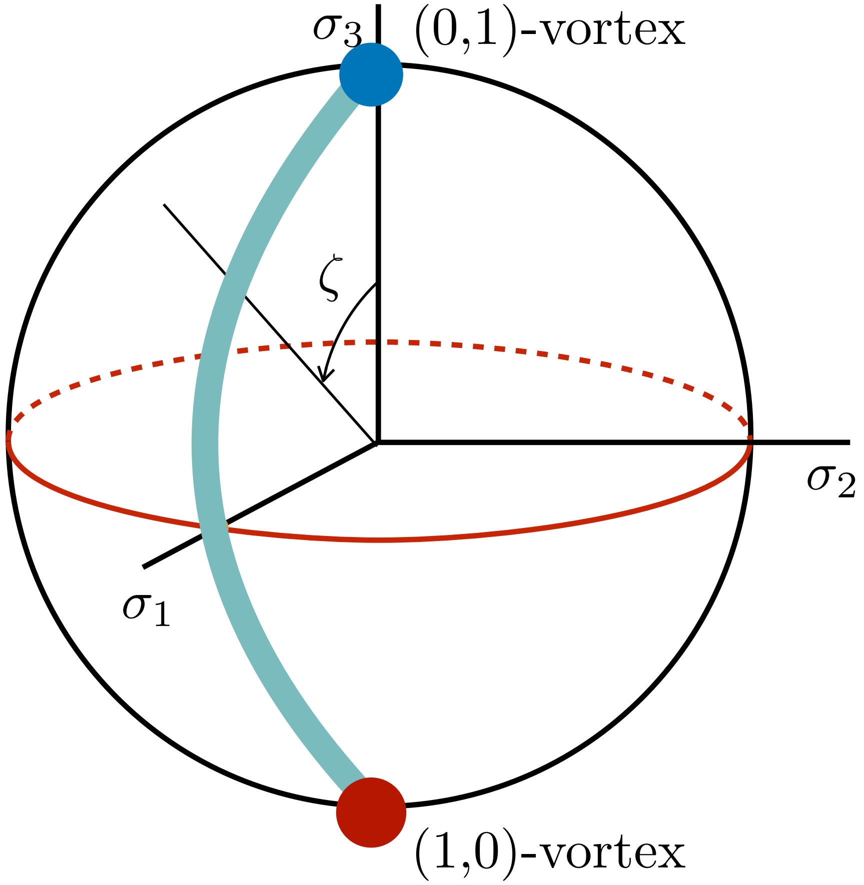
Magnetic Monopole as CP kink

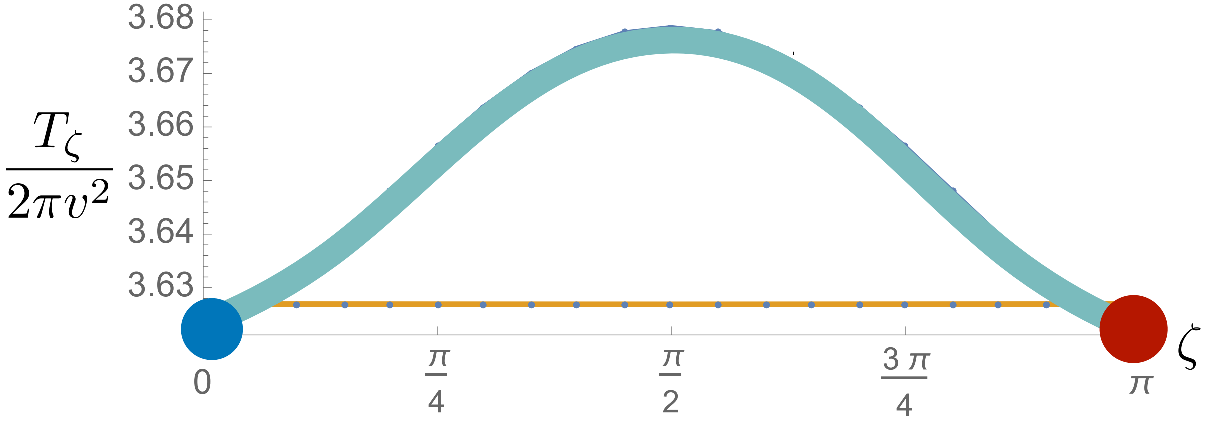
- Z-stringが存在するとき、CP対称性は自発的に破れている



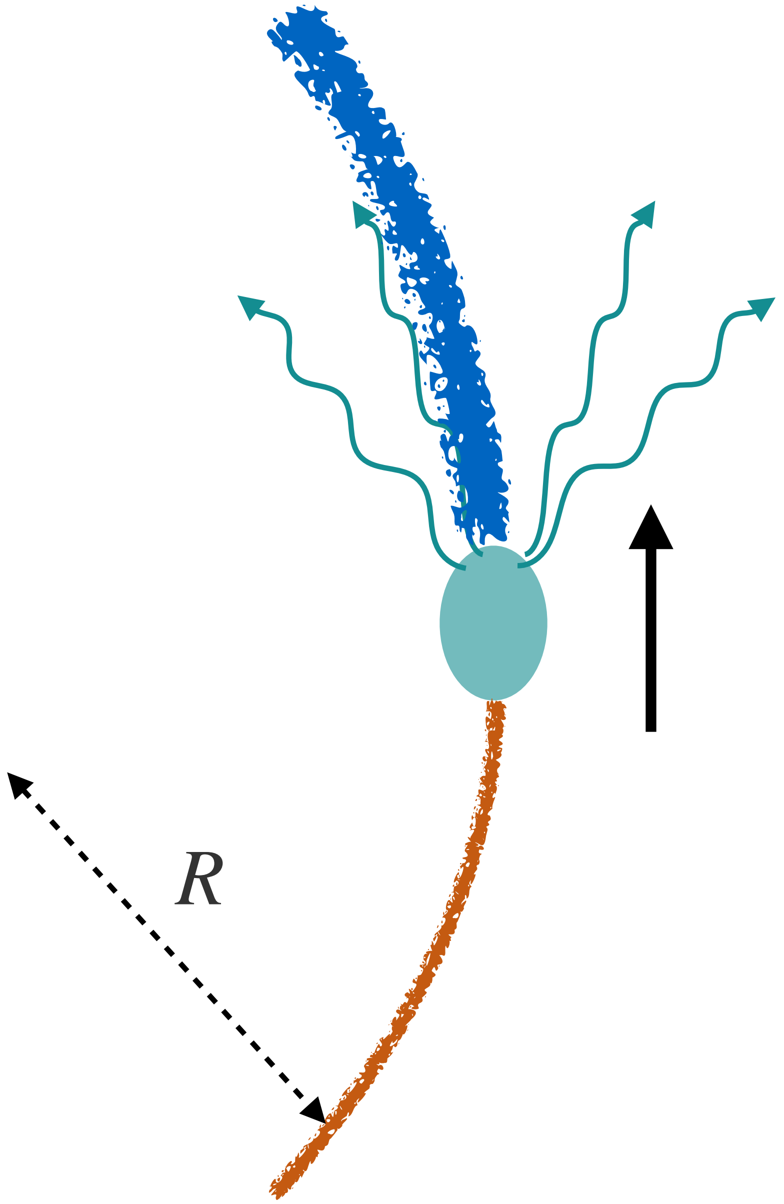
- **このSSBに付随するtopological kinkが生じる**

➡ **これがmagnetic monopoleとして振る舞う**





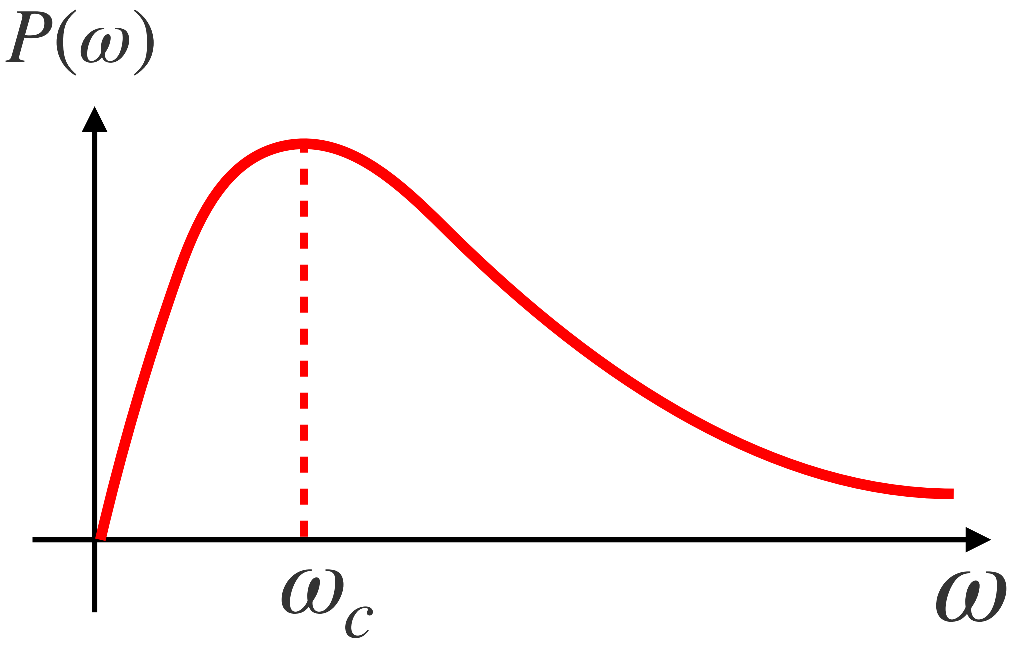
Spectrum of the synchrotron radiation



R : curvature radius of the string

$\sim$ (Hubble radius)

The radiation is the same spectrum as a synchrotron radiation



$$\omega_c \sim \gamma^2 R^{-1} \sim 10^{-6}\ \mathrm{GeV}$$

$$R \sim \left(\frac{\rho}{M_P^2}\right)^{-1/2} \sim \left(\frac{10^{10}}{10^{38}}\right)^{-1/2} \mathrm{GeV}^{-1} \sim 10^{14}\ \mathrm{GeV}^{-1}$$

2HDM in Matrix Notation

$$\begin{aligned} V(\Phi_1,\Phi_2) = {}& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h\,.\,c\,.}\right) + \frac{\beta_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\beta_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\ & +\beta_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \beta_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left\{\frac{\beta_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \mathrm{h\,.\,c\,.}\right\} \end{aligned}$$

$$m_{11}^2 = -m_1^2 - m_2^2, \quad m_{22}^2 = -m_1^2 + m_2^2, \quad m_{12} = m_3,$$

$$\beta_1 = 2(\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4), \quad \beta_2 = 2(\alpha_1 + \alpha_2 + \alpha_3 - \alpha_4),$$

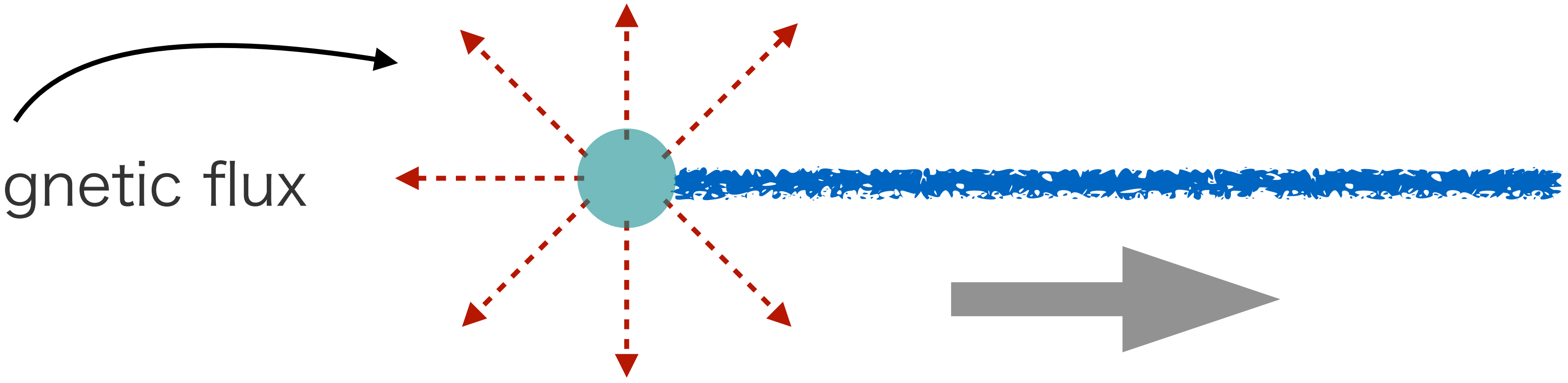
$$\beta_3 = 2(\alpha_1 + \alpha_2 - \alpha_3), \quad \beta_4 = 2(\alpha_3 - \alpha_1), \quad \beta_5 = 2\alpha_5$$

$$\begin{aligned} V(\Phi_1,\Phi_2) = {}& -m_1^2\ \mathrm{Tr}\,|H|^2 - m_2^2\ \mathrm{Tr}\left(|H|^2\sigma_3\right) - \left(m_3^2 \det H + \mathrm{h\,.\,c\,.}\right) \\ & +\alpha_1\ \mathrm{Tr}\,|H|^4 + \alpha_2\left(\mathrm{Tr}\,|H|^2\right)^2 + \alpha_3\ \mathrm{Tr}\left(|H|^2\sigma_3|H|^2\sigma_3\right) \\ & +\alpha_4\ \mathrm{Tr}\left(|H|^2\sigma_3|H|^2\right) + \left(\alpha_5 \det H^2 + \mathrm{h\,.\,c\,.}\right) \end{aligned}$$

$|H|^2 \equiv H^\dagger H$

Nambu monopole

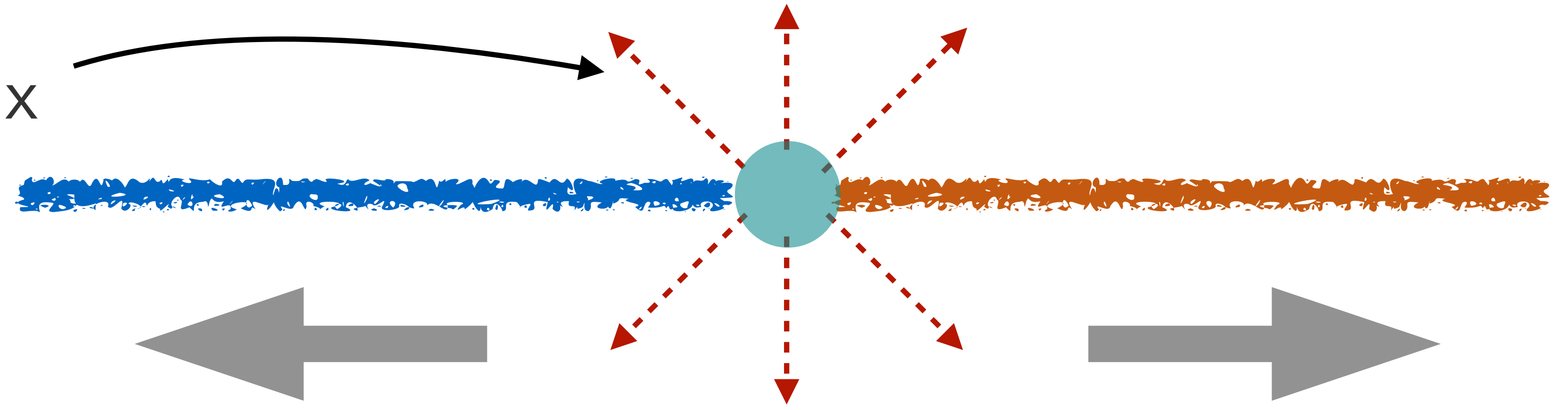
- **Nambu monopole in SM** [Nambu '77]



EM-magnetic flux

Unstable

- **Nambu monopole in 2HDM** **Our result !**



EM-magnetic flux

Stable!