Stable magnetic monopole in two Higgs doublet models

Yu Hamada (Kyoto Univ.)

Based on arXiv:1904.09269

Collaborators:
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Masafumi Kurachi (Keio U.), Muneto Nitta (Keio U.)

Cold Quantum Coffee @ Heidelberg University (22 Nov. 2019)

Introduction

Everyone (?) wonders that

Is there any object that has a single magnetic charge?

Magnetic Monopole (MM)

- MM has attracted attention from many physicist since the work by Dirac (1931)

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There are many projects searching magnetic monopoles.

(ATLAS, CMS, **MoEDAL**)

Two Higgs Doublet Model (2HDM)

- In 2HDM, two Higgs doublets are introduced:

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 has been widely studied because

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Today's message

Although 2HDM is a simple extension of the SM, it predicts stable magnetic monopoles depending on parameters.

Plan of talk

- Introduction (3p.) ←Done
- Vortex string in 2HDM (Review) (5p.)
- Magnetic monopole in 2HDM (6p.)
- Summary

Vortex string in 2HDM

[Dvali, Senjanovic ’93]

[Eto, Kurachi, Nitta ’18]

Vortex string (cosmic string)

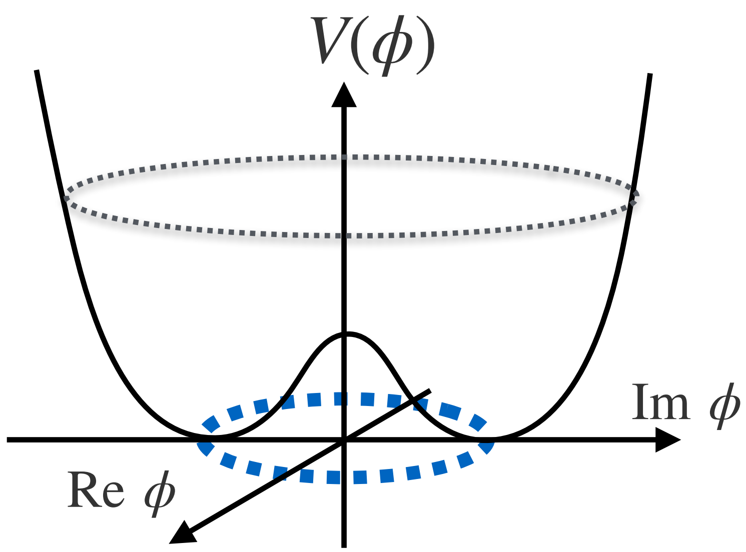
[Abrikosov '58]
[Nielsen-Olesen '73]

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

eg.) Let us consider Abelian-Higgs model:

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

Vacuum is S^1. $(\pi_1(\mathrm{Vac.}) = \mathbb{Z} \neq 0)$



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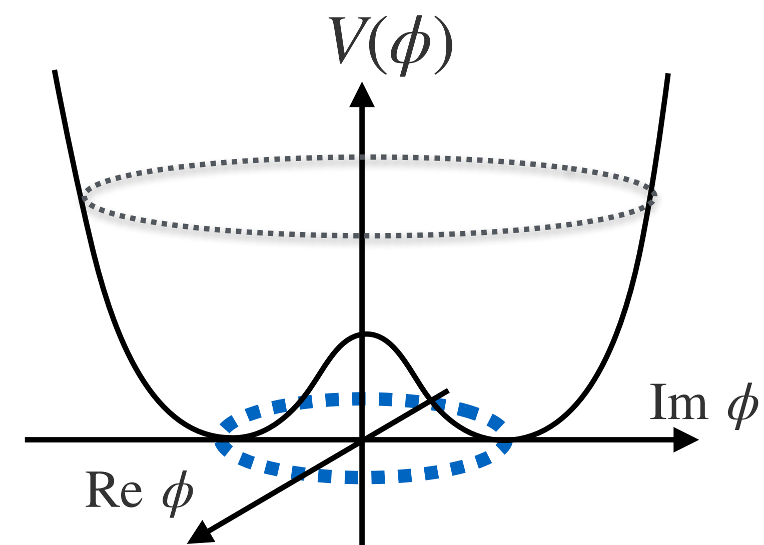

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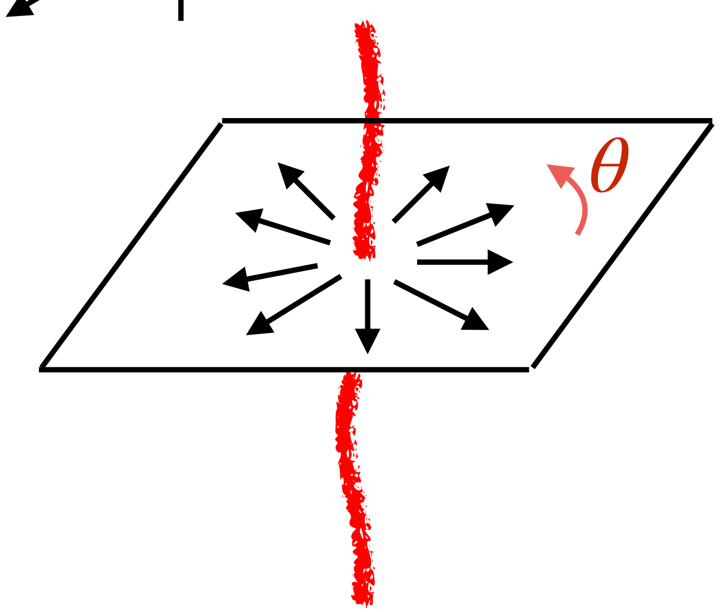

$$\begin{cases} \phi(x) \sim v e^{i\theta} \\ A_i(x) \sim i\partial_i\theta \end{cases} \quad (r \to \infty)$$

winding # $= 1$

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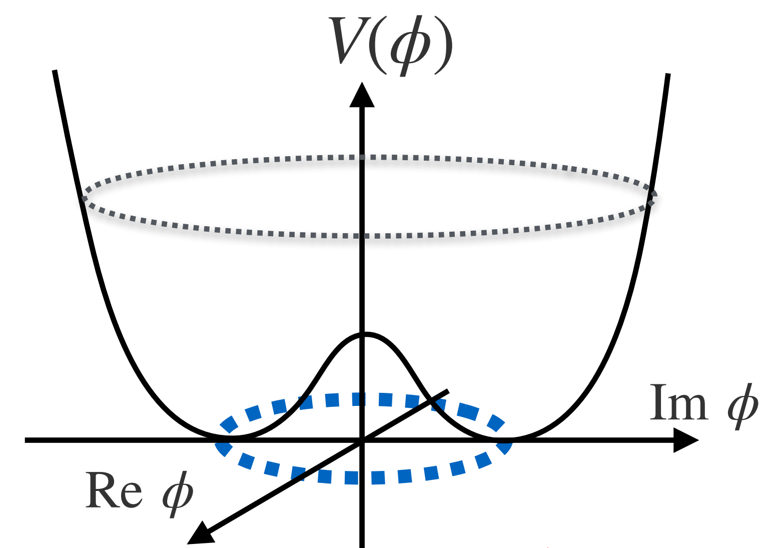

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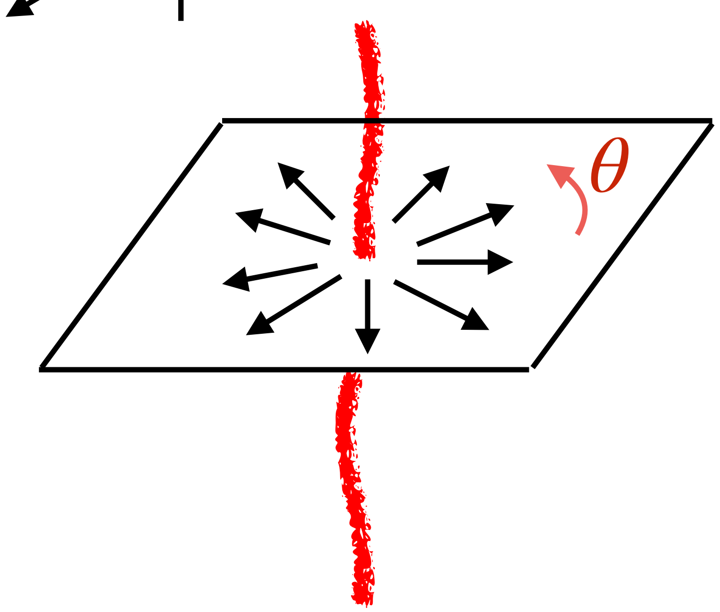

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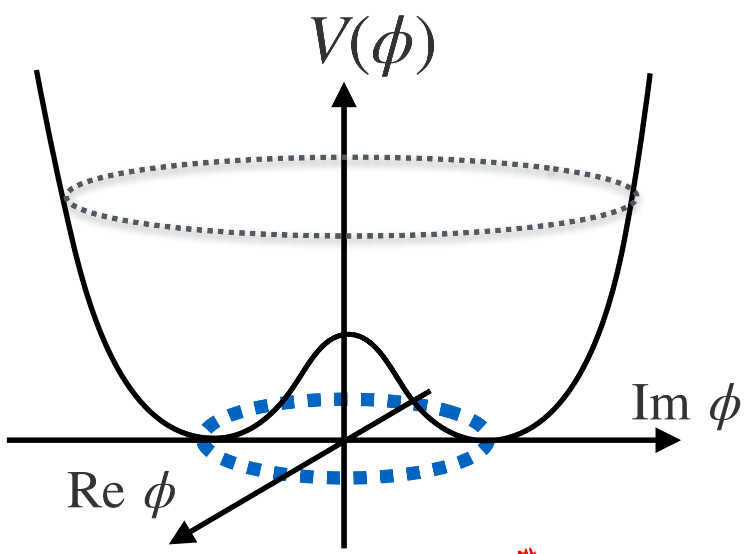

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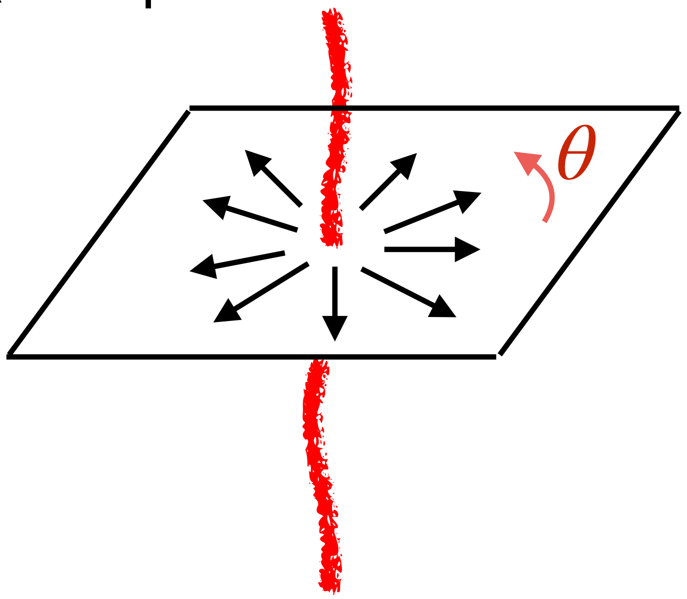

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There must be a vortex string at the center (topologically stable)

In the following, we will see that vortex strings can exist in 2HDM.

Higgs Potential in 2HDM

- Higgs potential can be expressed as

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

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

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

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- **Impose two global symmetries :**

$\boxed{\bullet\ U(1)_a \text{ sym.}:\ \Phi_1 \to e^{-i\alpha}\Phi_1,\ \ \Phi_2 \to e^{i\alpha}\Phi_2}$ (relative phase rotation)

This symmetry is broken in the vacuum.

→ The vacuum has a non-trivial topology ($\pi_1(\mathrm{Vac.}) = \mathbb{Z}$) and **vortex string can exist.**

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- **Impose two global symmetries :**

$\boxed{\bullet\ (\mathbb{Z}_2)_C \text{ sym. :}}$

(not broken in vacuum)

$$\begin{cases} \Phi_1 \to (i\sigma^2)\Phi_2^* \\ \Phi_2 \to (i\sigma^2)\Phi_1^* \\ W_i \to (i\sigma^1)\ W_i\ (i\sigma^1)^\dagger \\ B_i \to -B_i \end{cases} \sim$$

exchange of two doublets + CP transf.

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

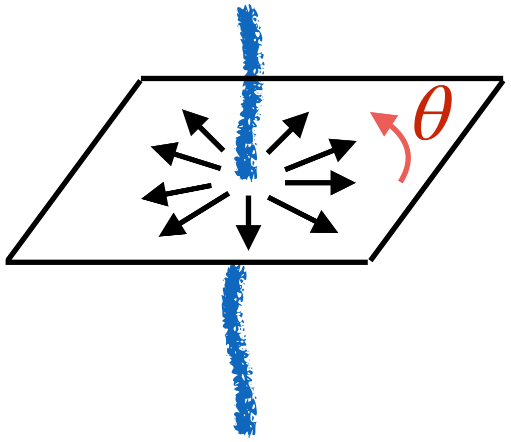
Topological Z-strings in 2HDM

[Dvali, Senjanovic '93]

[Eto, Kurachi, Nitta '18]

- There are two stable vortex strings (topological Z-strings).
  - **(0,1)-string** has an asymptotic form as follows:

$$H^{(0,1)} \sim v \begin{pmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{pmatrix} \qquad Z_i^{(0,1)} \sim \frac{\cos\theta_W}{g} \frac{\epsilon_{3ij}\, x^j}{r^2}$$



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

  - Φ_2 **has a winding #**
  - **Z-flux:** $\Phi_Z = 2\pi/g_Z$ **is confined in the string.**

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

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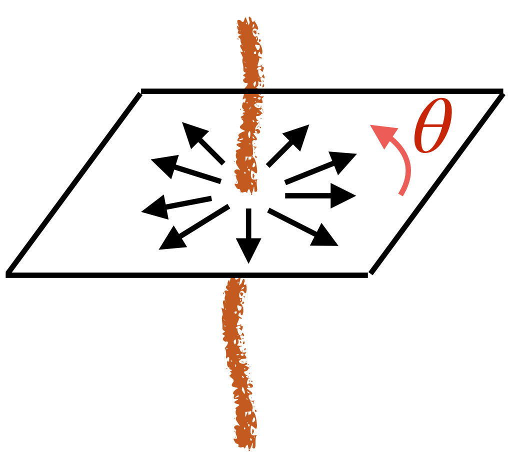

  - Φ_1 **has a winding #**
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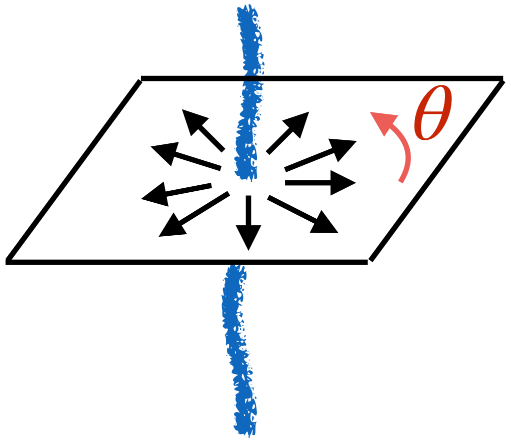

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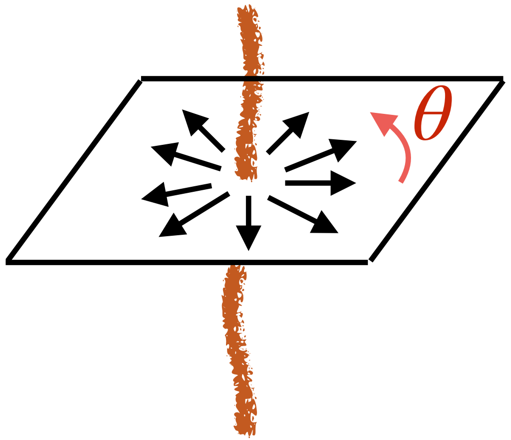

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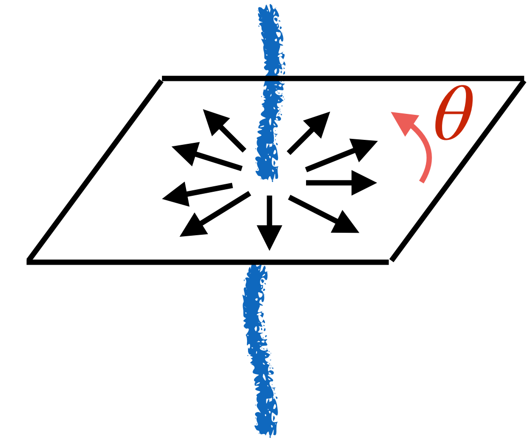

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Related by $(\mathbb{Z}_2)_C$ transf.

Tension(energy) of the strings are degenerate because of $(\mathbb{Z}_2)_C$ sym.

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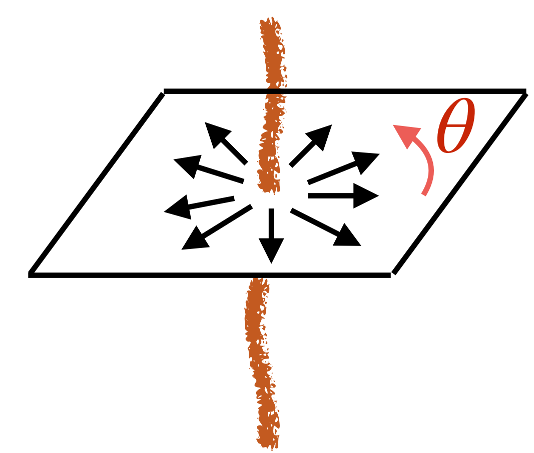

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Magnetic monopole in 2HDM

[Eto, **Hamada**, Kurachi, Nitta ’19]

Topology of 2HDM

- As we have seen, $\pi_1(\mathrm{Vac.}) \simeq \pi_1(U(2)) = \mathbb{Z}$ and vortex strings can exist in 2HDM.

- However, $\pi_2(\mathrm{Vac.}) \simeq \pi_2(U(2)) = 0$.

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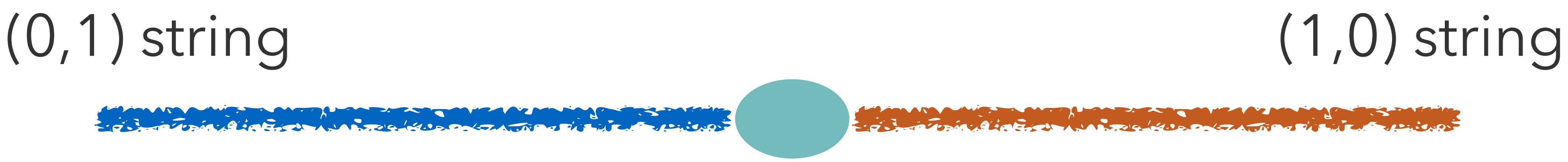
Key symmetries: $U(1)_a$ and $(\mathbb{Z}_2)_C$

Magnetic Monopole in 2HDM

- Interpolate the two Z-strings smoothly.



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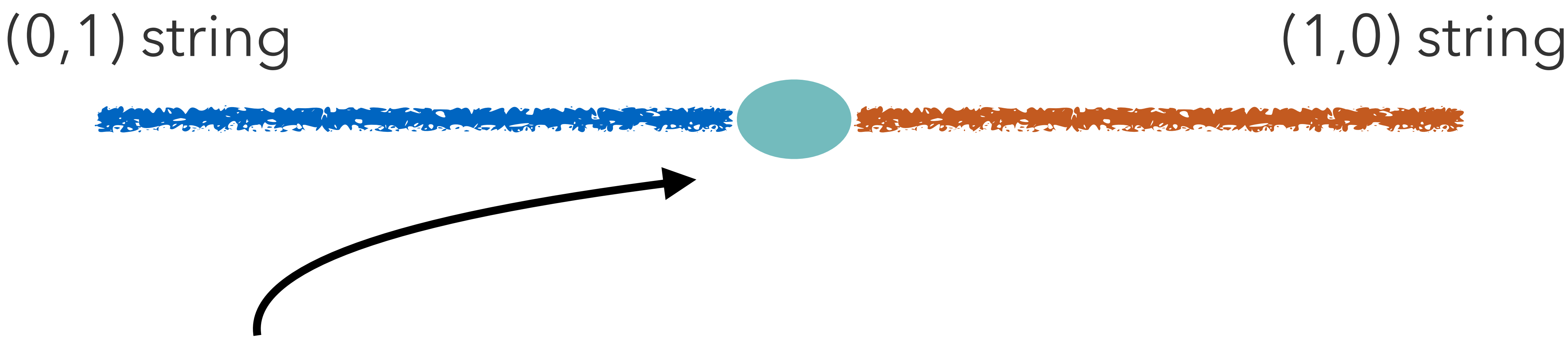
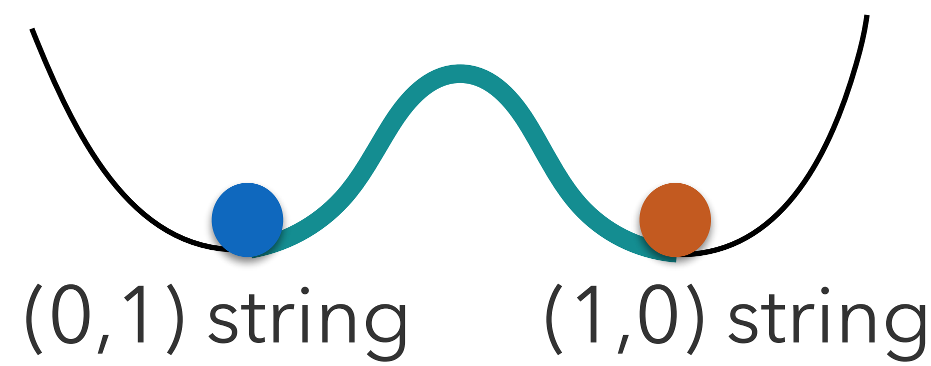


- **This object can be regarded as a topological $(\mathbb{Z}_2)_C$ kink interpolating the two stable configurations.**



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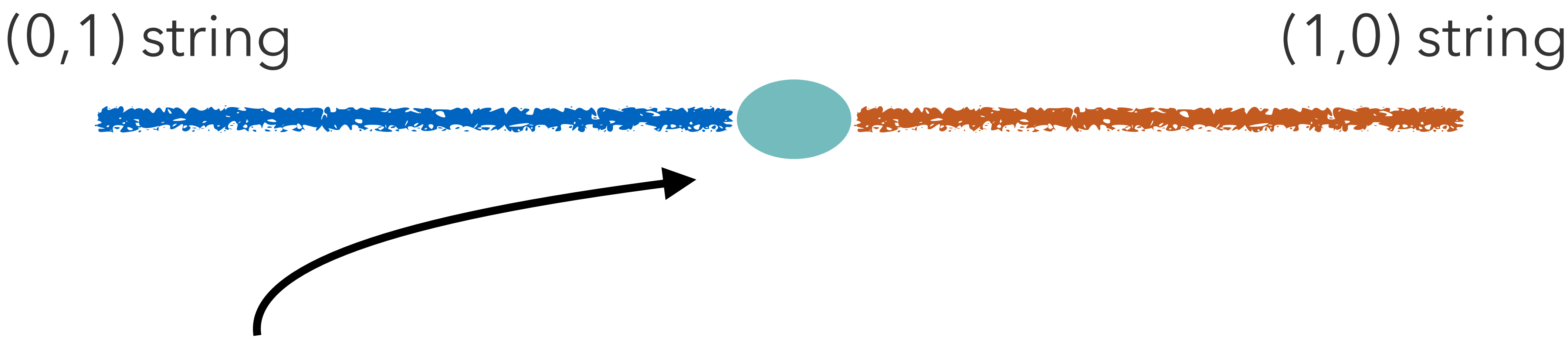

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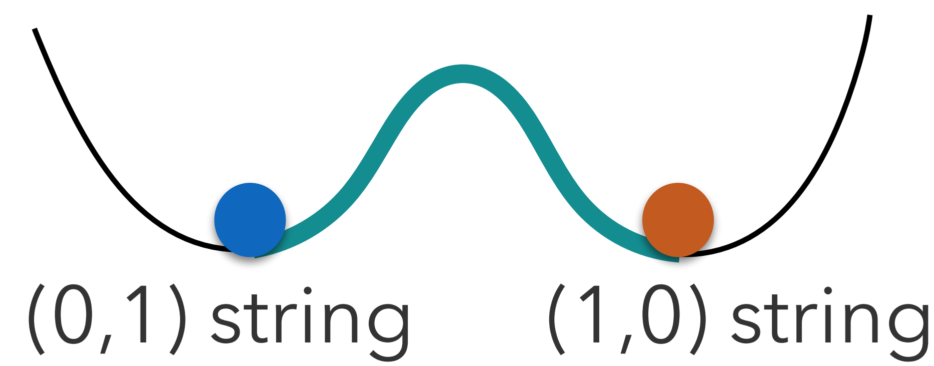
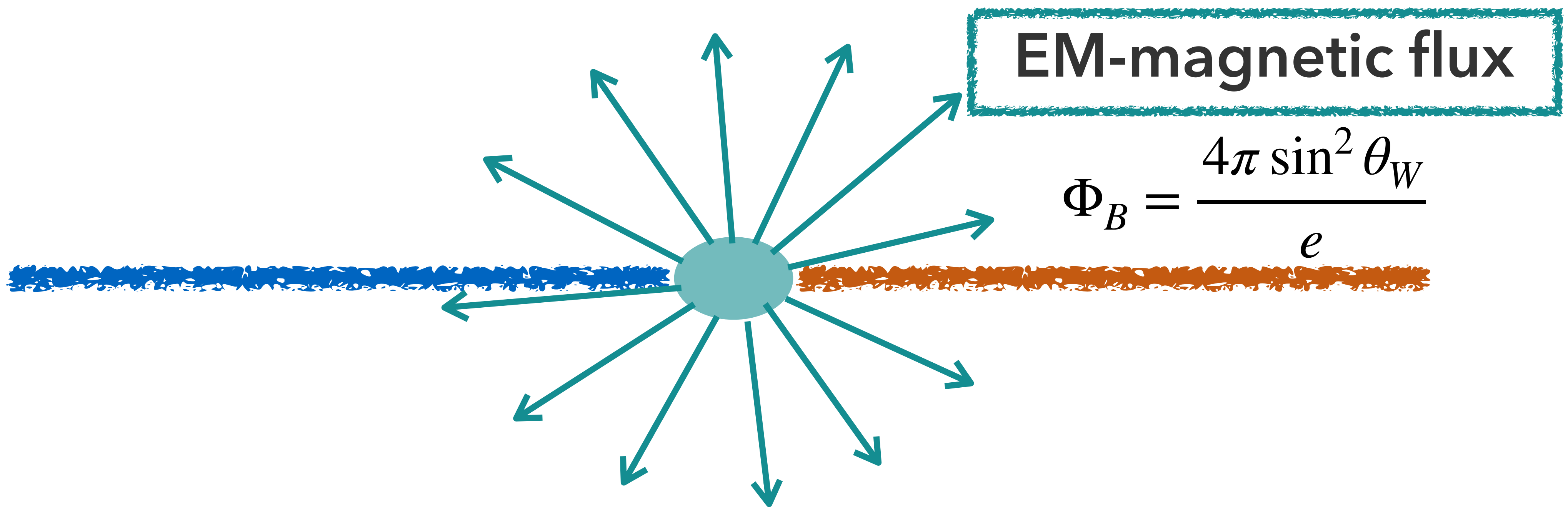


This kink behaves as a magnetic monopole !

Magnetic Flux

- **Magnetic flux spreads from this ``kink'' !**



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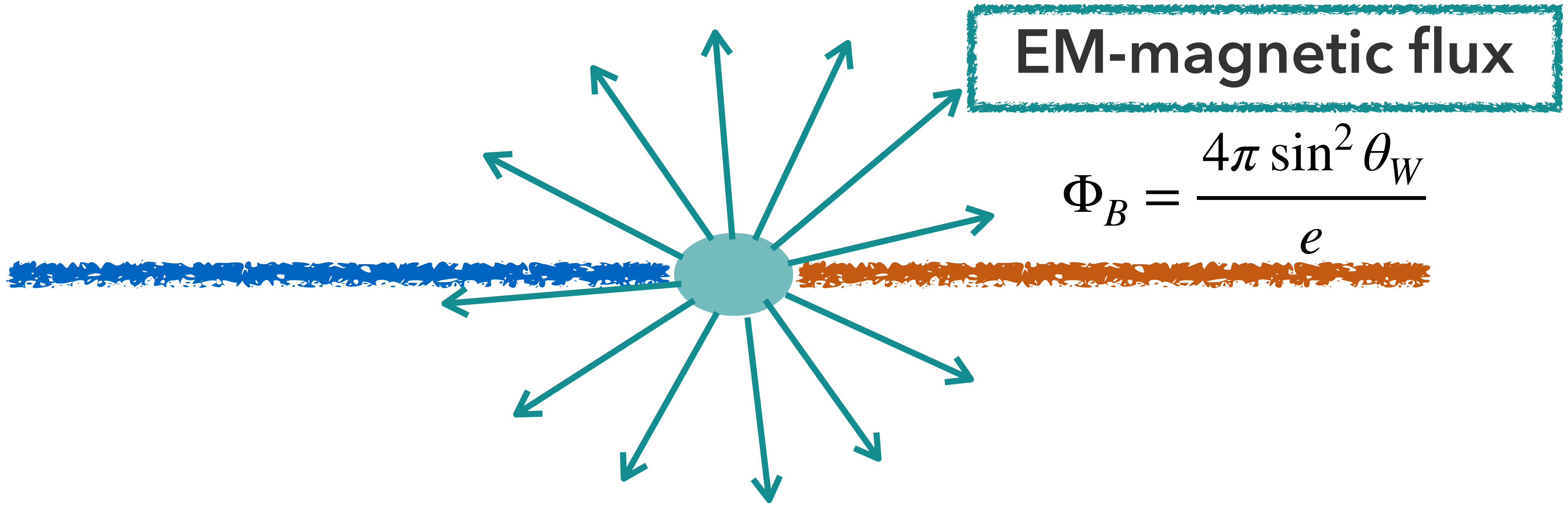

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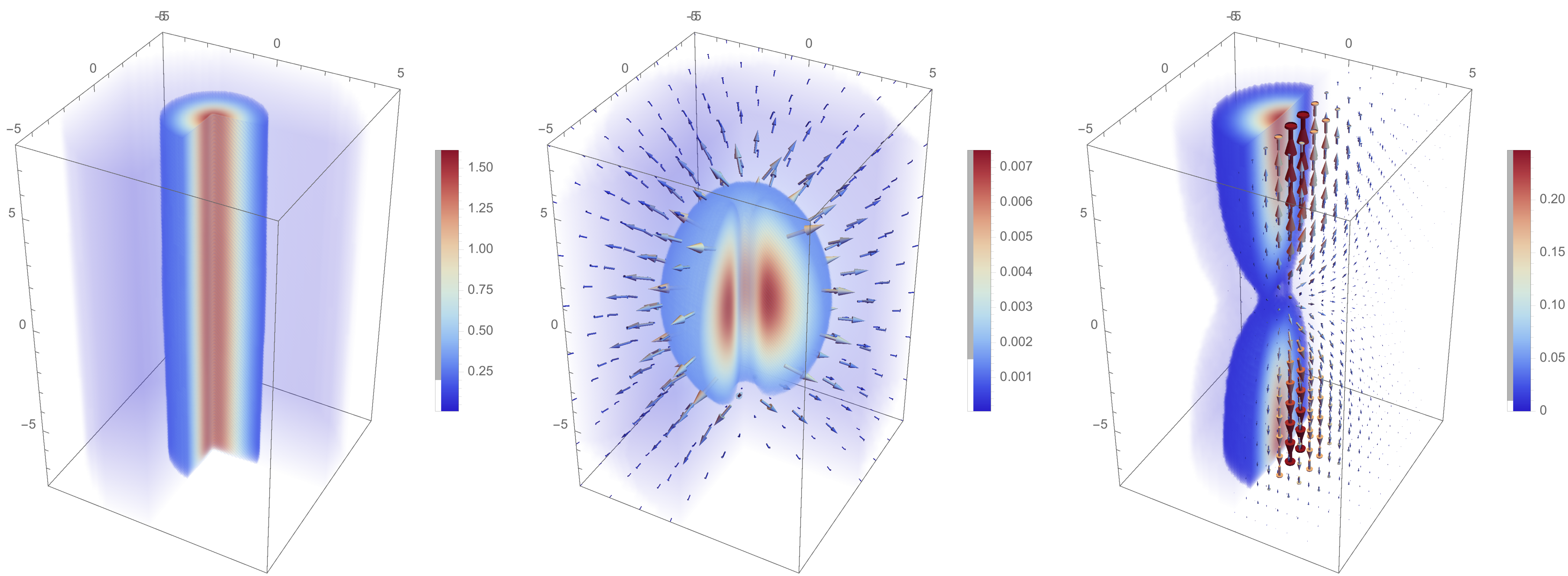
- **Topologically stable beause of $U(1)_a$ and $(\mathbb{Z}_2)_C$ sym.**
  (topological $(\mathbb{Z}_2)_C$ kink)

(the two string tensions are balanced → static)

Numerical Result

- We can numerically construct such a monopole solution to EOMs.



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

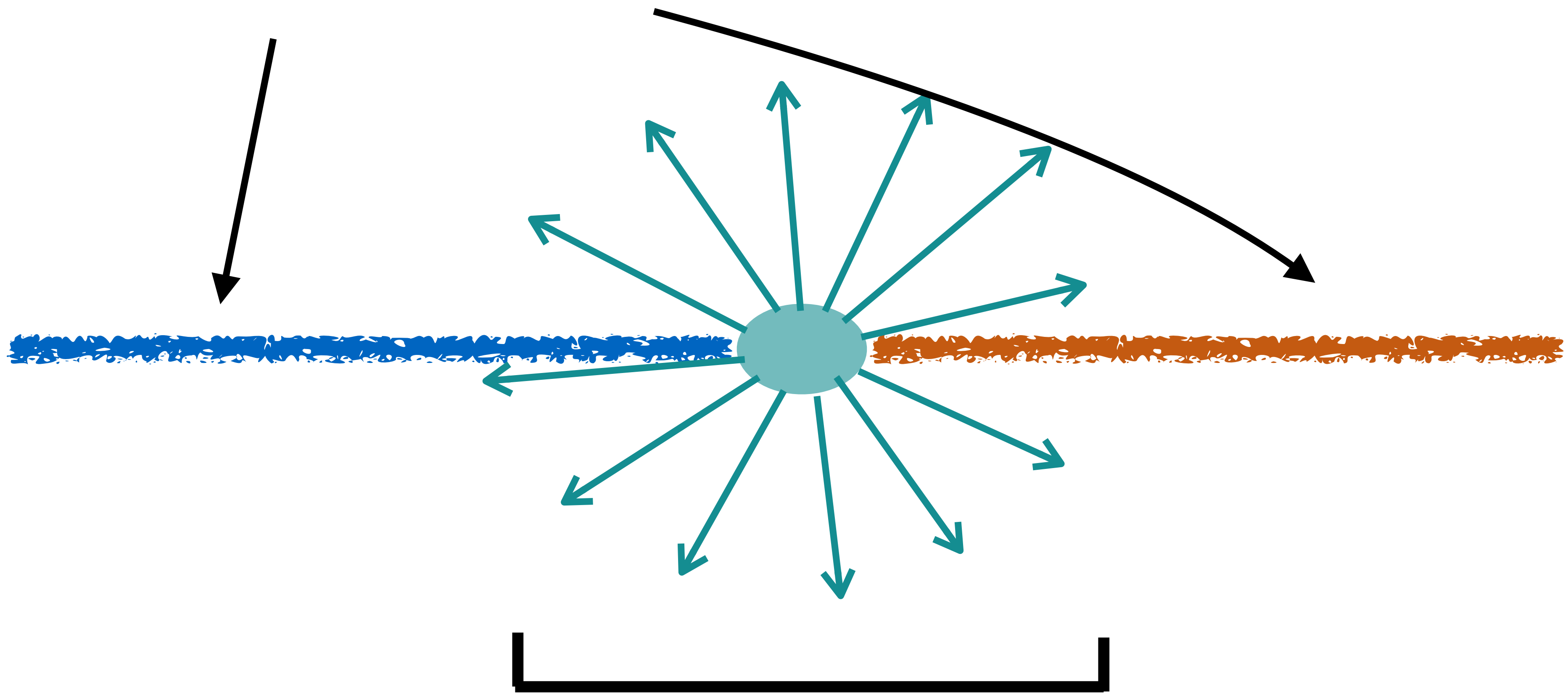
with $\sin^2\theta_W = 0.23,\ m_W = 80\ \text{GeV},\ v_{\text{EW}} = 246\ \text{GeV},$

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

Monopole Energy

- We can calculate the energy of the numerical solution :

string tension $\simeq (500\ \mathrm{GeV})^2$



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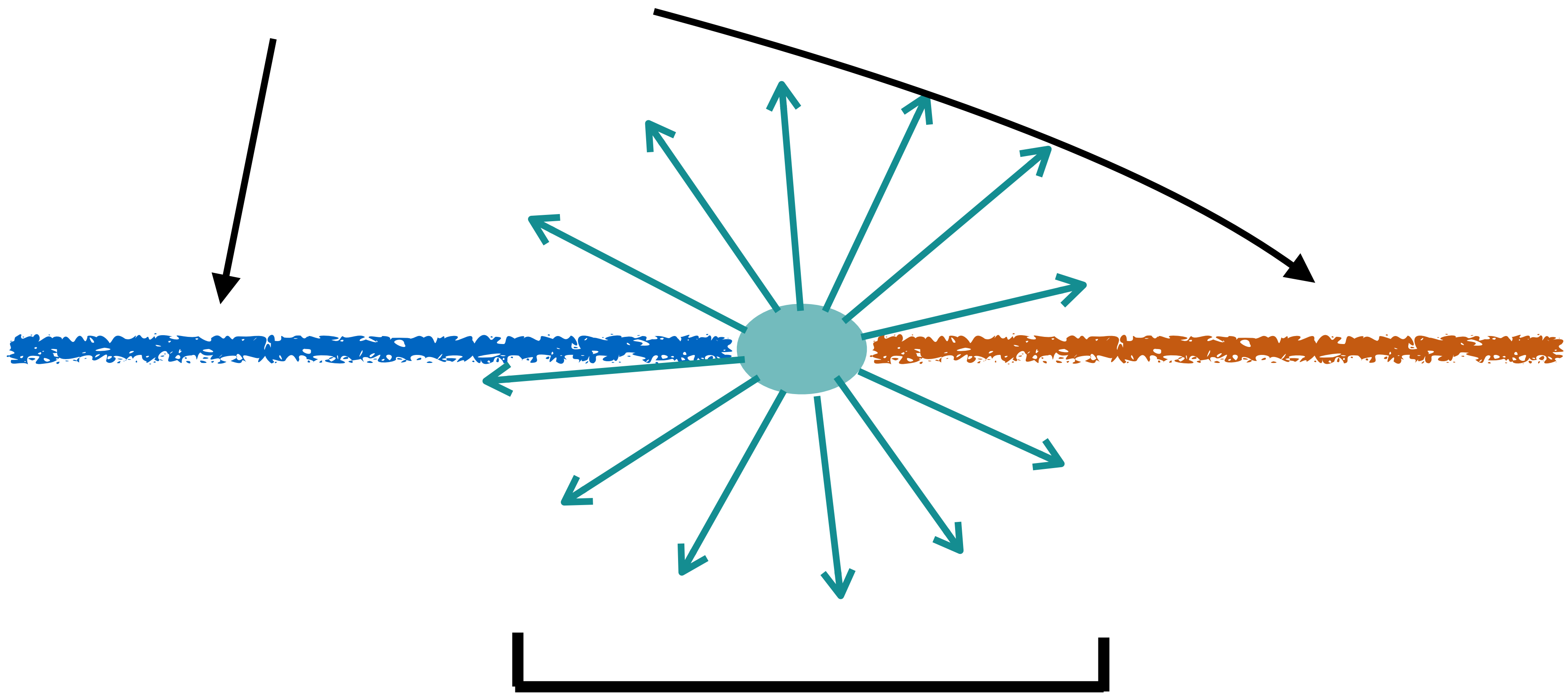

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TeV-scale phenomenon ! ➡ **can be seen in LHC !?**

Two Symmetries

- **We have imposed the two global symmetries :**

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

$$\boxed{\bullet \;\; (\mathbb{Z}_2)_C \text{ sym.}}$$

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→ A massless particle appears after the symmetry breaking.

→ Such a model is excluded by collider experiments.

$\boxed{\bullet\ (\mathbb{Z}_2)_C \text{ sym.}}$

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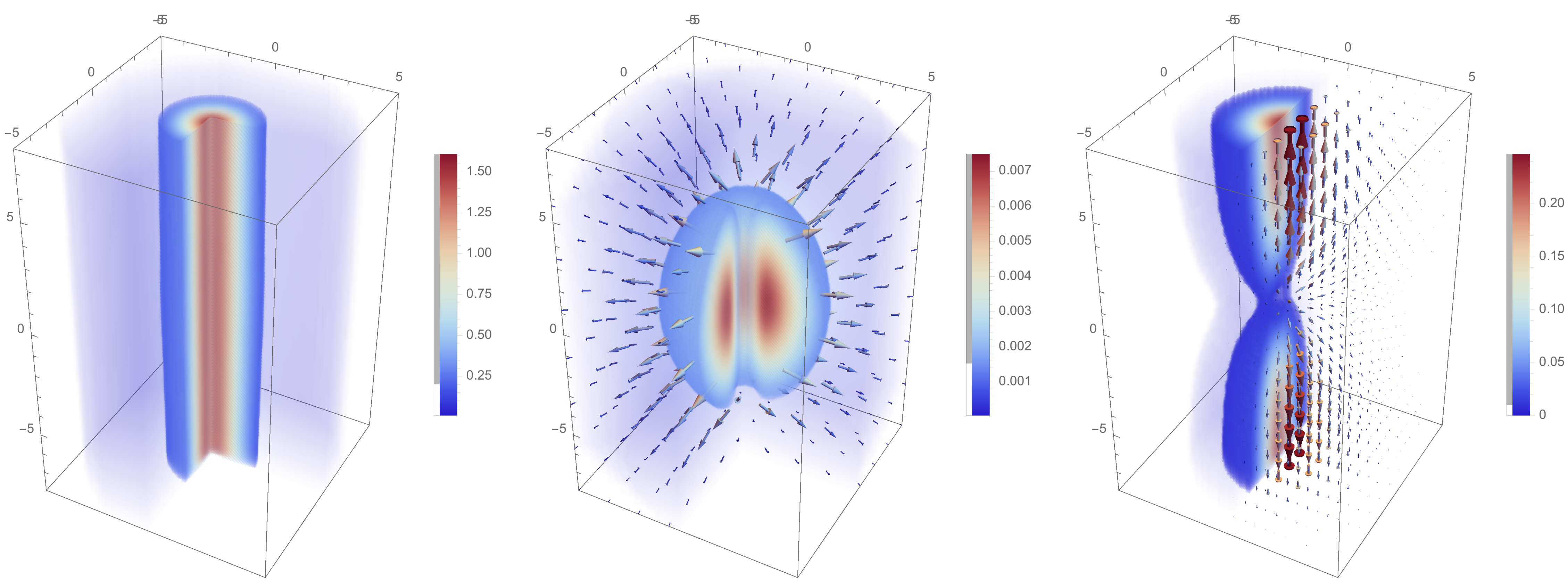
Whether they are sufficiently stable or not is a dynamical problem ! (work in progress)

Summary

- **In 2HDM, there can be a stable magnetic monopole solution.**
- Key symmetries:
  - $U(1)_a \Rightarrow$ **topological Z-strings**
  - $(\mathbb{Z}_2)_C \Rightarrow$ **monopole as topological kink**

  - TeV-scale → It might be seen in LHC ?



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

Future works

- In realistic case, $\cancel{U(1)_a}$, $\cancel{(\mathbb{Z}_2)_C}$ $\Rightarrow$ How unstable?
- How is it seen in LHC ?
- Monopole abundance in the universe
- Quantization of electric charges ?
- Relation between sphaleron configuration [Field-Vachasapati '94]

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and so on…

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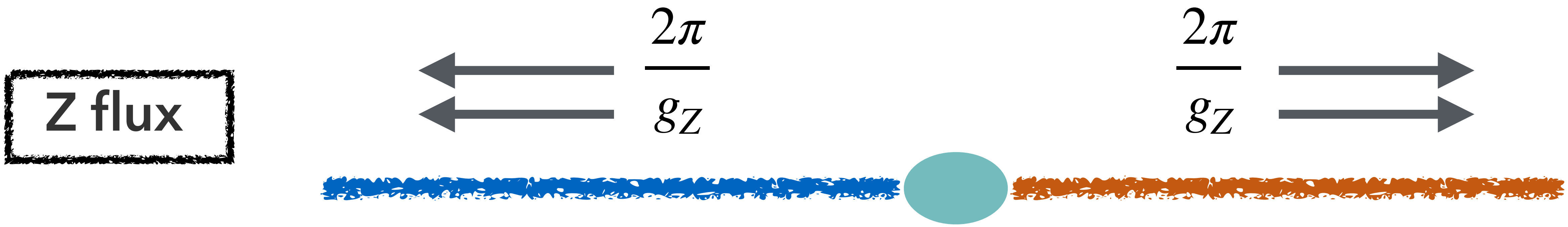
Although 2HDM is just a simple extension of the SM, there arise various aspects that have not been in the SM !

Backup Slides

Magnetic Flux



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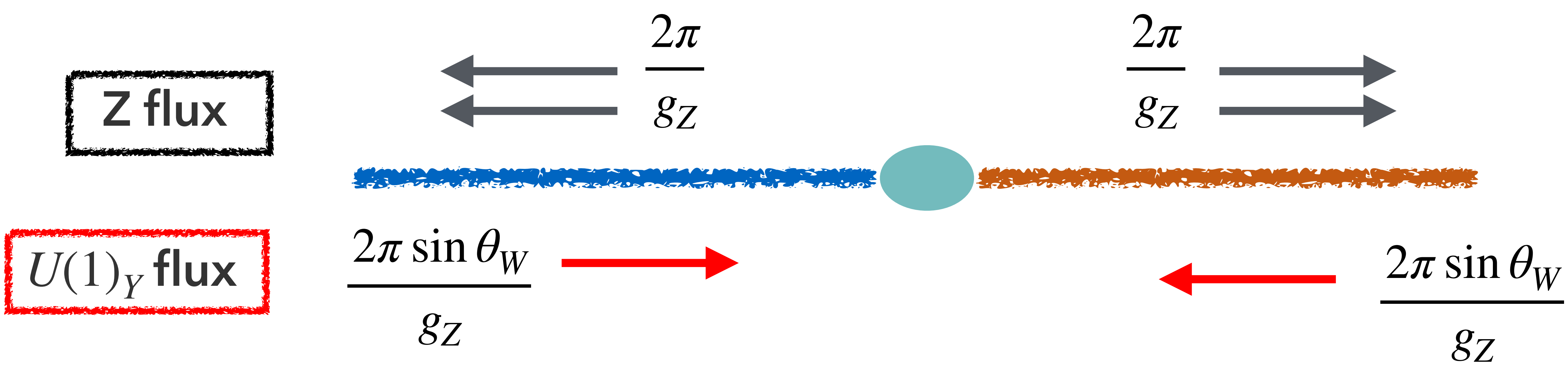

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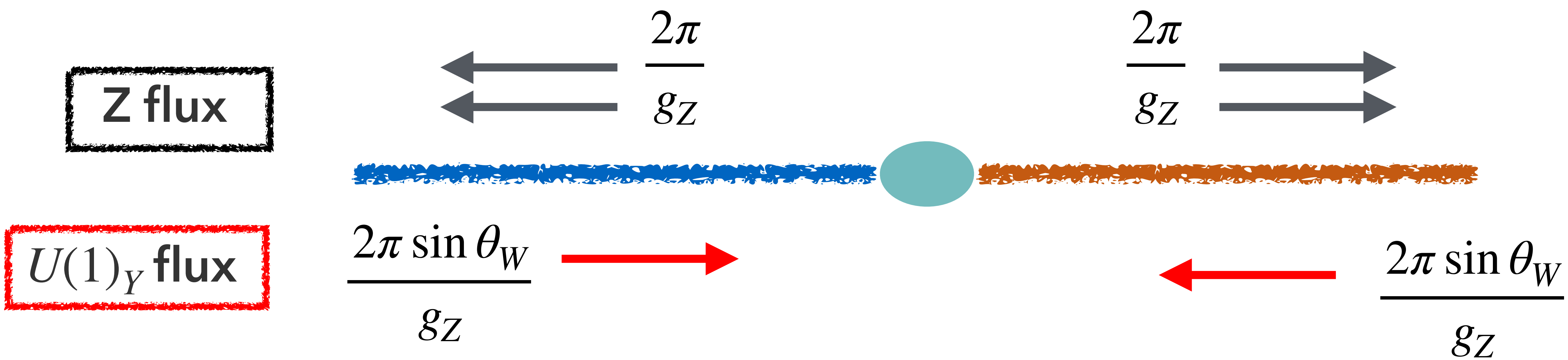

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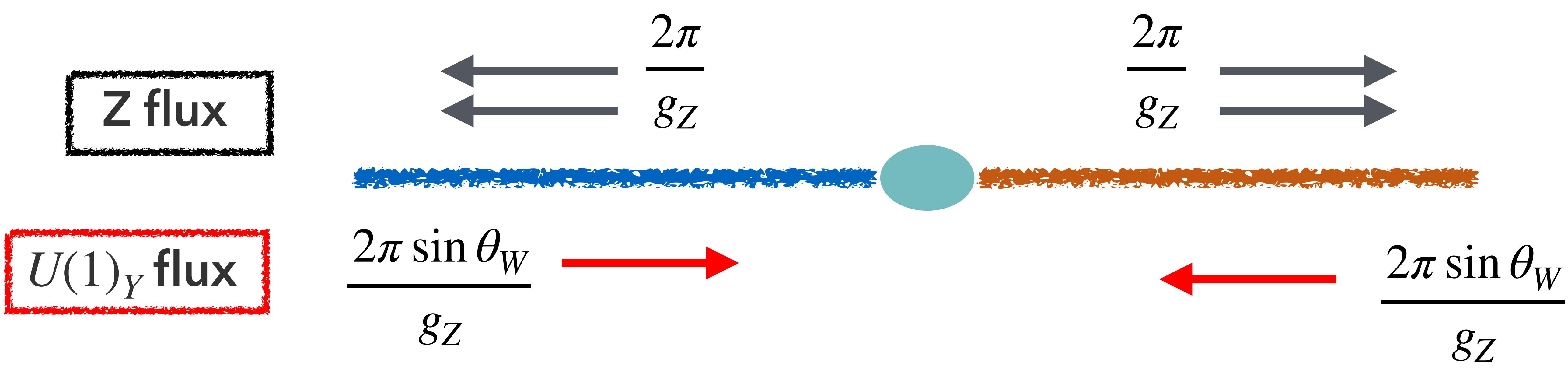

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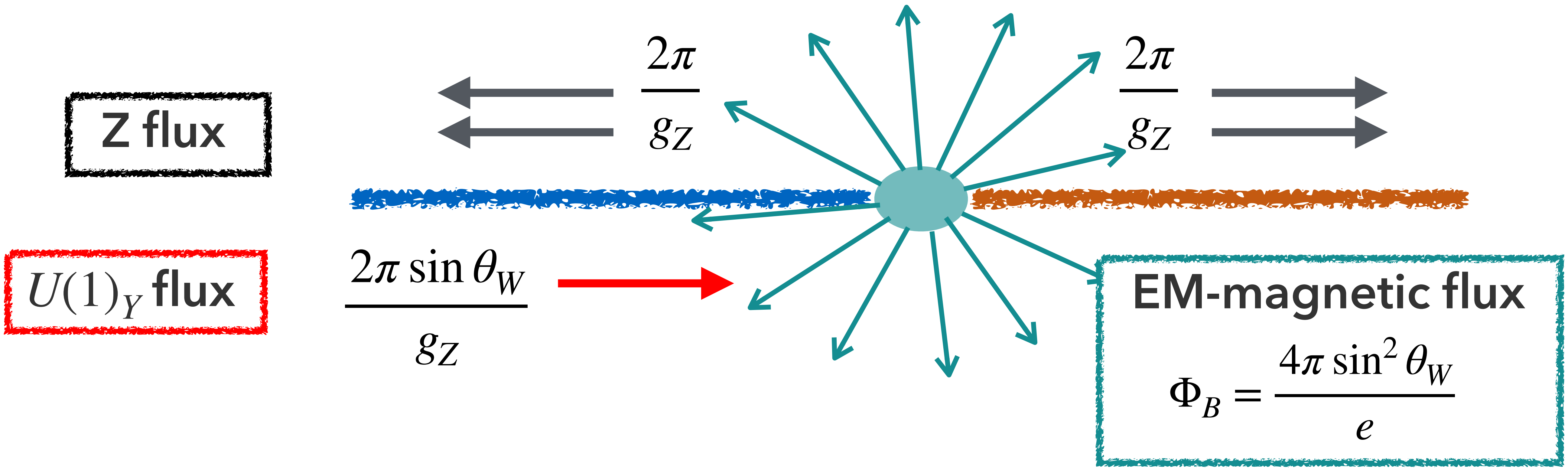

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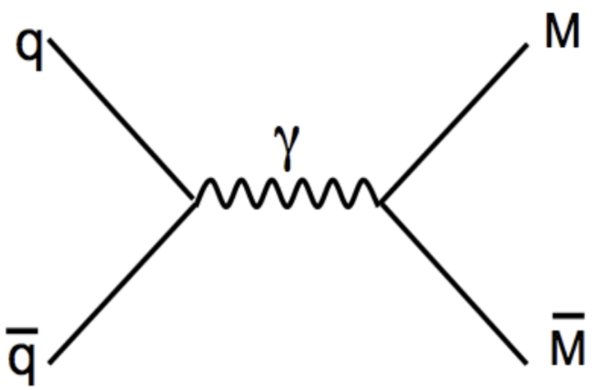
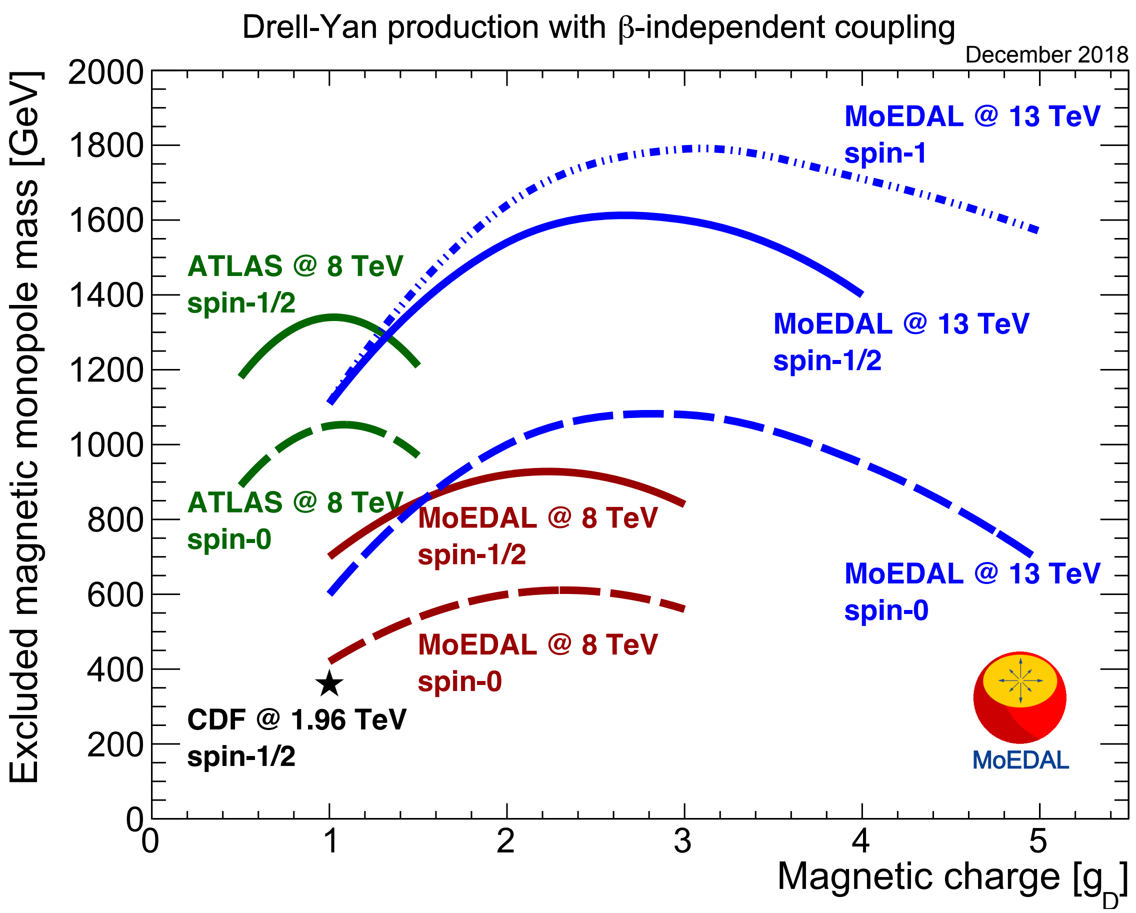
➧ **Elemag flux $4\pi \sin^2\theta_W / e$ spreads from the center.**

Monopole production at colliders

- Conventional process

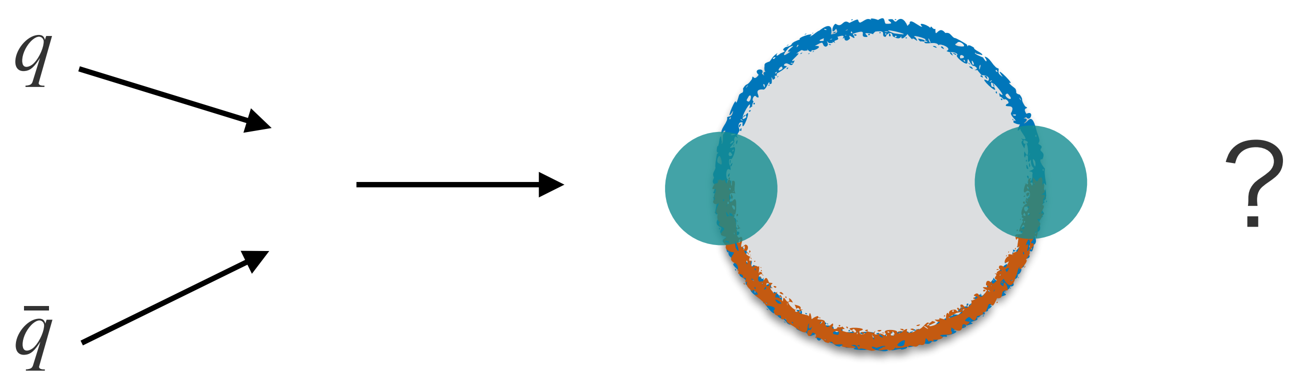


Drell Yan mechanism



From A. Santra's slide

- For our monopole,



monopole-antimonopole ring

If it decays into SM particles, can we see it as a resonance ?