Electroweak axion string and superconductivity

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Based on JHEP 06 (2021) 172 (arXiv:2010.02834)

w/
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Asia-Pacific Workshop on Particle Physics and Cosmology 2021 (3 Aug. 2021)

QCD Axion

[Peccei-Quinn '77]
[Weinberg '77] [Wilczek '77]

- one of the most popular BSMs

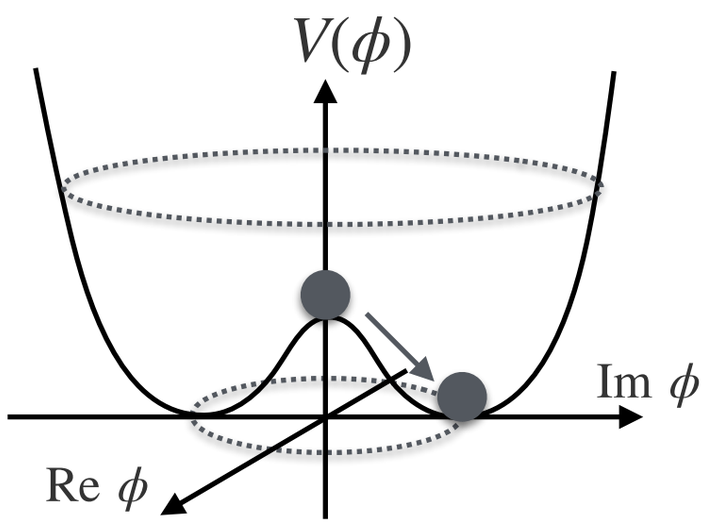
- appears when one extends SM scalar sector and introduces Peccei-Quinn sym. $U(1)_{PQ}$

  → SSB of $U(1)_{PQ}$ → **NG boson = axion** a

  - solves strong CP problem

$$|\theta_{QCD}| \lesssim 10^{-10}$$

  - axion a can be DM candidate



Axion string

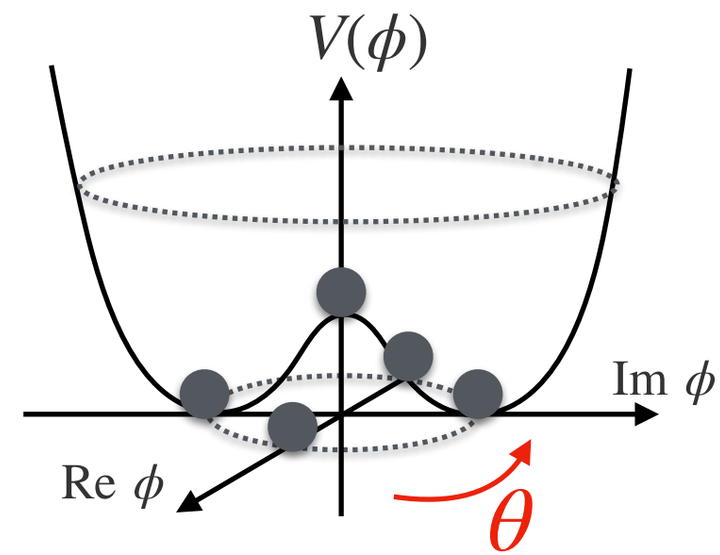
- string-like soliton (vortex string) associated with $U(1)_{PQ}$ breaking

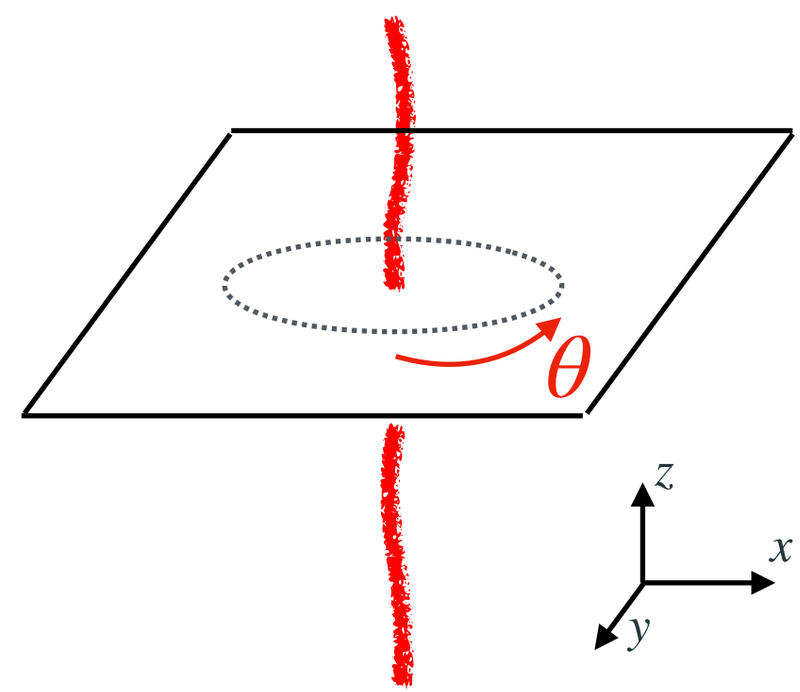
$$\phi(x) \sim v_{PQ}\, e^{i\theta}$$

- Spatial angle θ is identified with phase of $U(1)_{PQ}$ scalar ϕ

→ topologically non-trivial

(winding number 1)





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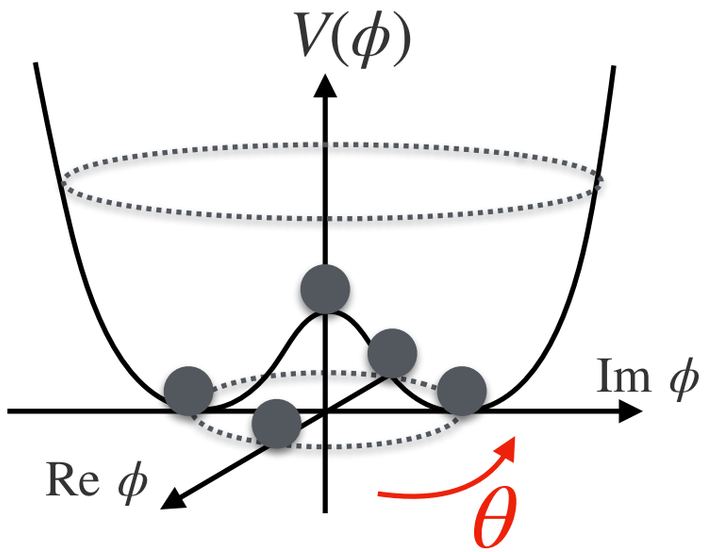
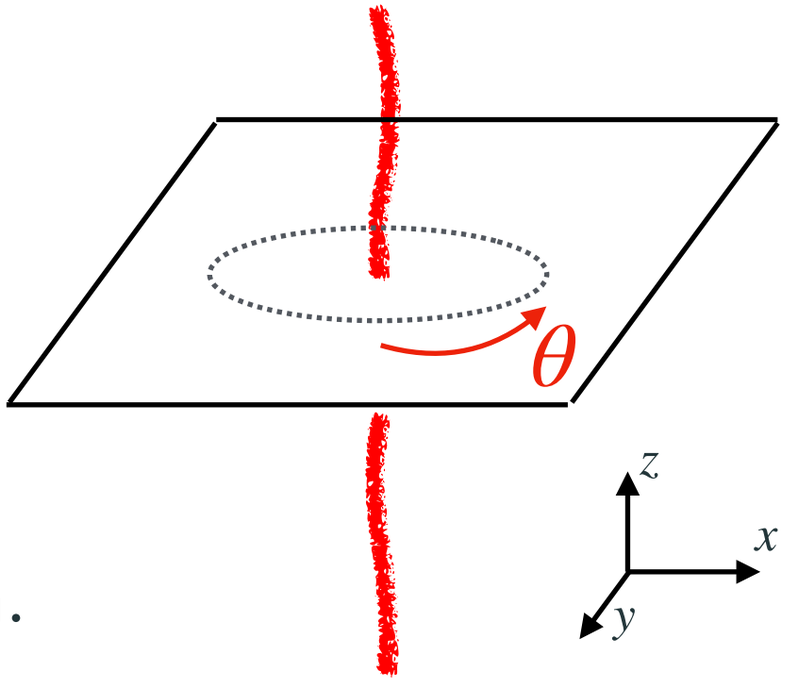


- Spatial angle θ is identified with phase of $U(1)_{PQ}$ scalar ϕ

→ topologically non-trivial **(winding number 1)**

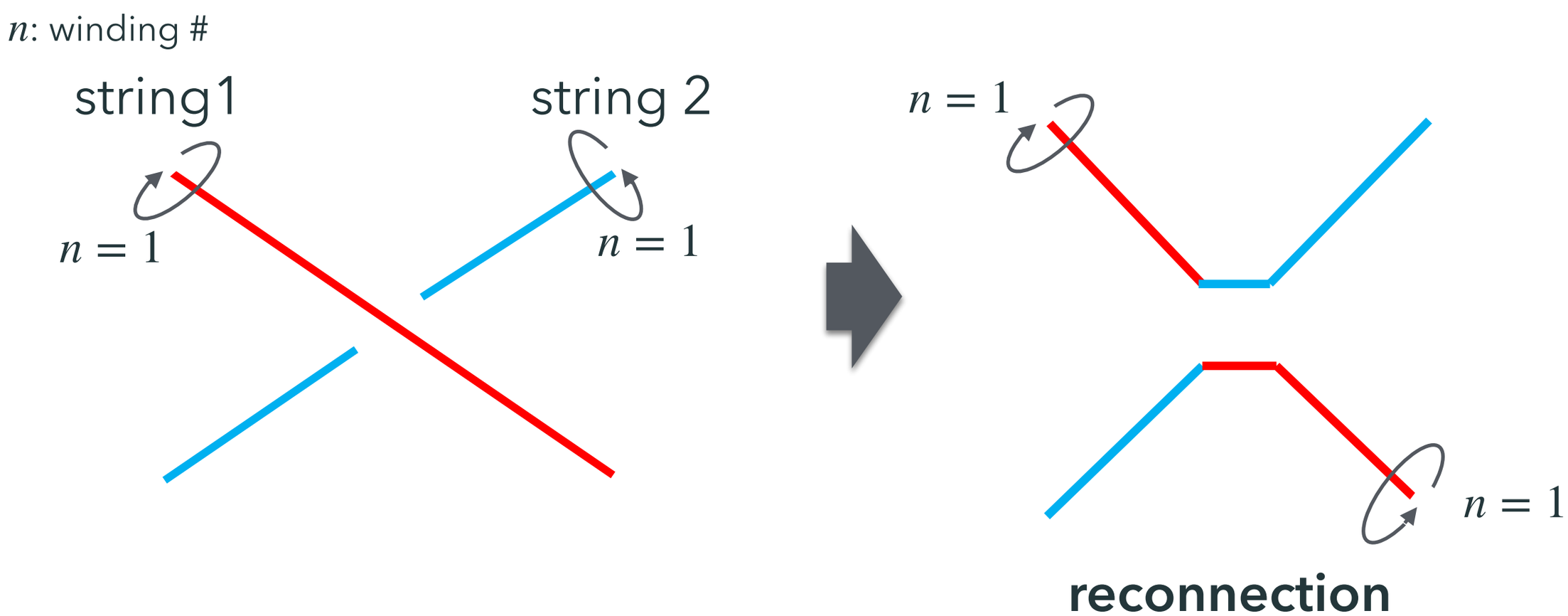


- Axion string is produced in the early universe if $U(1)_{PQ}$ is broken after inflation.

[Kibble, '80] [Zurek, '85]

String reconnection

- The most important property characterizing the string dynamics is **reconnection process.**



String reconnection

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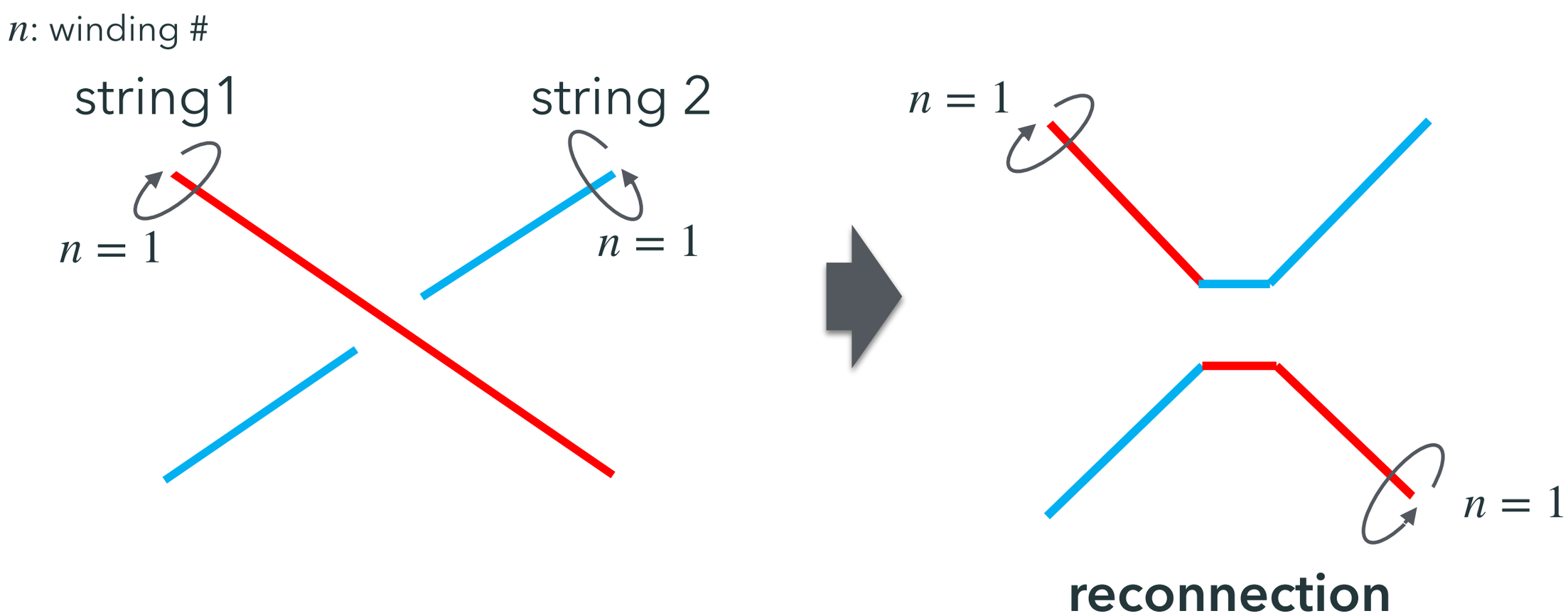
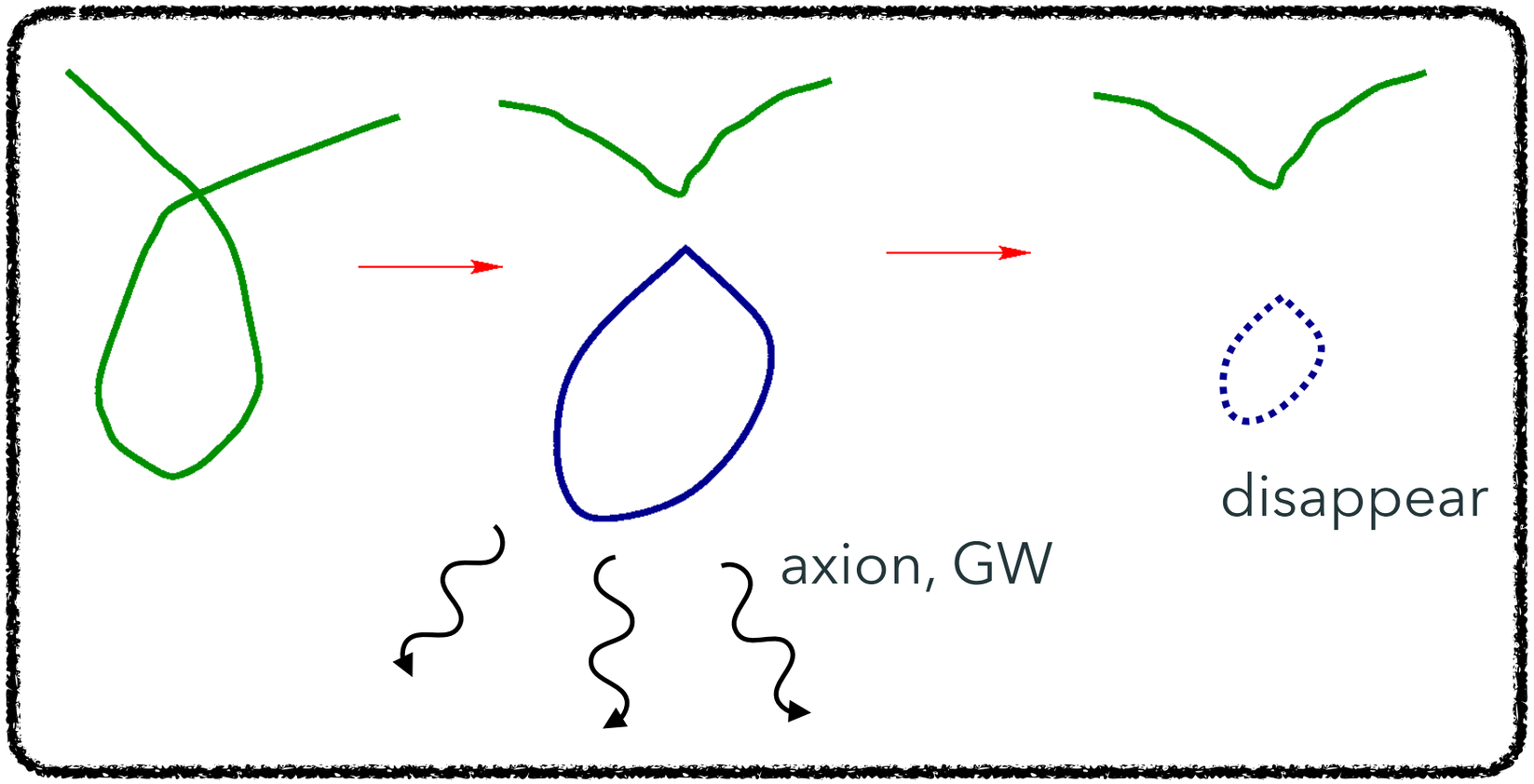


- It has been believed that **axion strings almost always reconnect** when they collide.

Energy-loss mechanism of strings

- Thanks to the reconnection, the axion strings can loose their energy by theirselves.



https://curl.irmp.ucl.ac.be/~chris/strings.html

$$\therefore \frac{\rho_{string}}{\rho_\gamma} \ll 1$$

Reconnection is a very important property, without which the strings dominate the universe $(\rho_{sting}/\rho_\gamma \to 1)$.

Question:
Do axion strings always reconnect?
(It has been believed that this is true.)

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Do axion strings always reconnect?
(It has been believed that this is true.)

Our answer is NO!
Key property is superconductivity!

Eg.) Witten's superconducting string

[Witten '80]

$$\mathscr{L} \supset |\partial_\mu \phi|^2 + |D_\mu \sigma|^2 - V(\phi, \sigma) \qquad \phi \sim v_\phi e^{i\theta}$$

EM neutral **EM charged**

$$V(\phi, \sigma) = \lambda_\phi(|\phi|^2 - v_\phi^2)^2 + \lambda_{mix}(|\phi|^2 - v_\phi^2)|\sigma|^2 + m_\sigma^2|\sigma|^2 + \lambda_\sigma|\sigma|^4$$

$$\longrightarrow \quad -(\lambda_{mix} v_\phi^2 - m_\sigma^2)|\sigma|^2 + \lambda_\sigma|\sigma|^4$$

(inside the string, $\phi = 0$)

$\langle\sigma\rangle \neq 0$ ➡ $\cancel{U(1)_{EM}}$

- EM-charged scalar boson σ condensates only inside the string.

→ breaks $U(1)_{EM}$ inside the string

→ string becomes **superconducting state**

Message of this talk

We found that, in DFSZ axion model, the axion strings can be superconducting string and may not reconnect successfully.

→Cosmological evolution of axion strings is non-trivial than previously thought!

Plan of talk

- Introduction
- Axion string with electroweak flux
- Implication of superconductivity
- Summary

Axion string with electroweak flux

DFSZ axion model

[Zhitnitsky, '80] [Dine-Fischler-Srednicki, '83]

two Higgs doublets: H_1, H_2 + singlet scalar: S

	H_1	H_2	S
$SU(2)_W$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	1	1	0

$$V(H_1, H_2, S) \supset \left(\kappa S^2 H_1^\dagger H_2 + \mathrm{h.c.}\right) + \kappa_{1S}|H_1|^2|S|^2 + \kappa_{2S}|H_2|^2|S|^2$$

- global $U(1)_{PQ}$ symmetry:

$$\boxed{S \to e^{i\alpha} S \qquad H_1 \to e^{i\alpha} H_1 \qquad H_2 \to e^{-i\alpha} H_2}$$

- assume VEVs:

$$\langle S \rangle = v_{PQ} \qquad \langle H_1 \rangle = (0, v_1)^T \qquad \langle H_2 \rangle = (0, v_2)^T$$

$$v_{PQ} \sim 10^{9-12}\,\mathrm{GeV} \qquad v_{EW}^2 = 2(v_1^2 + v_2^2) \simeq (246\,\mathrm{GeV})^2$$

In the following, $v_1 = v_2$ for simplicity

Axion string in DFSZ model

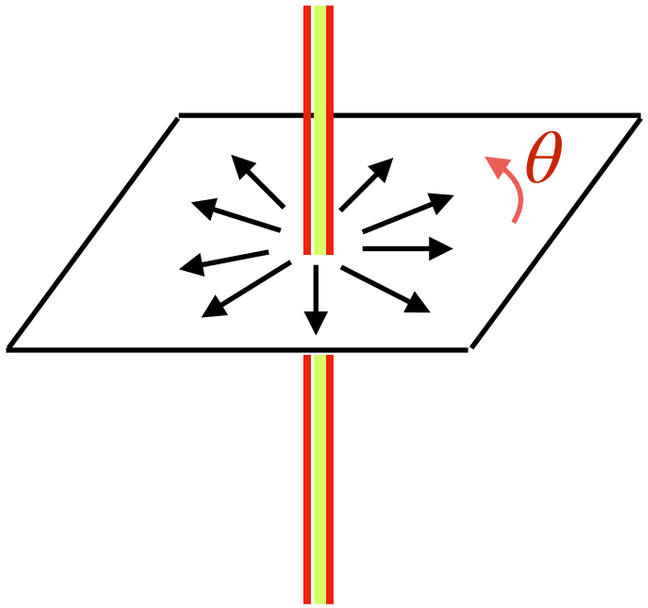
High Temperature: $v_{EW} \ll T \lesssim v_{PQ}$

- $U(1)_{PQ}$ is broken, but electroweak sym. remains

  →**ordinary axion string** in DFSZ model

$$x + iy = re^{i\theta}$$

- The Higgs doublets acquire **no VEVs.**



$$S \sim v_{PQ}\, e^{i\theta}$$

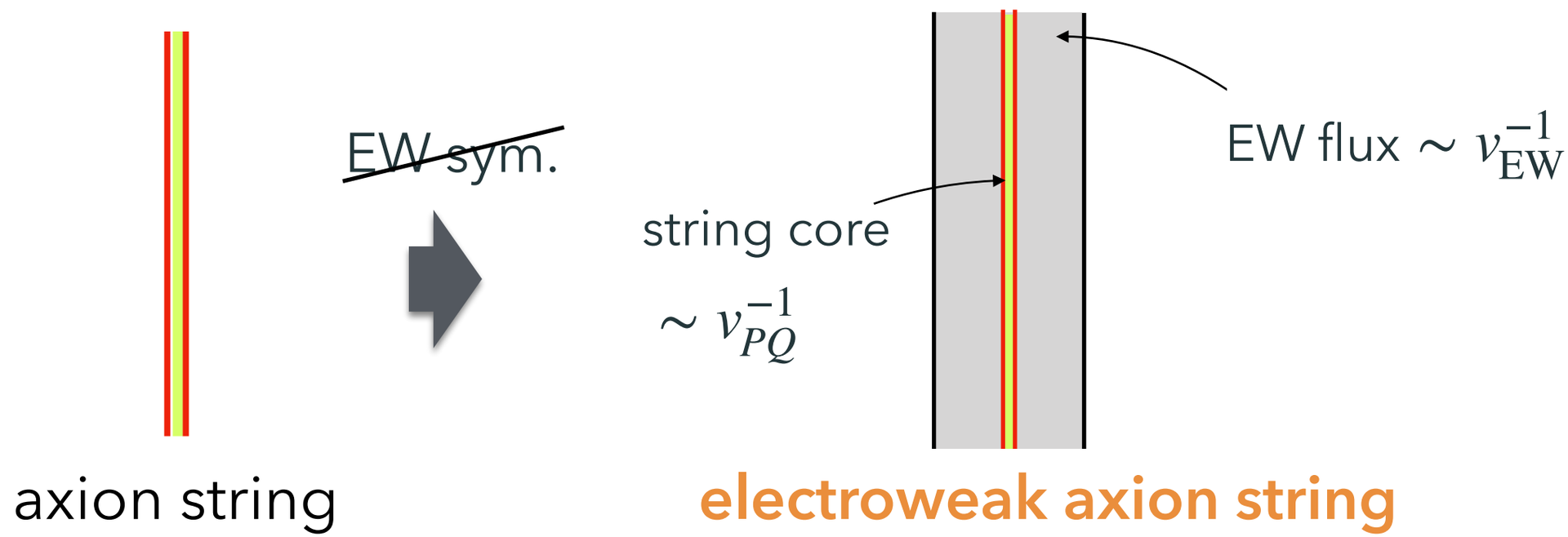
$$H_1 = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad H_2 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Axion string with EW flux (EW axion string)

Low temperature: $T \lesssim v_{EW}$ → EW sym. is also broken

- The Higgs doublets also **acquire non-zero VEVs.**

→ **The doublets can have winding phases → EW flux tube**



- There are three types of EW axion strings, but I will show one of them. (please see our paper)

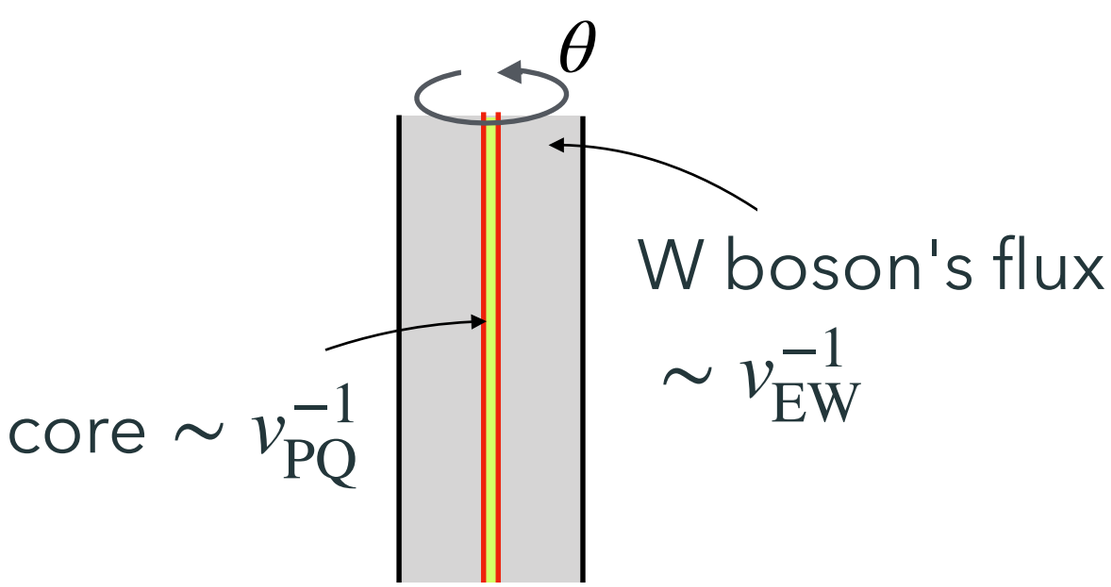
EW axion string is superconducting!

- configuration of EW axion string

$$S \sim v_{PQ} e^{i\theta} \qquad H_1 \sim e^{i\theta} e^{i\theta\sigma_1} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad H_2 \sim e^{-i\theta} e^{i\theta\sigma_1} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$U(1)_{PQ}$ **winding** **winding in σ_1-direction**

- contains W-flux tube (flux tube of W boson)



Charged bosons condensate in the string and break $U(1)_{\rm EM}$ sym!

→ superconducting string

Note: This configuration is a solution of EOM for some parameter.

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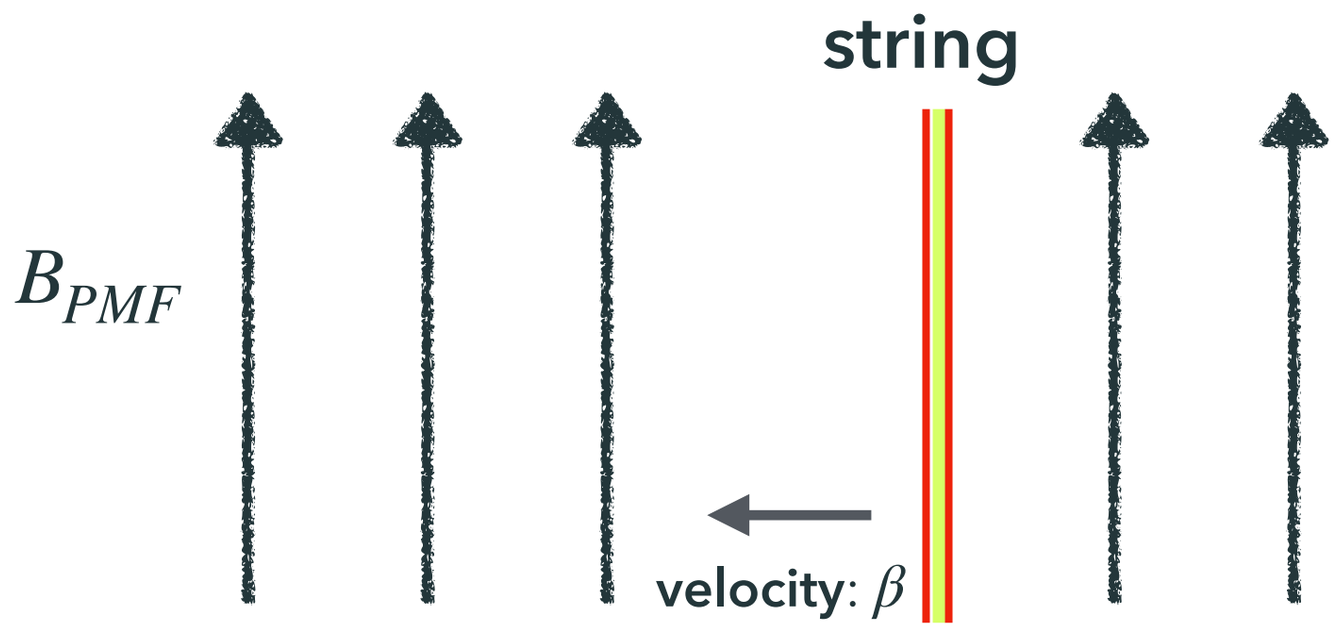
Implication of superconductivity

Primordial magnetic field induce current

- assume existence of primordial magnetic field in early universe
- When a superconducting string moves in the background of PMF, electric current is induced.



- Using observational upper bound on the magnetic field: $B_0 \lesssim 10^{-11}\,(\mathrm{Gauss})$,

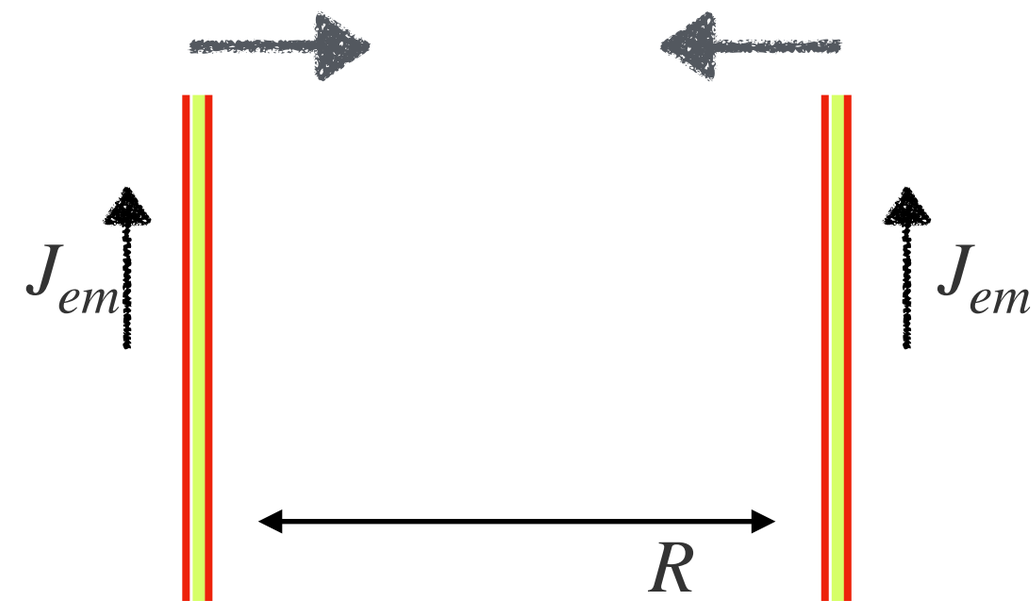
$$J_{em} \sim e^2 B \beta t \lesssim 10^{12}\,(\mathrm{GeV})$$

Large electric current can be induced.

Interaction between the strings

- Current-induced magnetic interaction between the strings

attractive force: $F_{mag} \simeq \dfrac{v_{PQ}^2}{e^2 R}$



- On the other hand, axion-induced interaction is repulsive force:

$$F_{axion} \sim v_{PQ}^2 / R$$

- The magnetic interaction can dominate the string interaction.

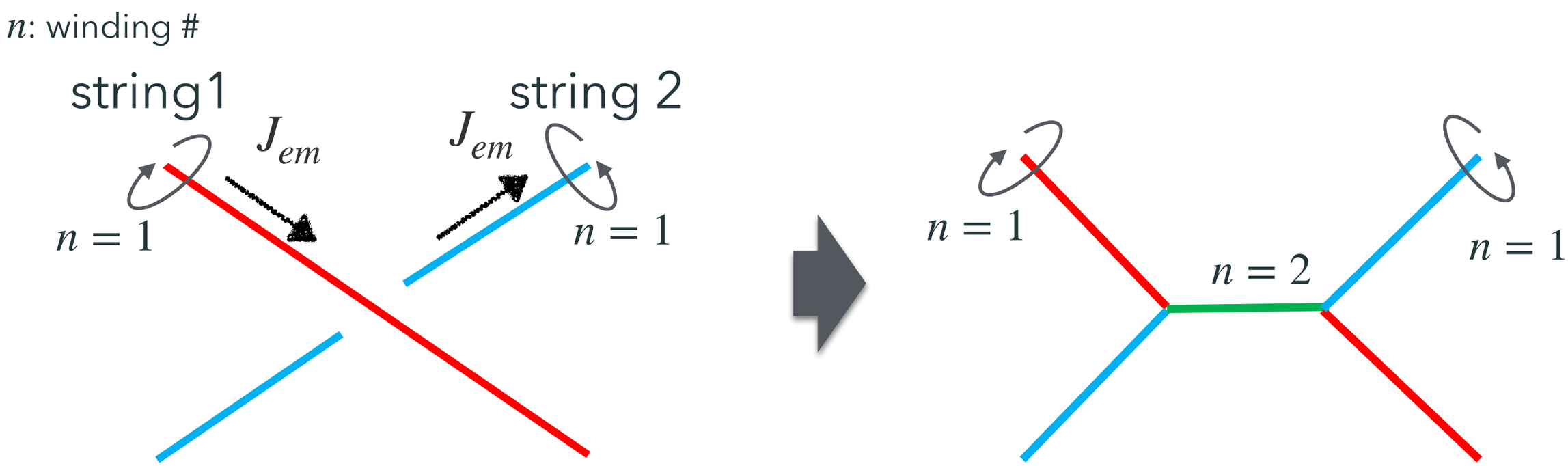
→ **affect the reconnection process of the strings**

String Y-junction

[Bettencourt-Kibble '94]

[Bettencourt-Laguna-Matzner '96]

- Due to such a long-range attractive force, the strings can form **a bound state, called Y-junction.**



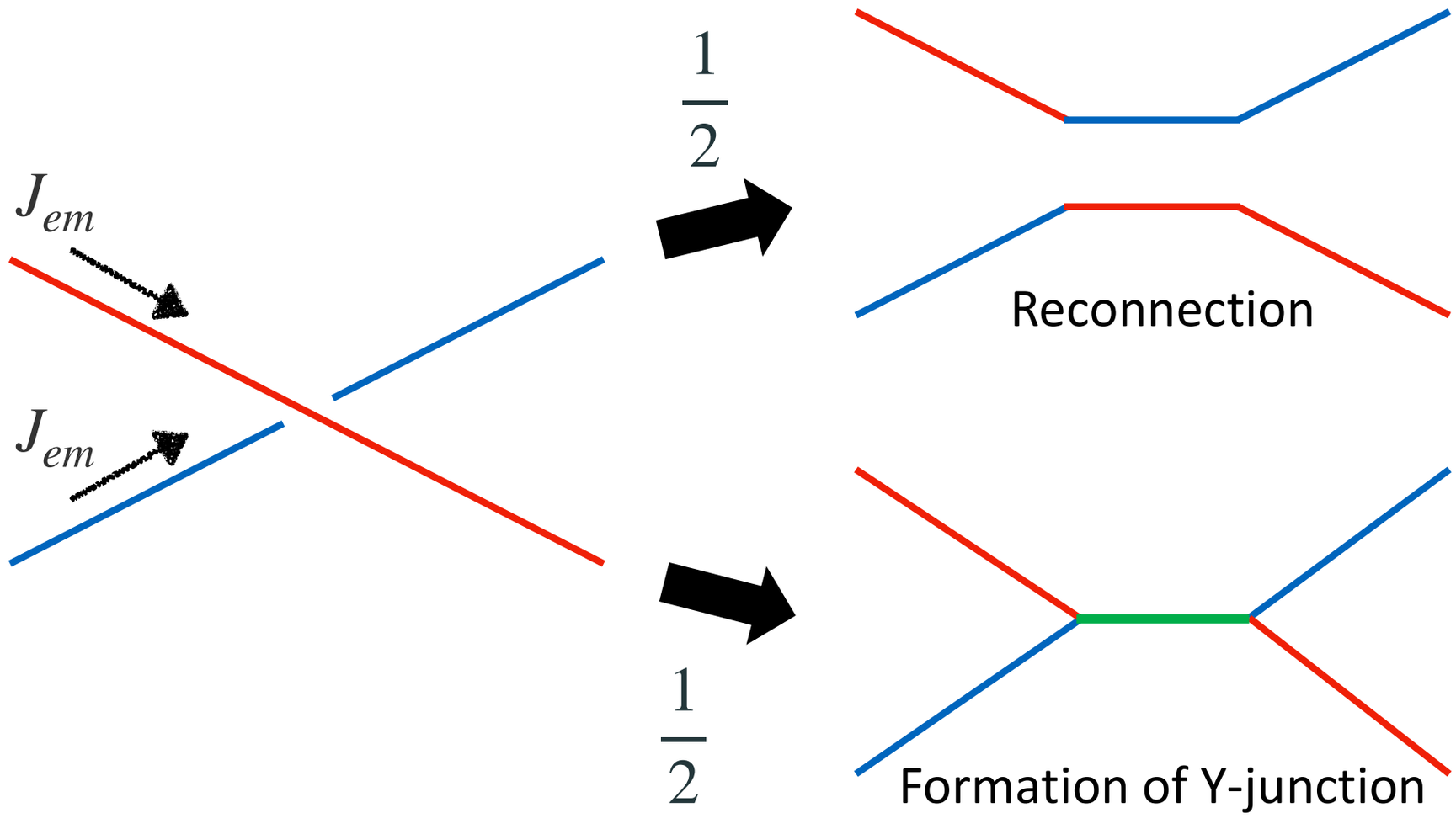
Y-junction = bound state

→ Reconnection doesn't work

Superconductivity may spoil the reconnection property!

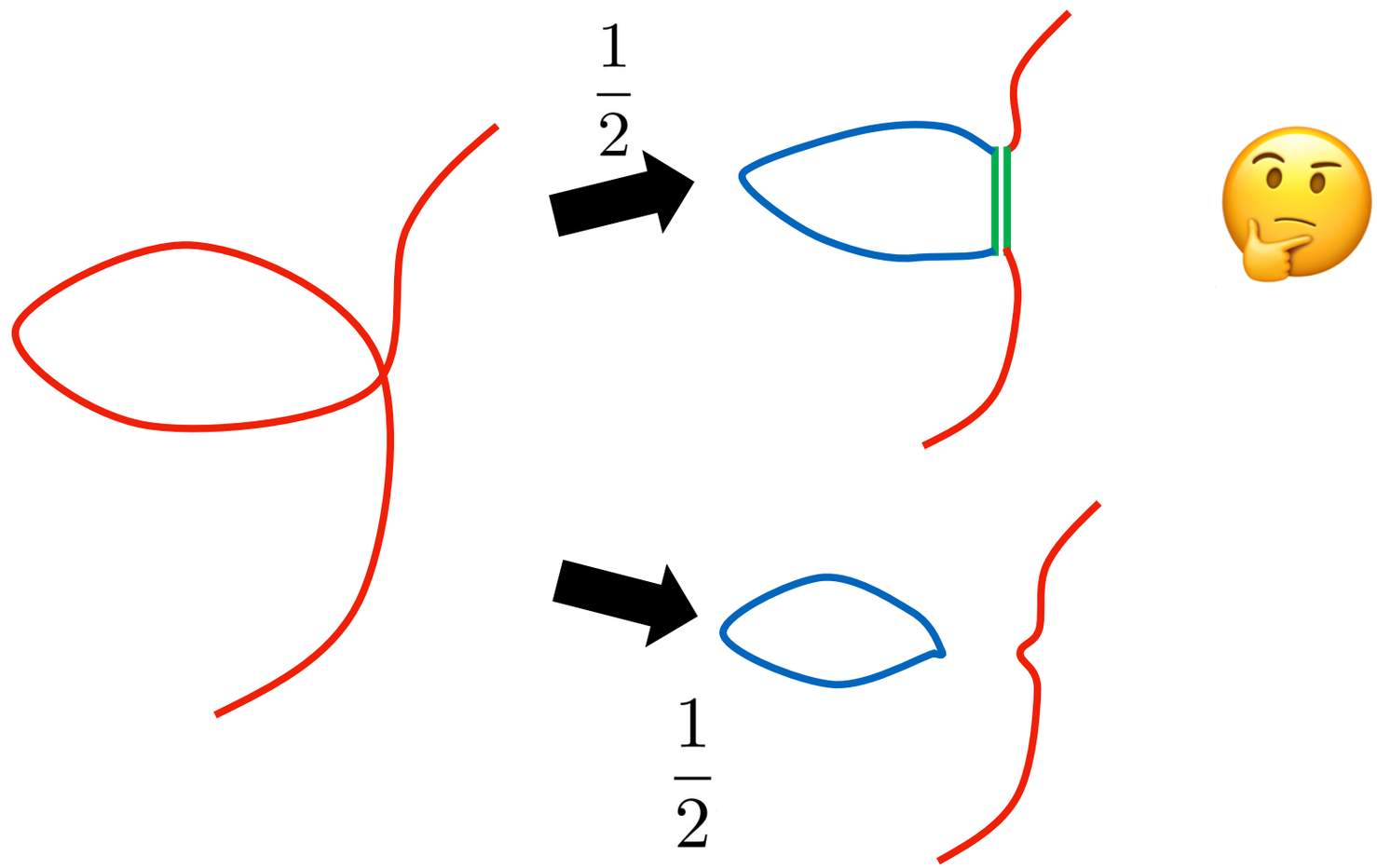
Probability of formation of Y-junctions

- The probability of the formation of Y-junctions is roughly estimated to be $\sim 1/2$.



Probability of formation of Y-junctions

- When an EW axion string intersects with itself, it creates an exotic object with probability 1/2.



Cosmological evolution is non-trivial any more!

Summary

- Reconnection of axion strings is a very important process to avoid dominating the energy of the universe.

- In DFSZ model, axion strings obtain electroweak gauge fluxes after the EW sym. breaking. (EW axion string)

- EW axion string breaks $U(1)_{EM}$ inside it, leading to superconductivity.

- Assuming background of PMF, the strings do not reconnect successfully, but form a bound state (Y-junction).

→ affect cosmology?

Backup

Three types of EW axion strings

- type-A string :

$$S \sim v_{PQ}\, e^{i\theta} \qquad H_1 \sim \underline{e^{i\theta}} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad H_2 \sim \underline{e^{-i\theta}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$U(1)_{PQ}$ winding

- type-B string :

$$S \sim v_{PQ}\, e^{i\theta} \qquad H_1 \sim \underline{e^{i\theta}}\, \underline{e^{-i\theta\sigma_3}} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad H_2 \sim \underline{e^{-i\theta}}\, \underline{e^{-i\theta\sigma_3}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$U(1)_{PQ}$ $U(1)_Z$

- type-C string :

$$S \sim v_{PQ}\, e^{i\theta} \qquad H_1 \sim \underline{e^{i\theta}}\, \underline{e^{i\theta\sigma_1}} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad H_2 \sim \underline{e^{-i\theta}}\, \underline{e^{i\theta\sigma_1}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$U(1)_{PQ}$ $U(1)_{W^1}$

String tensions

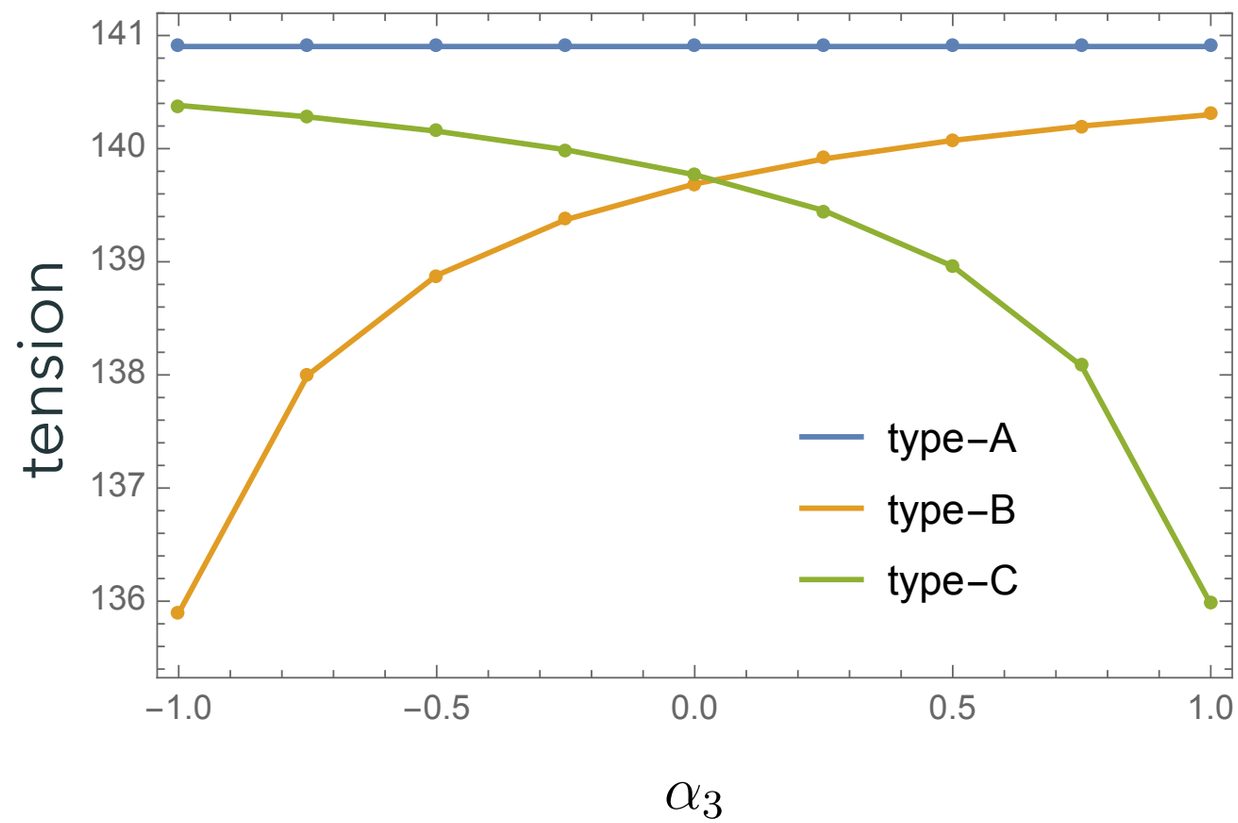
- Compare the tensions of the three strings

$v_{PQ} = 10\, v_1 \qquad m_h^2 = (125\ \mathrm{GeV})^2 \qquad \tan\beta = 1$

$\kappa_{1S} = \kappa_{2S} = 1 \qquad \kappa = -2(v/v_s)^2 \qquad \lambda_S = 1$

length unit: $v_1 = 0.2$

$$\alpha_3 \equiv \frac{1}{8}\left(\beta_1 + \beta_2 - 2\beta_3\right)$$



- Type-C string can be the most stable string

→ not exotic, but **energetically favored in some parameter range!**

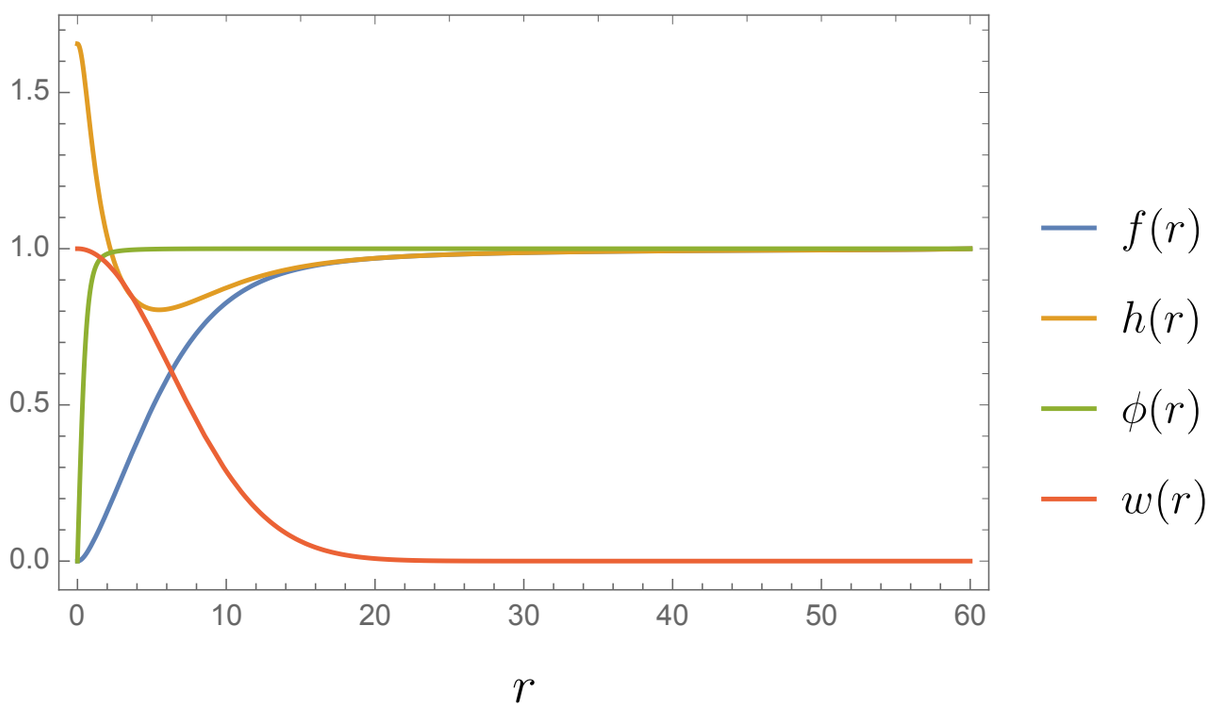
- In the range, **the axion string necessarily becomes type-C string** after the EW sym. breaking.

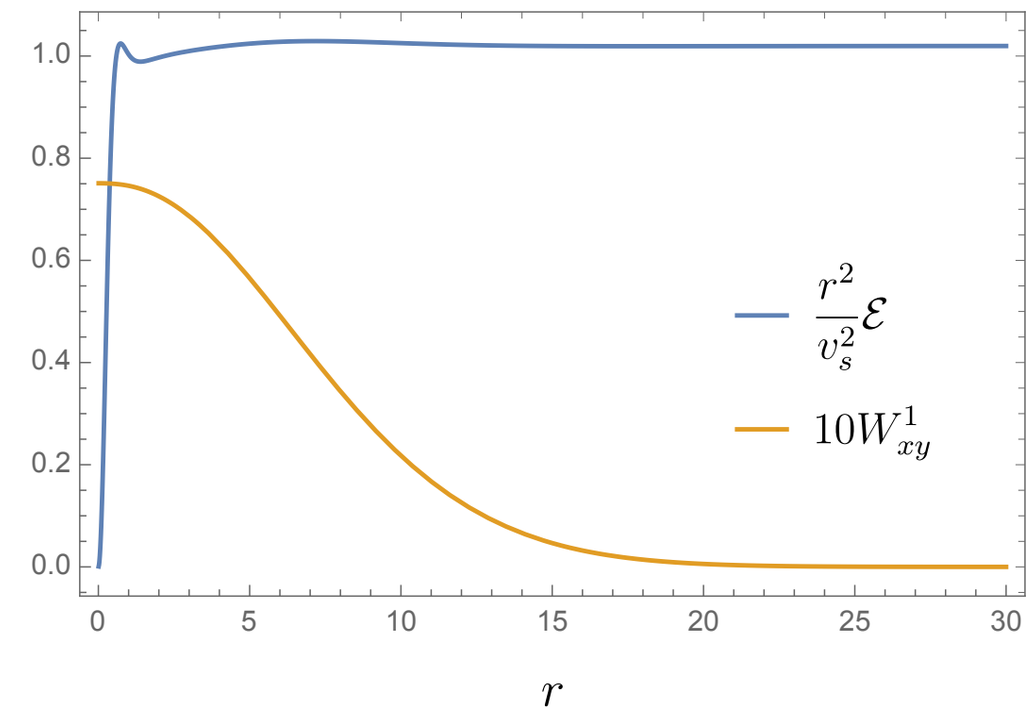
Numerical solution of type-C string

Again we take $\tan\beta = 1 \rightarrow Z$ flux vanishes.

$$H_1 = \frac{1}{2} v_1 \begin{pmatrix} f(r)e^{2i\theta} - h(r) \\ f(r)e^{2i\theta} + h(r) \end{pmatrix} \qquad H_2 = \frac{1}{2} v_2 \begin{pmatrix} h(r) - f(r)e^{-2i\theta} \\ h(r) + f(r)e^{-2i\theta} \end{pmatrix}$$

$$S = v_{PQ}\, \phi(r)\, e^{i\theta} \qquad W_\theta^1 = \frac{-4\pi}{g}(1 - w(r))$$





$$v_{PQ} = 10\, v_1 \qquad m_h^2 = (125\ \text{GeV})^2 \qquad \tan\beta = 1$$

$$\kappa_{1S} = \kappa_{2S} = 0.4 \qquad \kappa = -2(v/v_{PQ})^2 \qquad \lambda_S = 1$$

length unit: $v_1 = 0.2$

$U(1)_{EM}$ is broken inside the string!

- To see the inside of the string, we should use the "smeared" ansatz:

$$H_1 = \frac{1}{2} v_1 \begin{pmatrix} f(r)e^{2i\theta} - h(r) \\ f(r)e^{2i\theta} + h(r) \end{pmatrix} \qquad H_2 = \frac{1}{2} v_2 \begin{pmatrix} h(r) - f(r)e^{-2i\theta} \\ h(r) + f(r)e^{-2i\theta} \end{pmatrix}$$

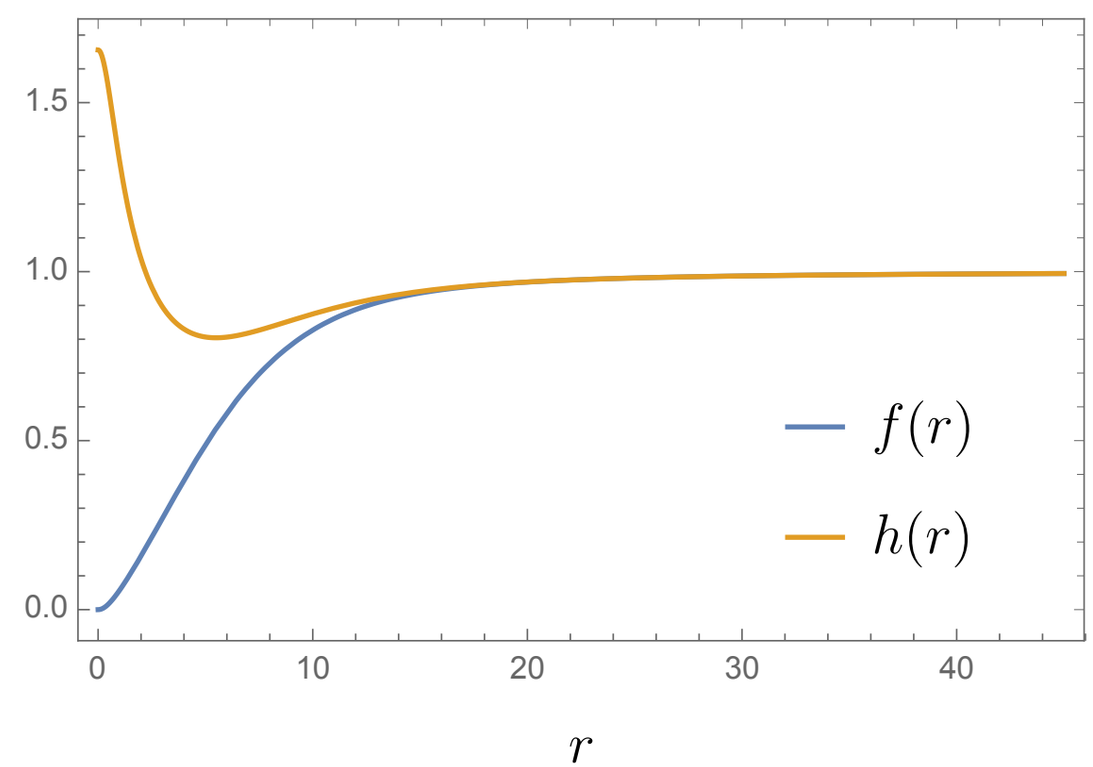
$\hat{Q}_{EM} : U(1)_{EM}$ generator

$$\hat{Q}_{EM} H_i \propto f - h \begin{cases} \to 0 & (r \to \infty) \\ \neq 0 & (r \lesssim v_{\mathrm{EW}}^{-1}) \end{cases}$$

$U(1)_{EM}$ **is spontaneously broken!**

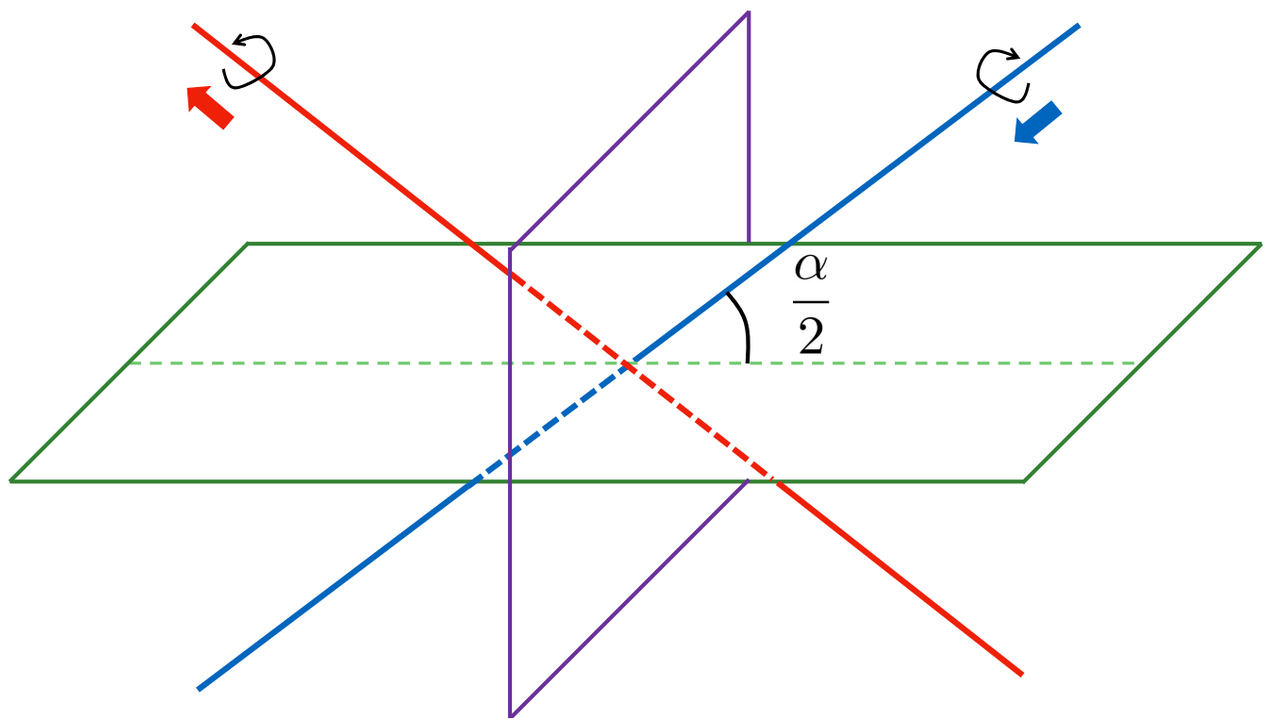
→ **superconducting state!**

$v_{PQ} = 2, \ v_1 = v_2 = 0.2$



Probability of formation of Y-junctions

- Reduce the 3D collision to two 2D collisions



- vortex-vortex collision forms a bound sate for $\alpha \gtrsim 10^{-3}$