Deconfinement-Higgs continuity in SU(2) adjoint Higgs model at finite temperature

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Hiromasa Watanabe (Keio U.)

Based on arXiv:2510.15493[hep-th]

- Motivation
- Our setup and proposal
- Lattice model and its schematic phase diagram
- Center-destabilizing deformation
- Summary and Discussion

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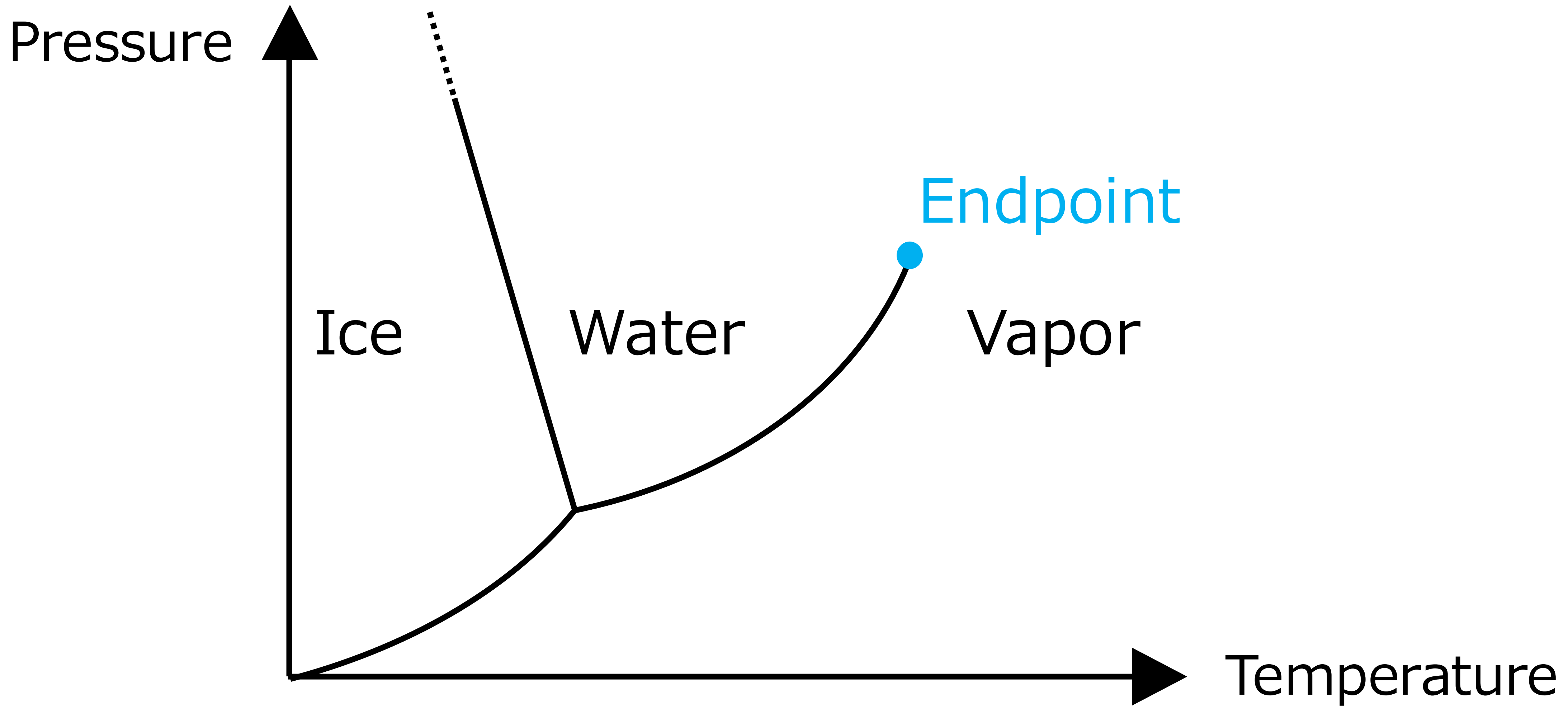
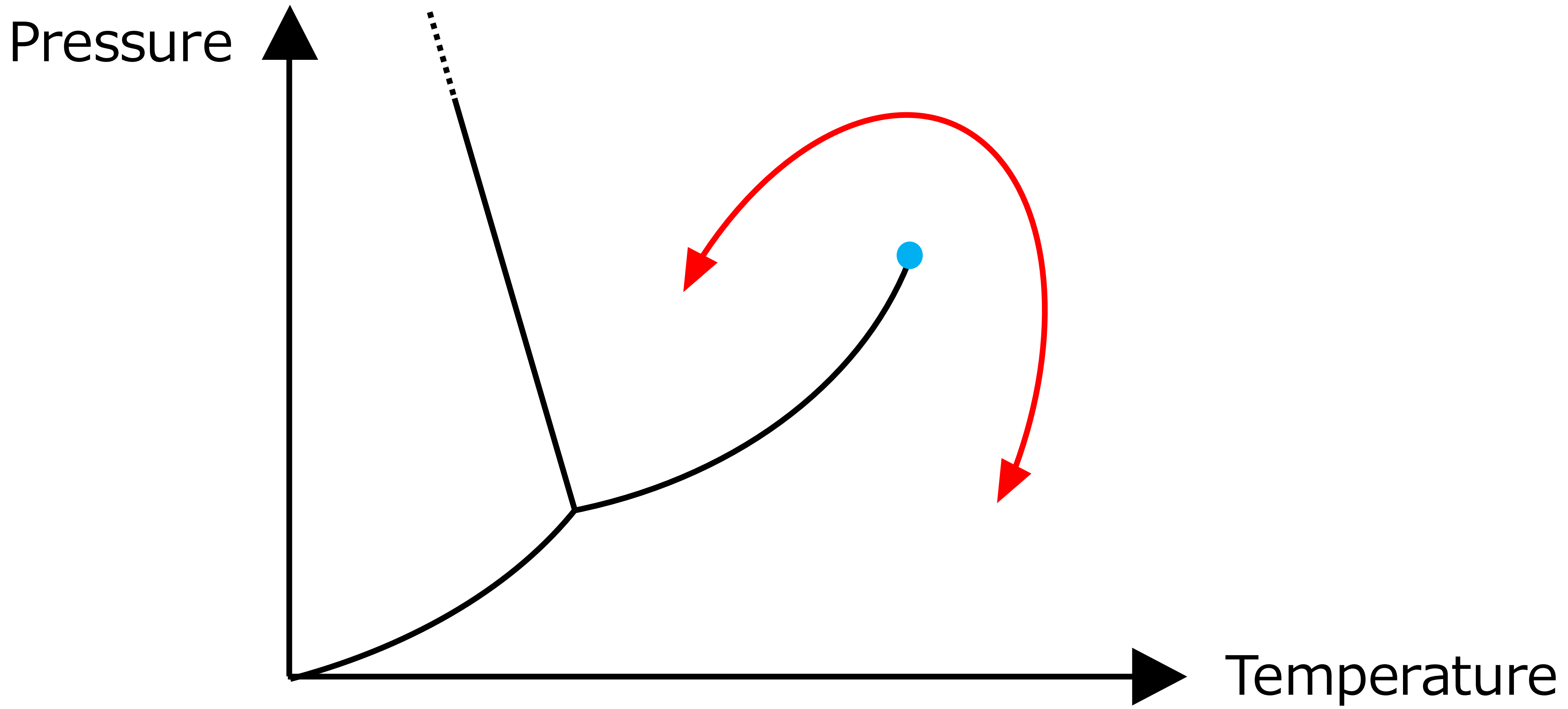
Continuity appears
in a wide range of physical phenomena.

Example 1: H_2O



Example 1: H_2O

This is the continuity between water and vapor.



Example 2: the Standard Model

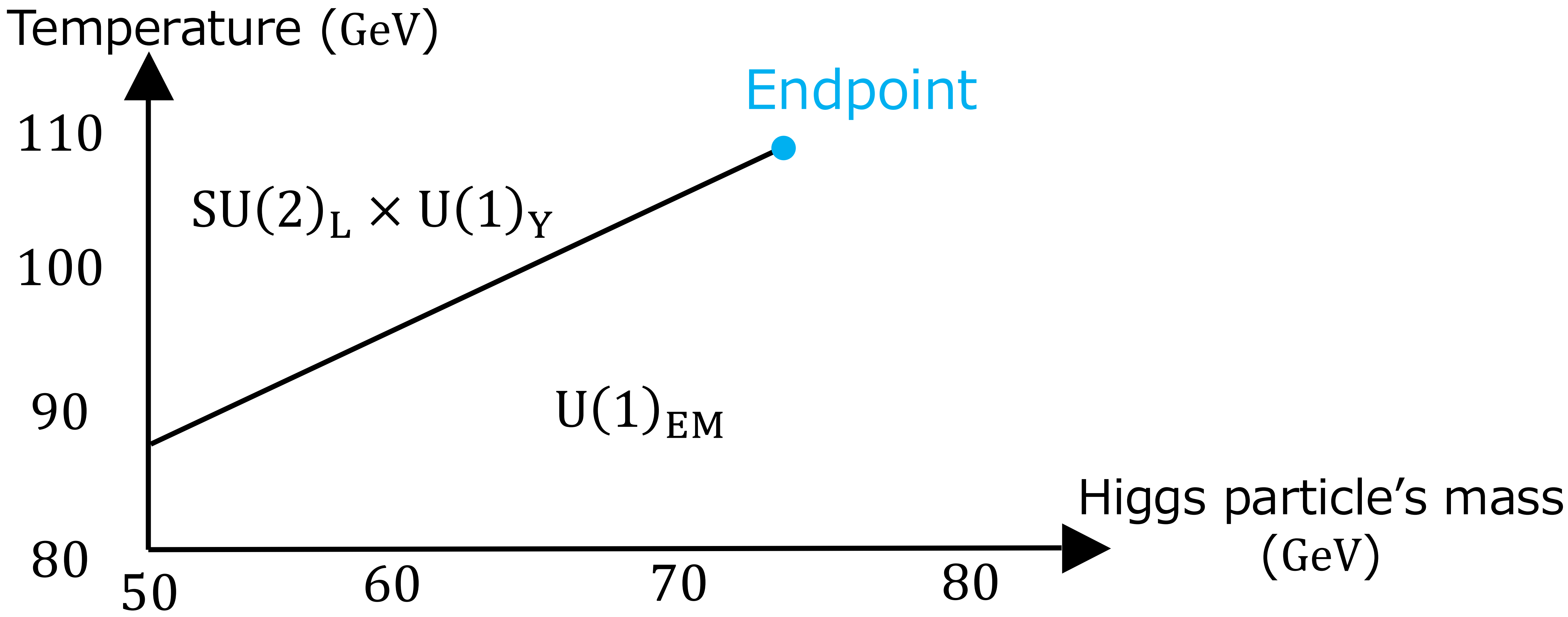
U

Electroweak sector

$$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$$ (at high temperature)

$$\mathrm{U}(1)_\mathrm{EM}$$ (at low temperature)

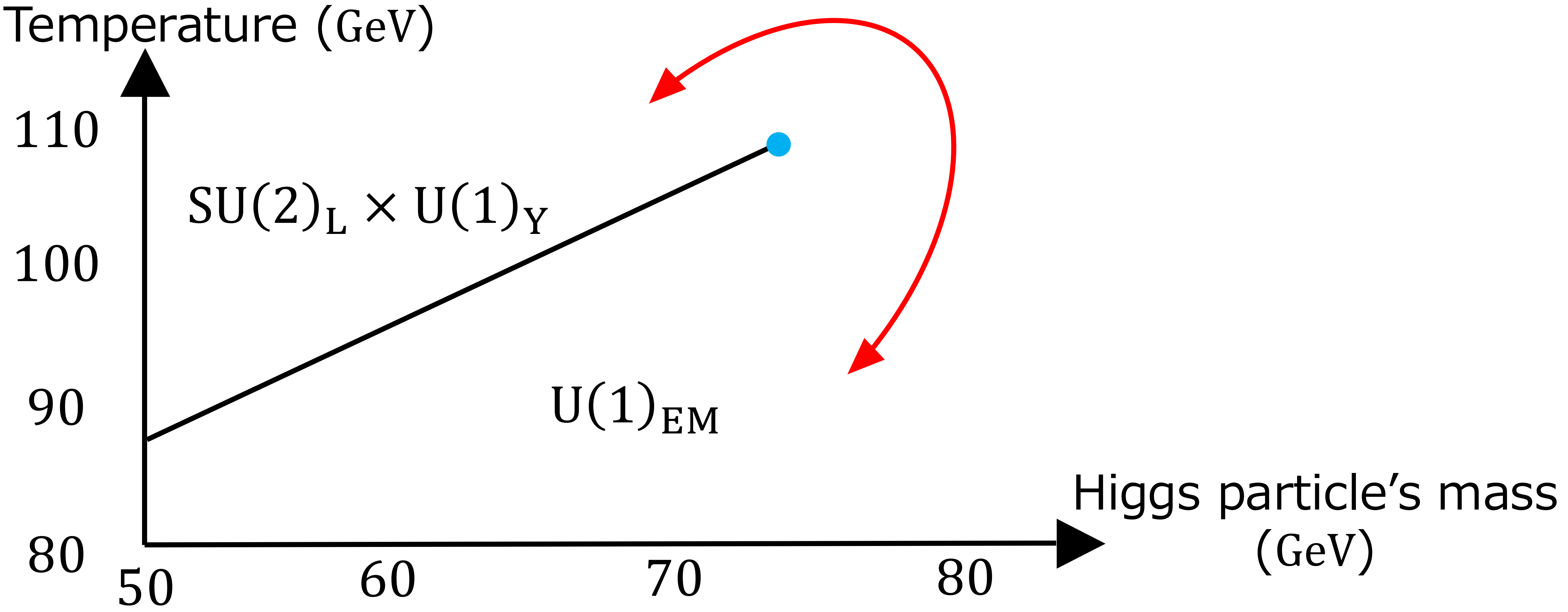
Example 2: the Standard Model



(based on [Laine(2000),⋯])

Example 2: the Standard Model

The continuity between symmetric and Higgs phases



(based on [Laine(2000),⋯])

Our motivation

The phase diagram with a fundamental Higgs

- Many studies

  e.g. Fradkin-Shenker's work, Electroweak Higgs, ⋯.

The phase diagram with an adjoint Higgs

- Few studies

Our motivation

The phase diagram with a fundamental Higgs

- Many studies

  e.g. Fradkin-Shenker’s work, Electroweak Higgs, ⋯.

The phase diagram with an adjoint Higgs

- Few studies, but important for BSMs like GUTs

GUTs need adjoint Higgs fields.

GUTs

- Spin(10) GUT — so called SO(10) GUT
- Pati-Salam GUT
- SU(5) GUT
- ⋮

adjoint Higgs

↓

the Standard Model

Phenomenology and cosmology usually assume that
the adjoint Higgs field induces the phase transition.

However, no one knows
whether this assumption is valid at the nonperturbative level.

If there is continuity,
some changes might be needed these areas.

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Our setup

SU(2) gauge field + adjoint Higgs field

$a_\mu = a_\mu^i \sigma^i$ $\qquad\qquad$ $\phi = \phi^i \sigma^i$

▶ $f_{\mu\nu} = f_{\mu\nu}^i \sigma^i$

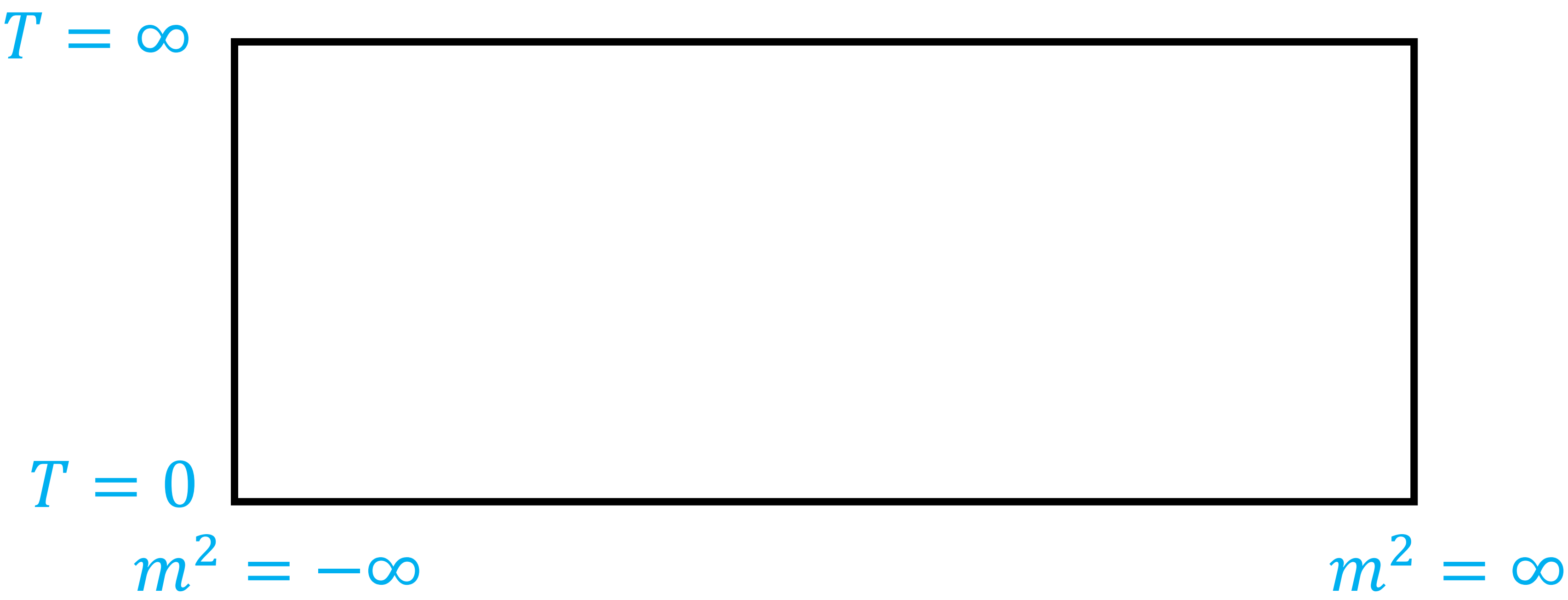
$$S = \int_0^\beta \mathrm{d}t \int \mathrm{d}^3\boldsymbol{x} \left[\frac{1}{4g^2}\mathrm{tr}\left(f^{\mu\nu} f_{\mu\nu}\right) + \frac{1}{2}\mathrm{tr}\left(D^\mu \phi D_\mu \phi\right) + V(\phi)\right]$$

$$D_\mu \phi = \partial_\mu \phi + i\left[a_\mu, \phi\right]$$

$$V(\phi) = m^2 \mathrm{tr}(\phi^2) + \lambda \mathrm{tr}(\phi^4)$$

Phase diagram

$$S = \int_0^{\beta} \mathrm{d}t \int \mathrm{d}^3\boldsymbol{x} \left[\frac{1}{4g^2} \mathrm{tr}\left(f^{\mu\nu} f_{\mu\nu}\right) + \frac{1}{2} \mathrm{tr}\left(D^{\mu} \phi D_{\mu} \phi\right) + m^2 \mathrm{tr}(\phi^2) + \lambda \mathrm{tr}(\phi^4) \right]$$



Phase diagram

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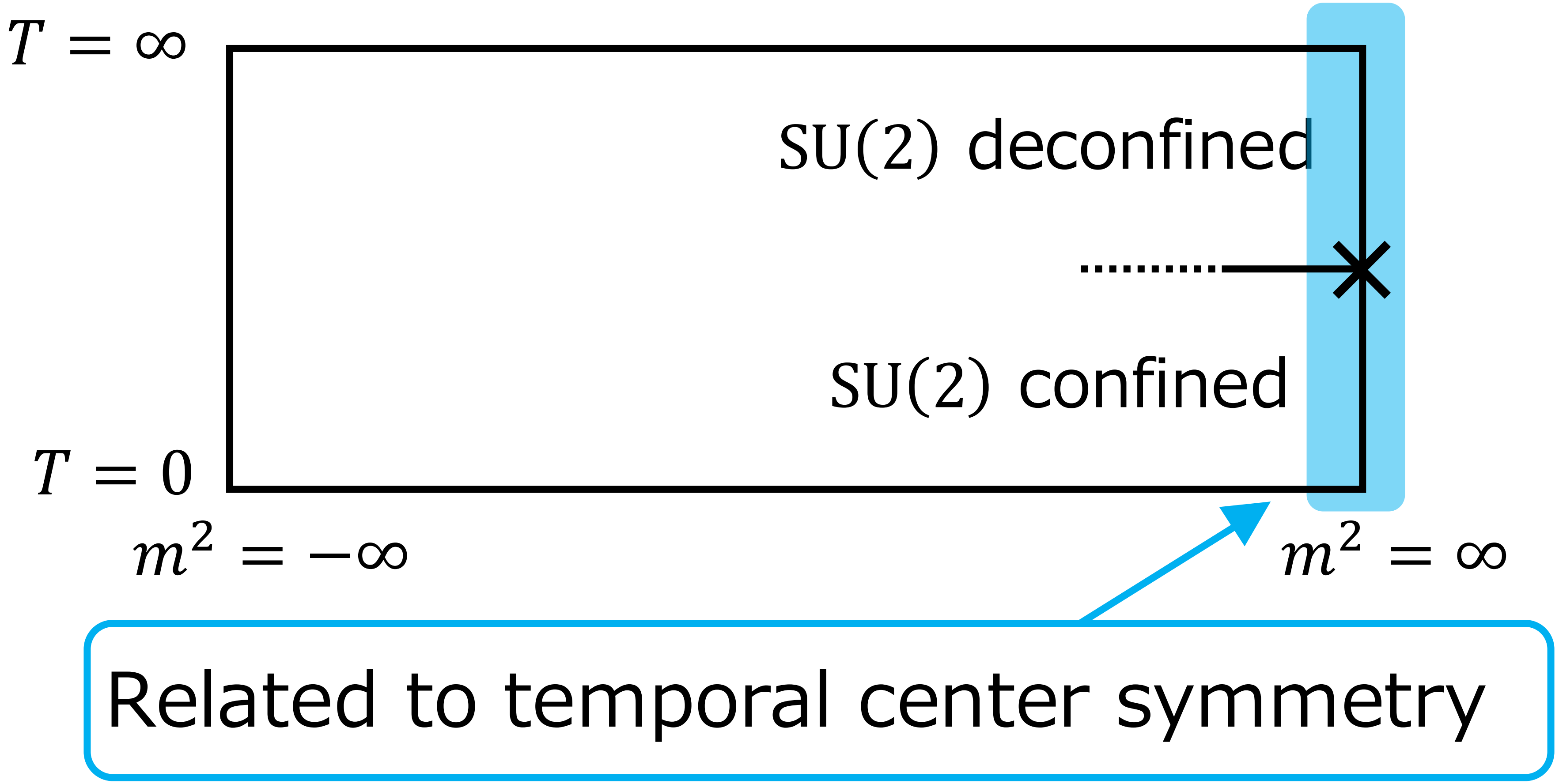

Phase diagram

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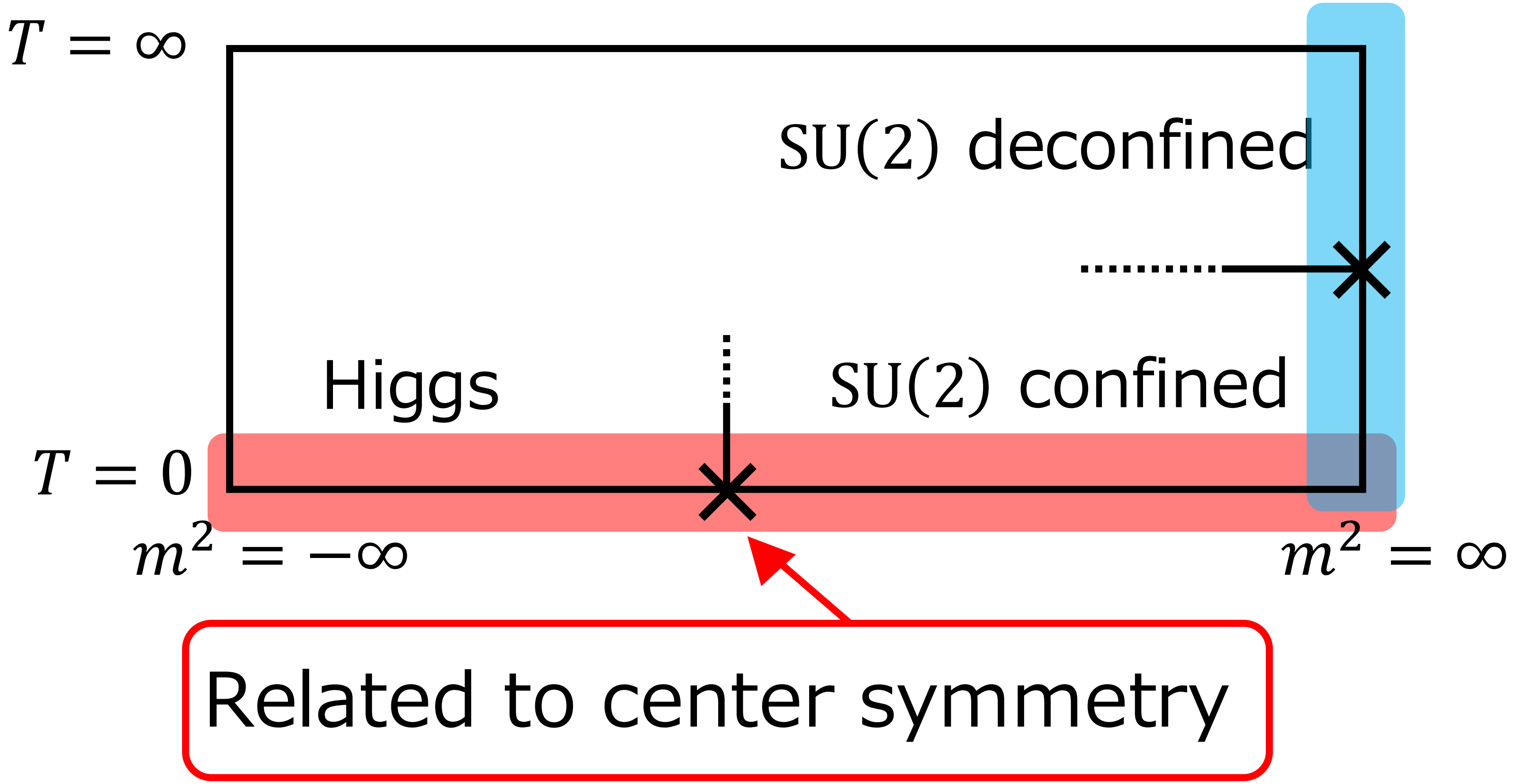

Phase diagram

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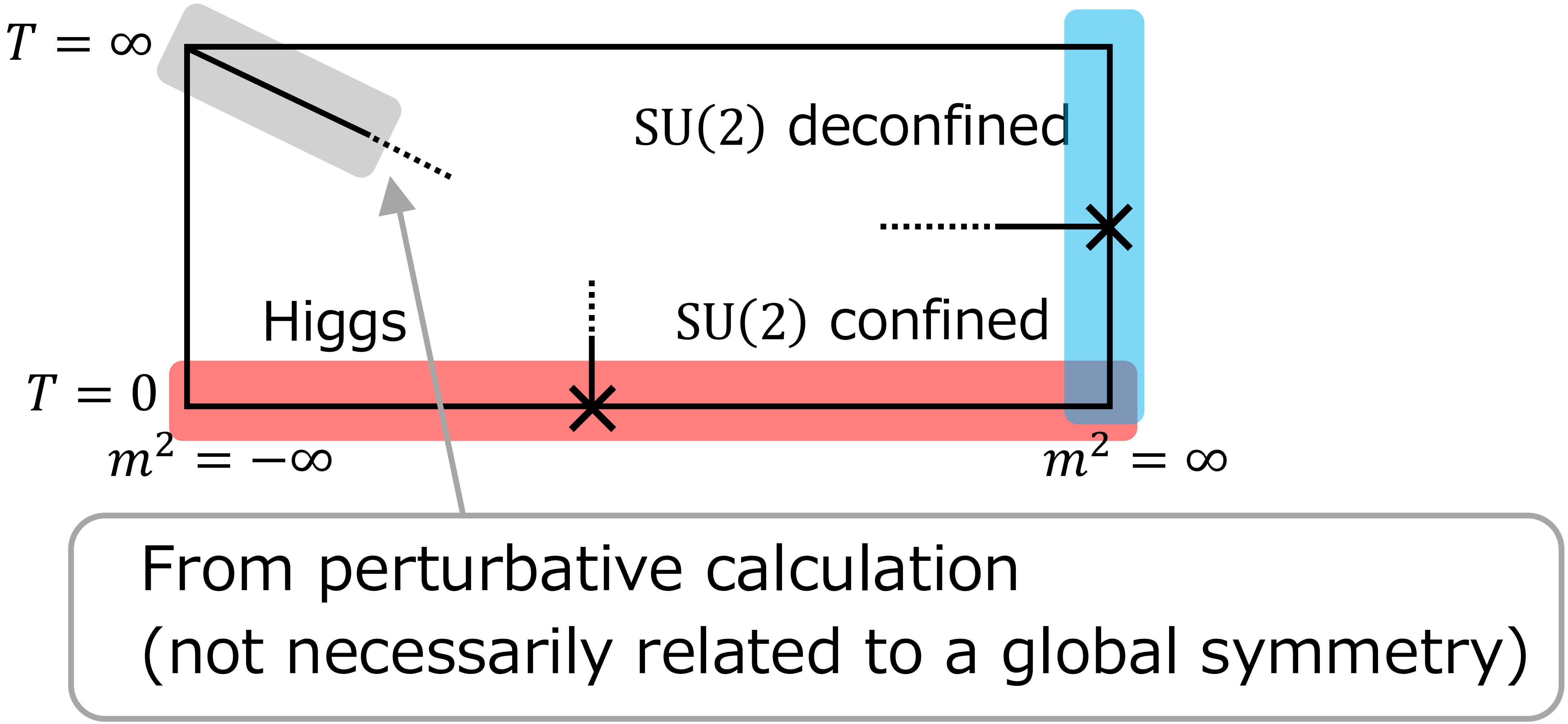

Phase diagram

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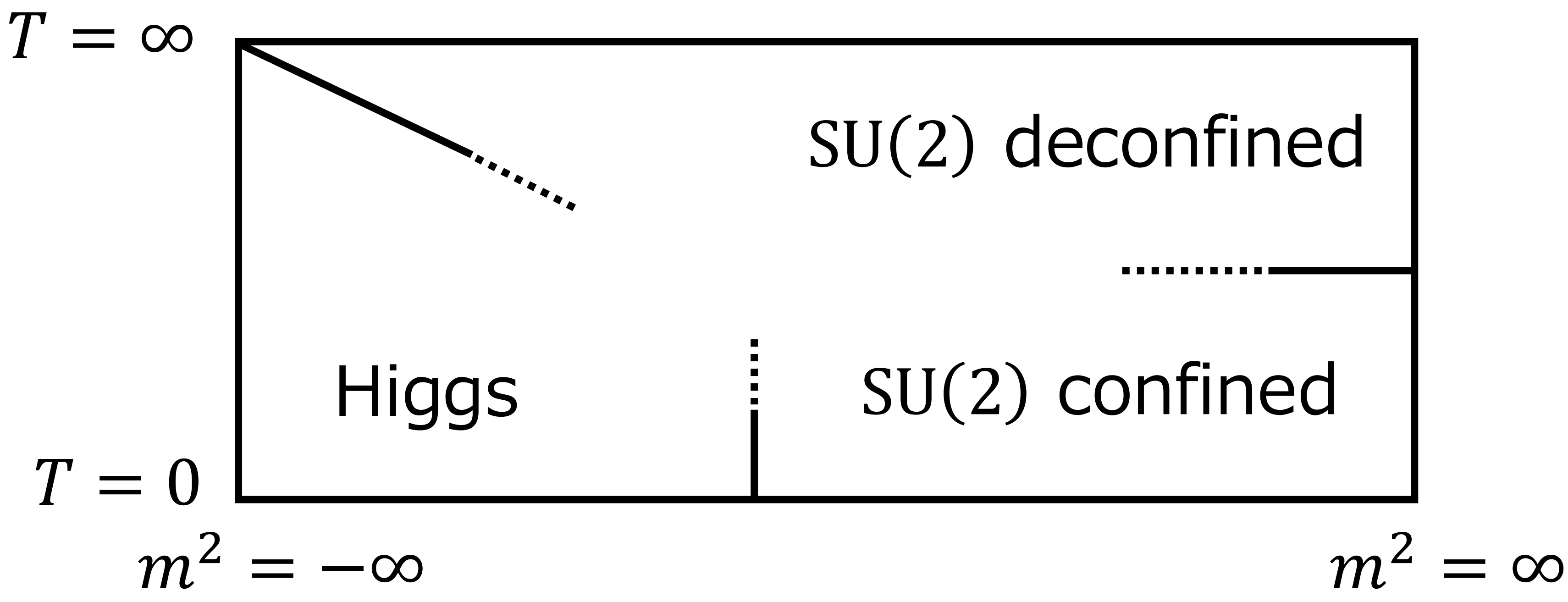
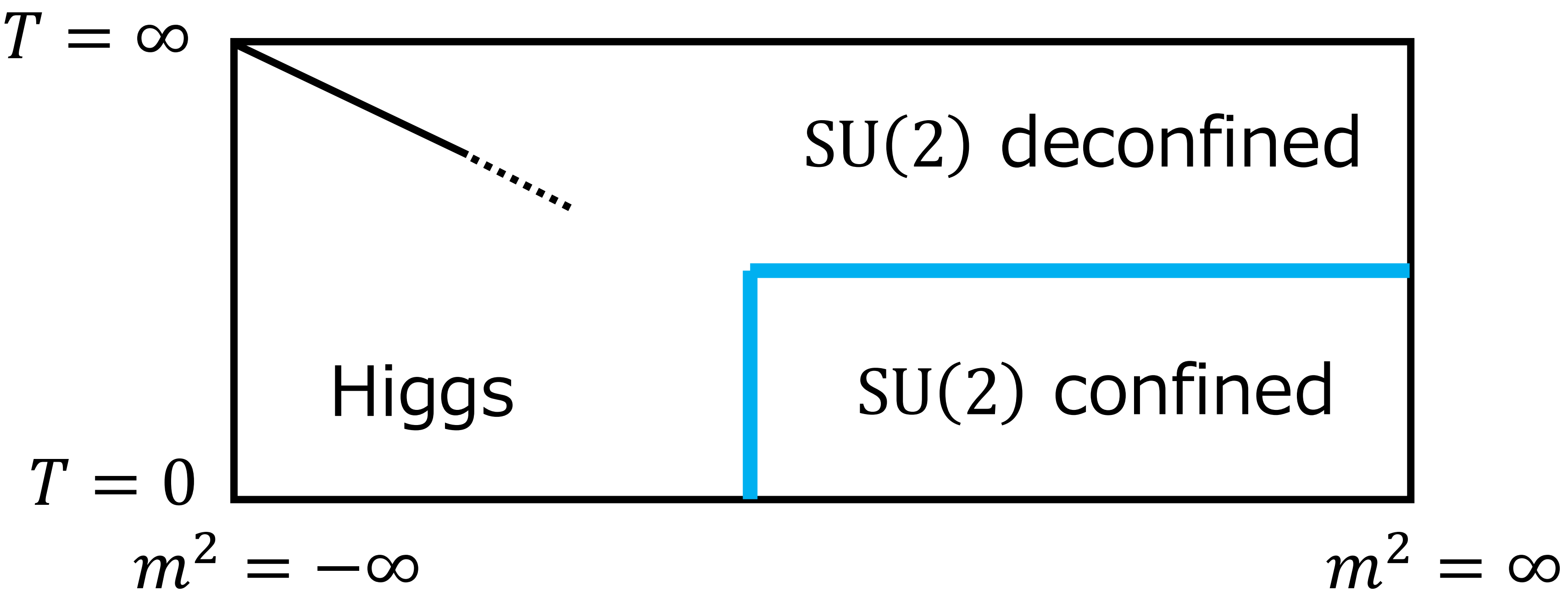


Phase diagram

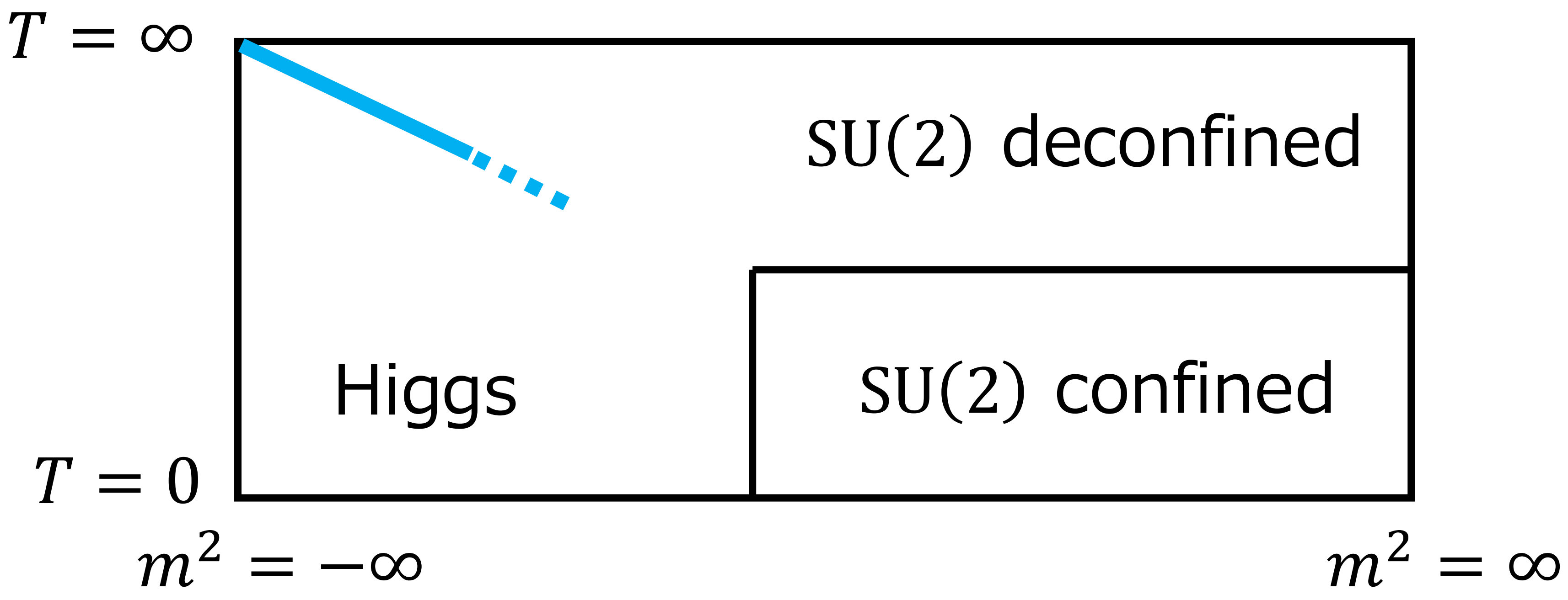
$$S=\int_0^\beta \mathrm{d}t \int \mathrm{d}^3\boldsymbol{x}\left[\frac{1}{4g^2}\mathrm{tr}\left(f^{\mu\nu}f_{\mu\nu}\right)+\frac{1}{2}\mathrm{tr}\left(D^\mu\phi D_\mu\phi\right)+m^2\mathrm{tr}(\phi^2)+\lambda\mathrm{tr}(\phi^4)\right]$$



SSB completely separates the phases.

Phase diagram

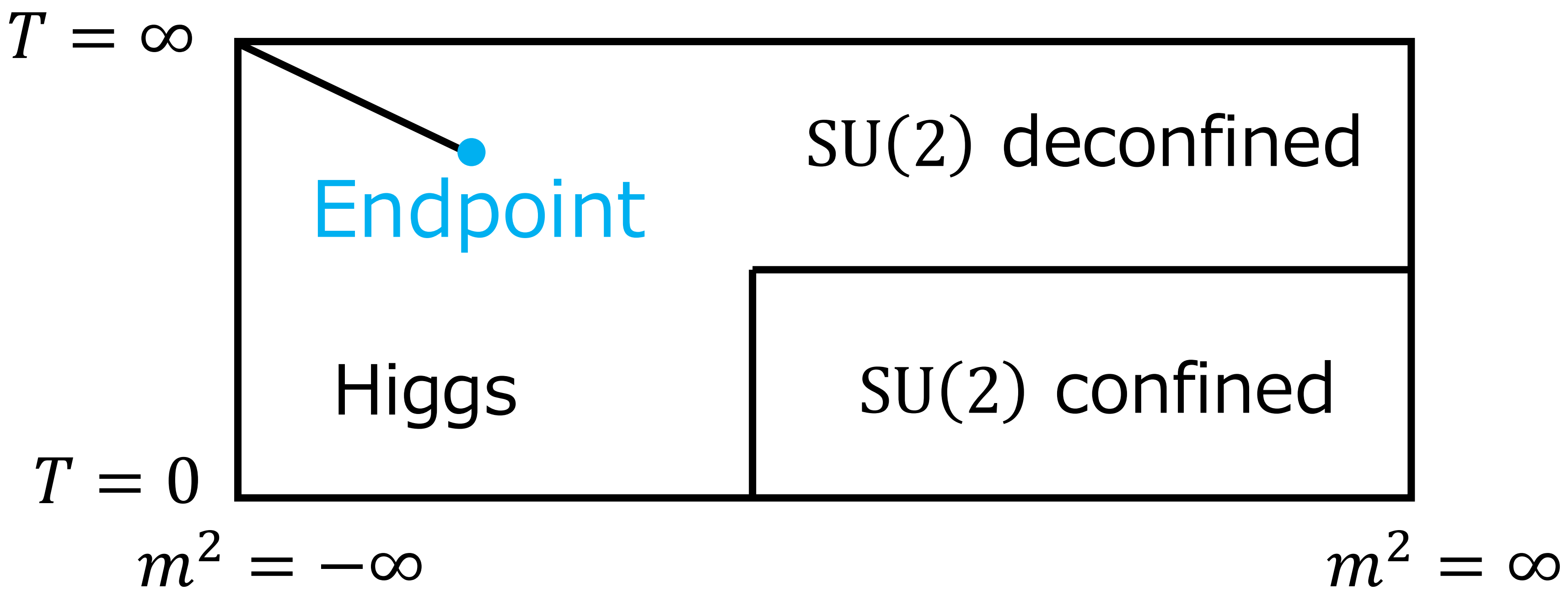
$$S = \int_0^\beta \mathrm{d}t \int \mathrm{d}^3\boldsymbol{x} \left[\frac{1}{4g^2}\mathrm{tr}\left(f^{\mu\nu}f_{\mu\nu}\right) + \frac{1}{2}\mathrm{tr}\left(D^\mu\phi D_\mu\phi\right) + m^2\mathrm{tr}(\phi^2) + \lambda\mathrm{tr}(\phi^4)\right]$$



It is unclear whether this line separates the phases.

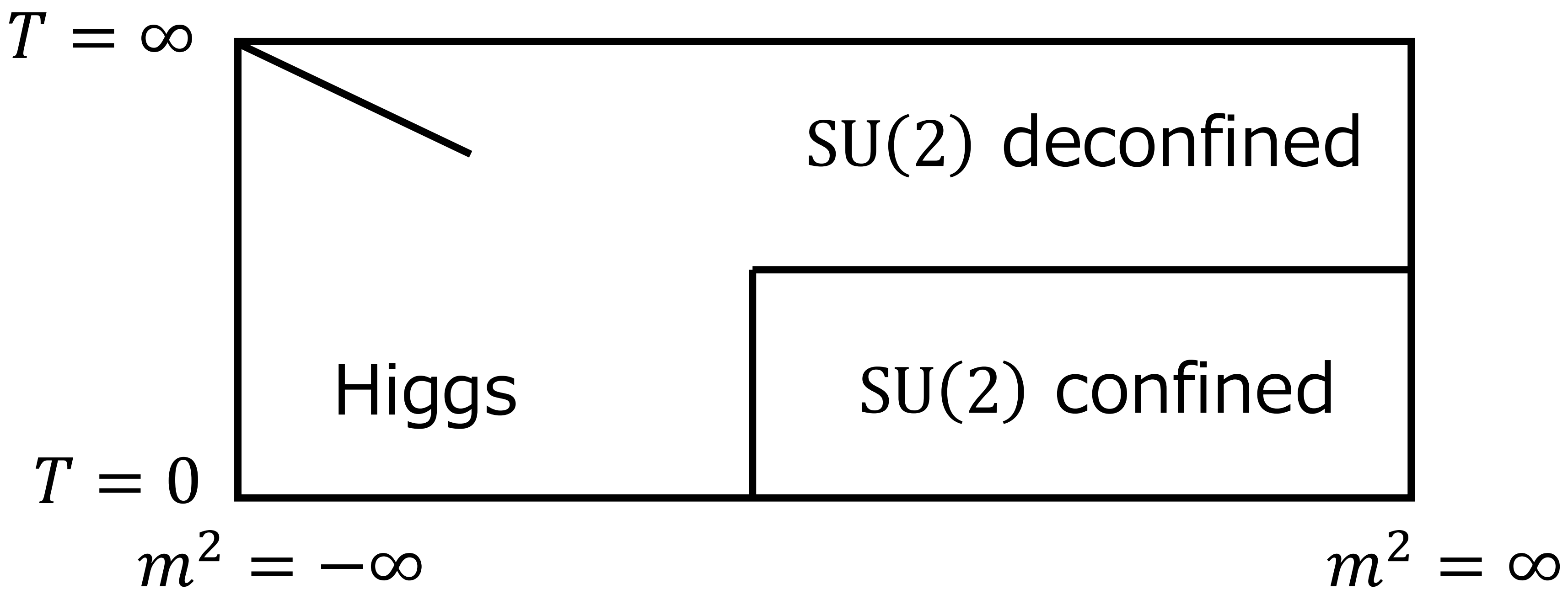
Our proposal

$$S = \int_0^\beta \mathrm{d}t \int \mathrm{d}^3\boldsymbol{x} \left[\frac{1}{4g^2}\mathrm{tr}\left(f^{\mu\nu} f_{\mu\nu}\right) + \frac{1}{2}\mathrm{tr}\left(D^\mu \phi D_\mu \phi\right) + m^2 \mathrm{tr}(\phi^2) + \lambda \mathrm{tr}(\phi^4)\right]$$



Continuity between deconfined phase and Higgs phase.
(Deconfinement-Higgs continuity)

Today, I will discuss this proposal in a lattice model.



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Lattice model

$$S[U,\phi] = \frac{\beta}{2} S_{\mathrm{Plaquette}}[U]$$

$$- \frac{\beta_{\mathrm{H}}}{2} \sum_{x,\mu} \phi^i(x) \phi^j\left(x + \hat{e}_\mu\right) \mathrm{tr}\left[U_\mu(x) \sigma^i U_\mu^\dagger(x) \sigma^j\right]$$

where we imposed a condition :

$$\sum_{i=1}^{3} \left(\phi^i\right)^2 = 1$$

Roughly, it corresponds to $\lambda \to \infty$.

$$S[U,\phi] = \frac{\beta}{2} S_{\text{Plaquette}}[U]$$

$$- \frac{\beta_{\text{H}}}{2} \sum_{x,\mu} \phi^i(x)\phi^j\left(x+\hat{e}_\mu\right) \operatorname{tr}\left[U_\mu(x)\sigma^i U_\mu^\dagger(x)\sigma^j\right]$$

In addition, we take a unitary gauge

$$\phi^i(x)\sigma^i = \sigma^y$$

▶ $\phi^i(x)\phi^j\left(x+\hat{e}_\mu\right) \operatorname{tr}\left[U_\mu(x)\sigma^i U_\mu^\dagger(x)\sigma^j\right] \ \to\ \operatorname{tr}\left[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y\right]$

$$S[U,\phi] = \frac{\beta}{2} S_{\mathrm{Plaquette}}[U] - \frac{\beta_{\mathrm{H}}}{2} \sum_{x,\mu} \mathrm{tr}\left[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y\right]$$

Schematic phase diagram

$$S[U,\phi] = \frac{\beta}{2} S_{\mathrm{Plaquette}}[U] - \frac{\beta_{\mathrm{H}}}{2} \sum_{x,\mu} \mathrm{tr}\left[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y\right]$$

We use a lattice $N_{\mathrm{t}} \times N_{\mathrm{s}}^3$ with finite N_{t} and large N_{s}.

(Finite temperature)

$$S[U,\phi] = \frac{\beta}{2} S_{\mathrm{Plaquette}}[U] - \frac{\beta_{\mathrm{H}}}{2} \sum_{x,\mu} \mathrm{tr}\left[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y\right]$$

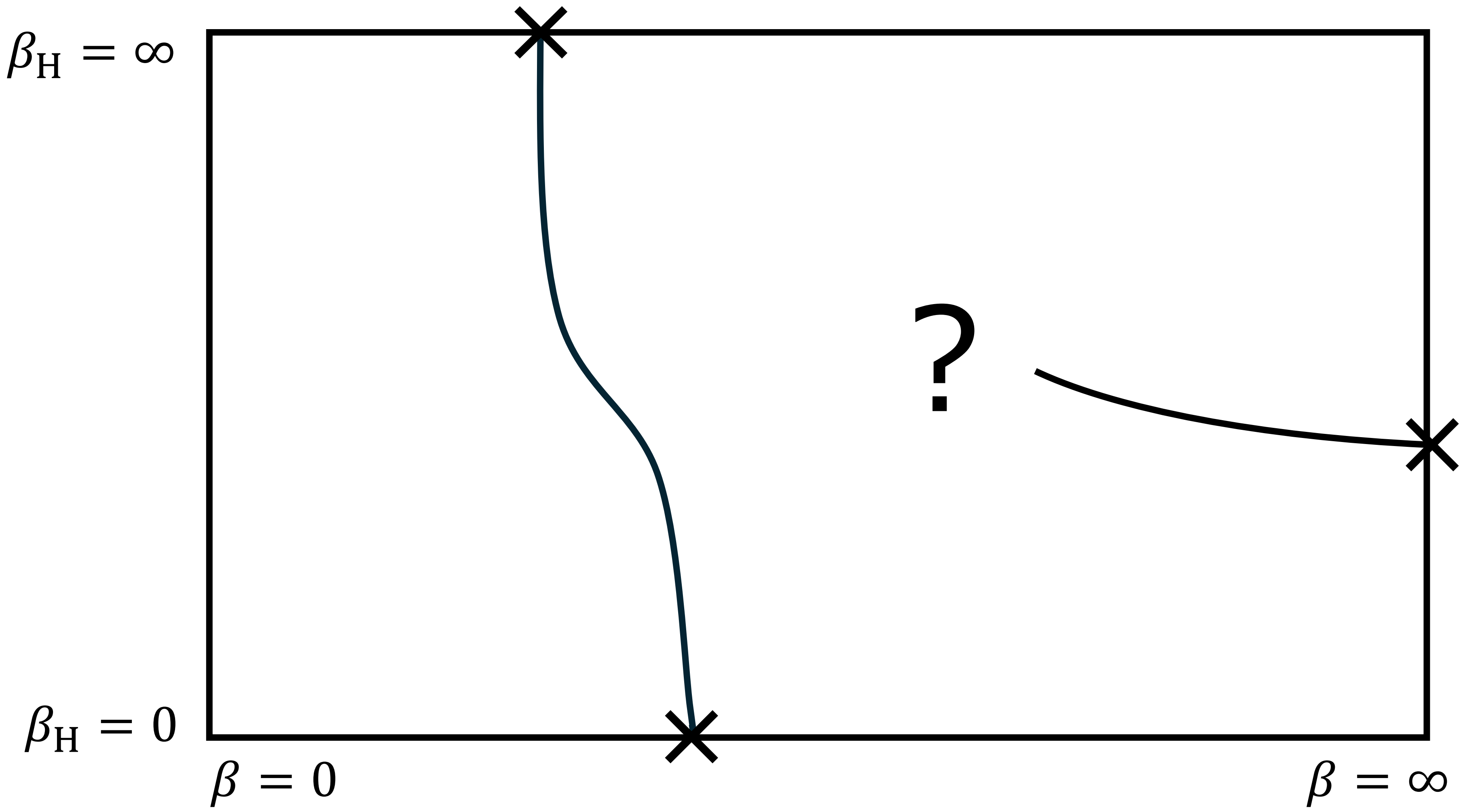
We use a lattice $N_{\mathrm{t}} \times N_{\mathrm{s}}^3$ with finite N_{t} and large N_{s}.

(Finite temperature)

Instead of varying the physical temperature,

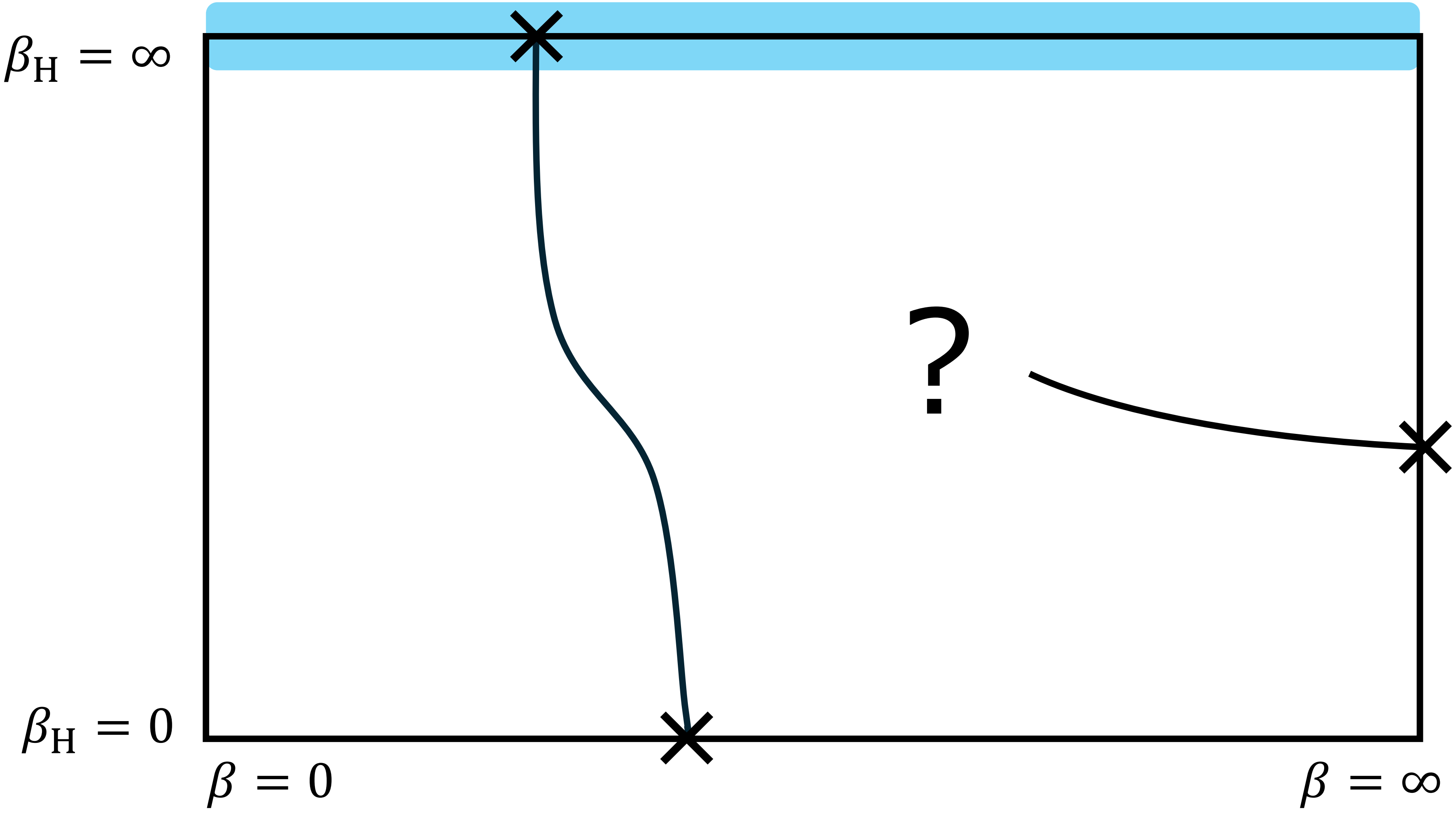
we consider the $\beta - \beta_{\mathrm{H}}$ phase diagram.

$$S[U,\phi] = \frac{\beta}{2} S_{\mathrm{Plaquette}}[U] - \frac{\beta_{\mathrm{H}}}{2} \sum_{x,\mu} \mathrm{tr}\left[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y\right]$$



(schematic phase diagram based on [Karsch-Seiler-Stamatescu(1983)])

$$S[U,\phi] = \frac{\beta}{2} S_{\mathrm{Plaquette}}[U] - \frac{\beta_{\mathrm{H}}}{2} \sum_{x,\mu} \mathrm{tr}[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y]$$



compact U(1) gauge theory

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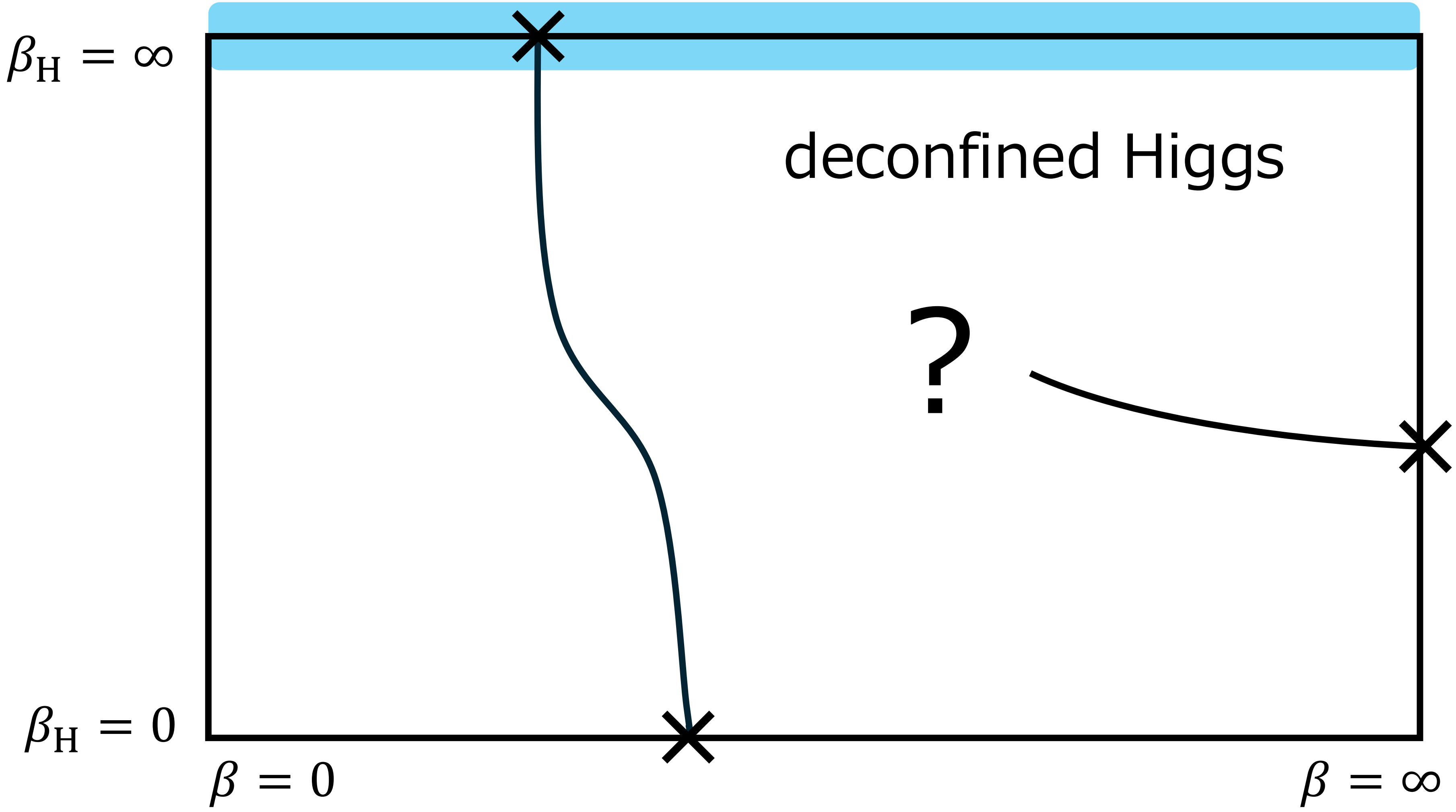

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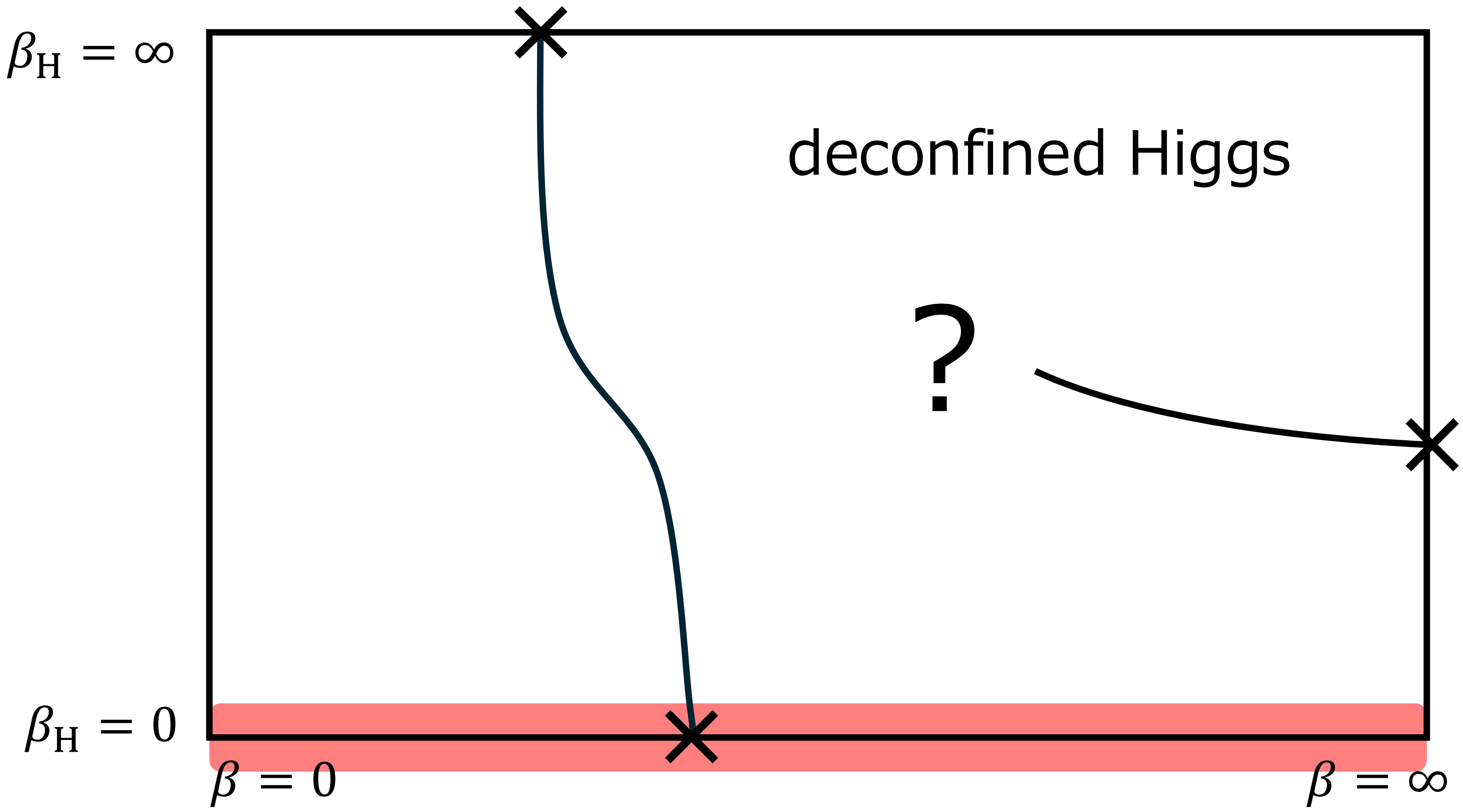

SU(2) gauge theory

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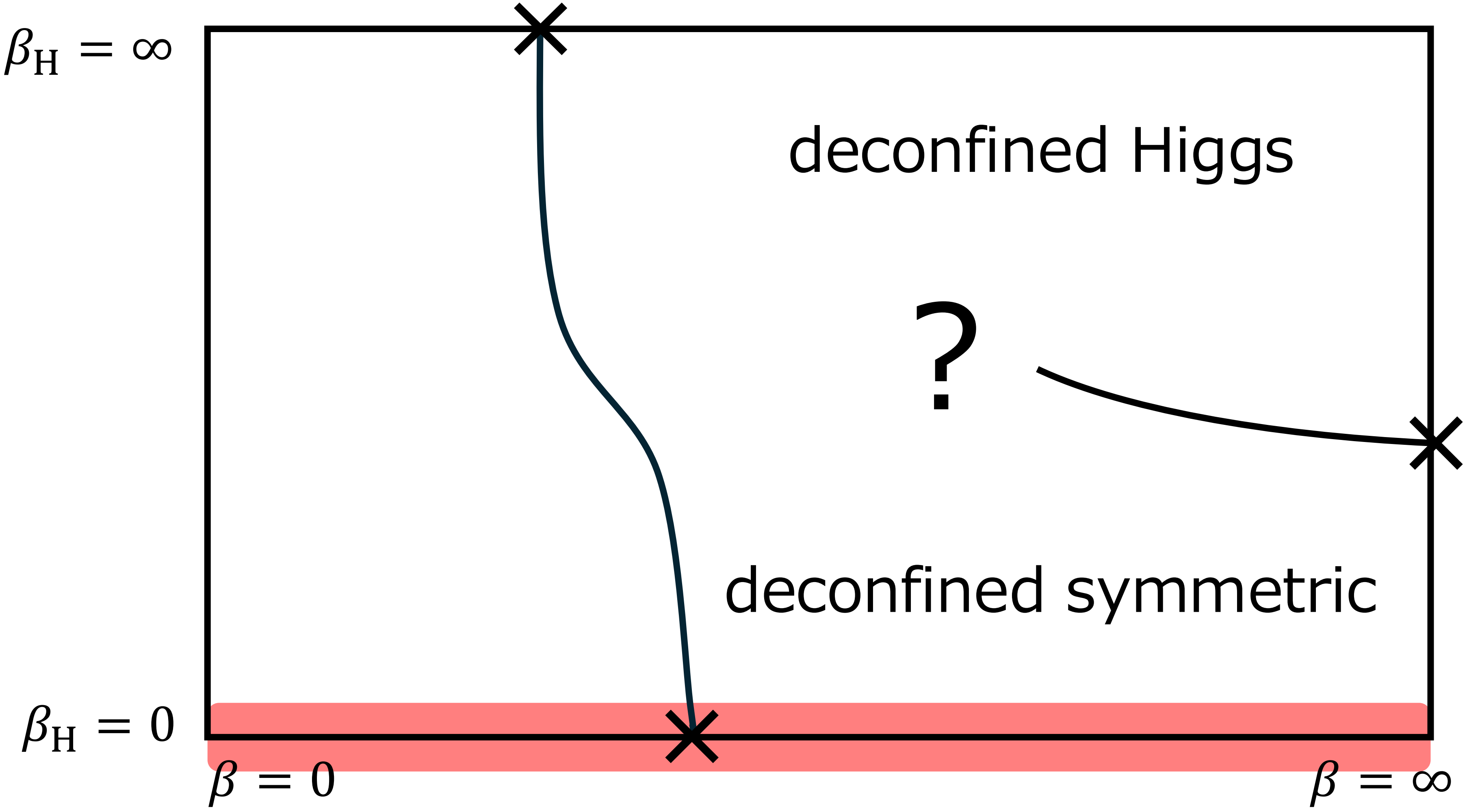
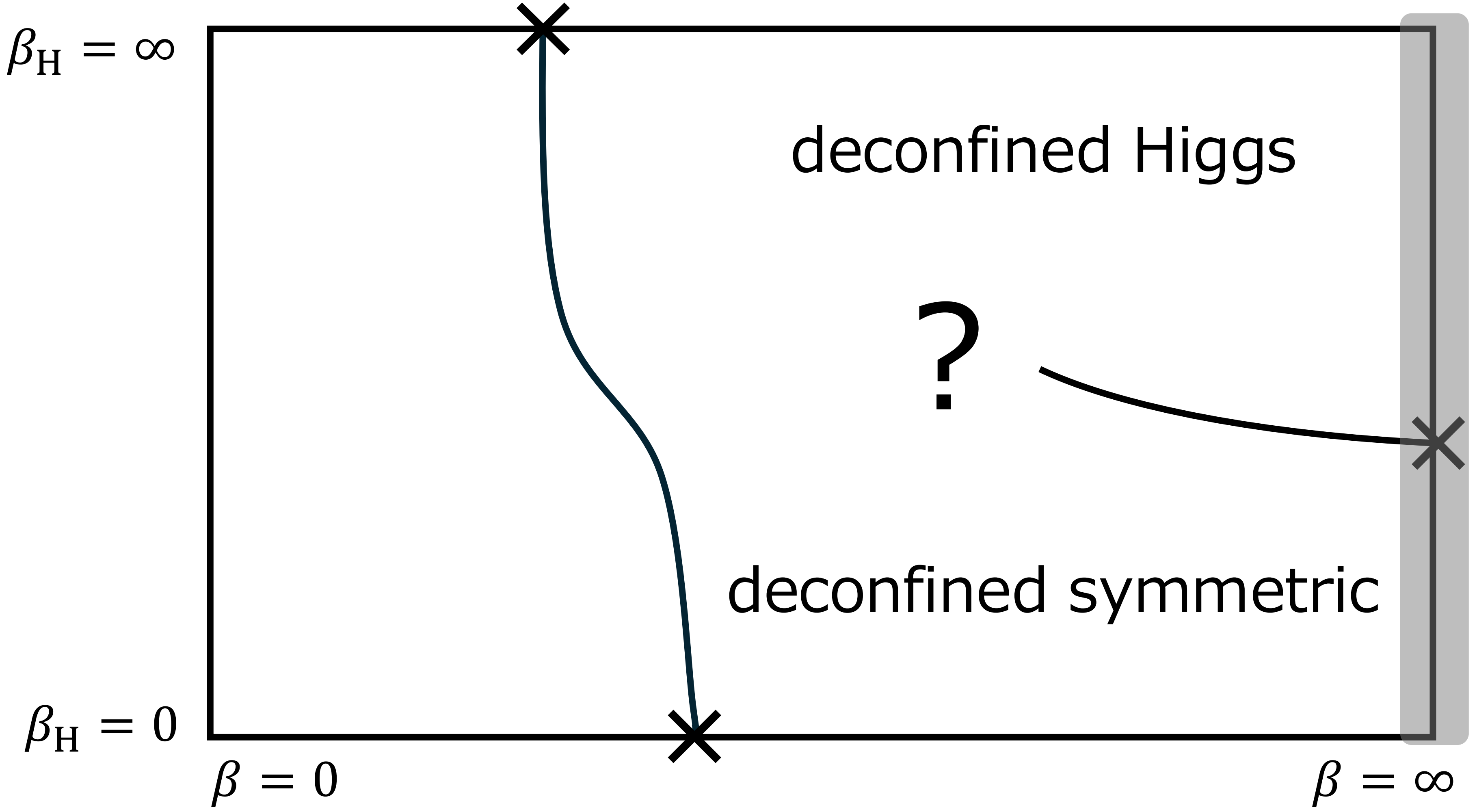


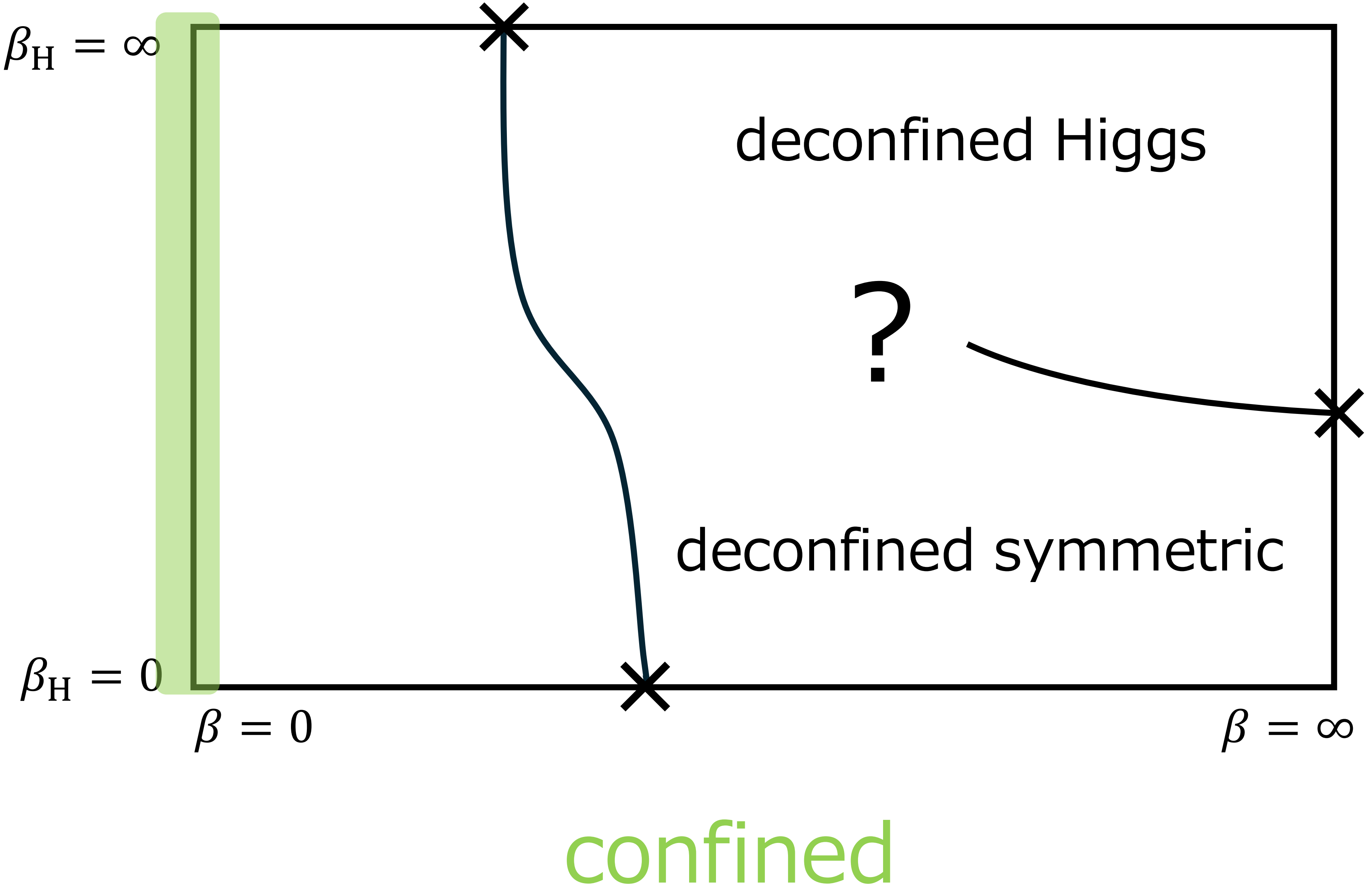
SU(2) gauge theory

$$S[U,\phi] = \frac{\beta}{2} S_{\text{Plaquette}}[U] - \frac{\beta_{\text{H}}}{2} \sum_{x,\mu} \phi^i(x)\phi^j(x+\hat{e}_\mu)\, \text{tr}\left[U_\mu(x)\sigma^i U_\mu^\dagger(x)\sigma^j\right]$$

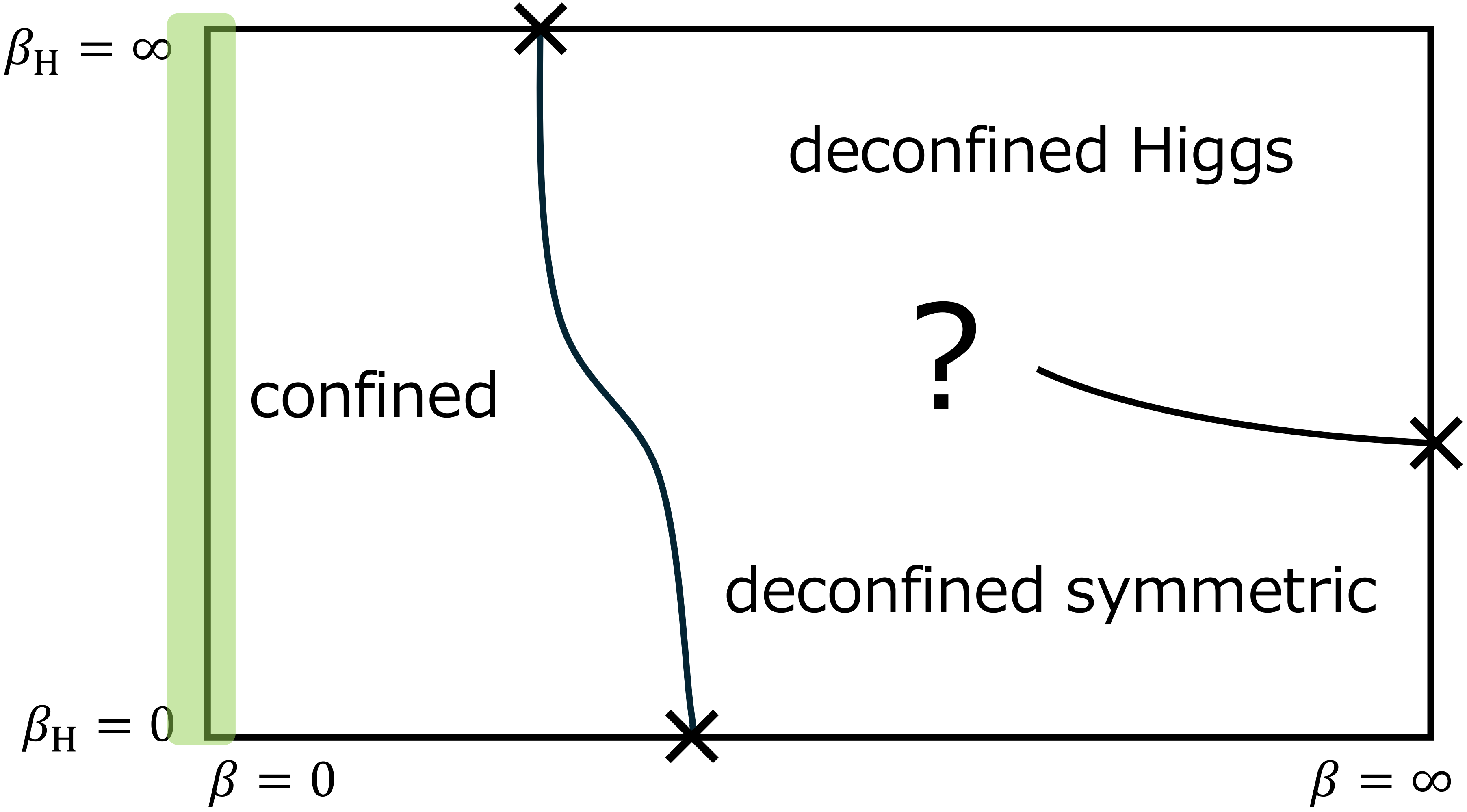


O(3) Heisenberg model ($\because$ U $\to$ 1 as $\beta \to \infty$)

$$S[U,\phi] = \frac{\beta}{2} S_{\text{Plaquette}}[U] - \frac{\beta_{\text{H}}}{2} \sum_{x,\mu} \operatorname{tr}\left[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y\right]$$

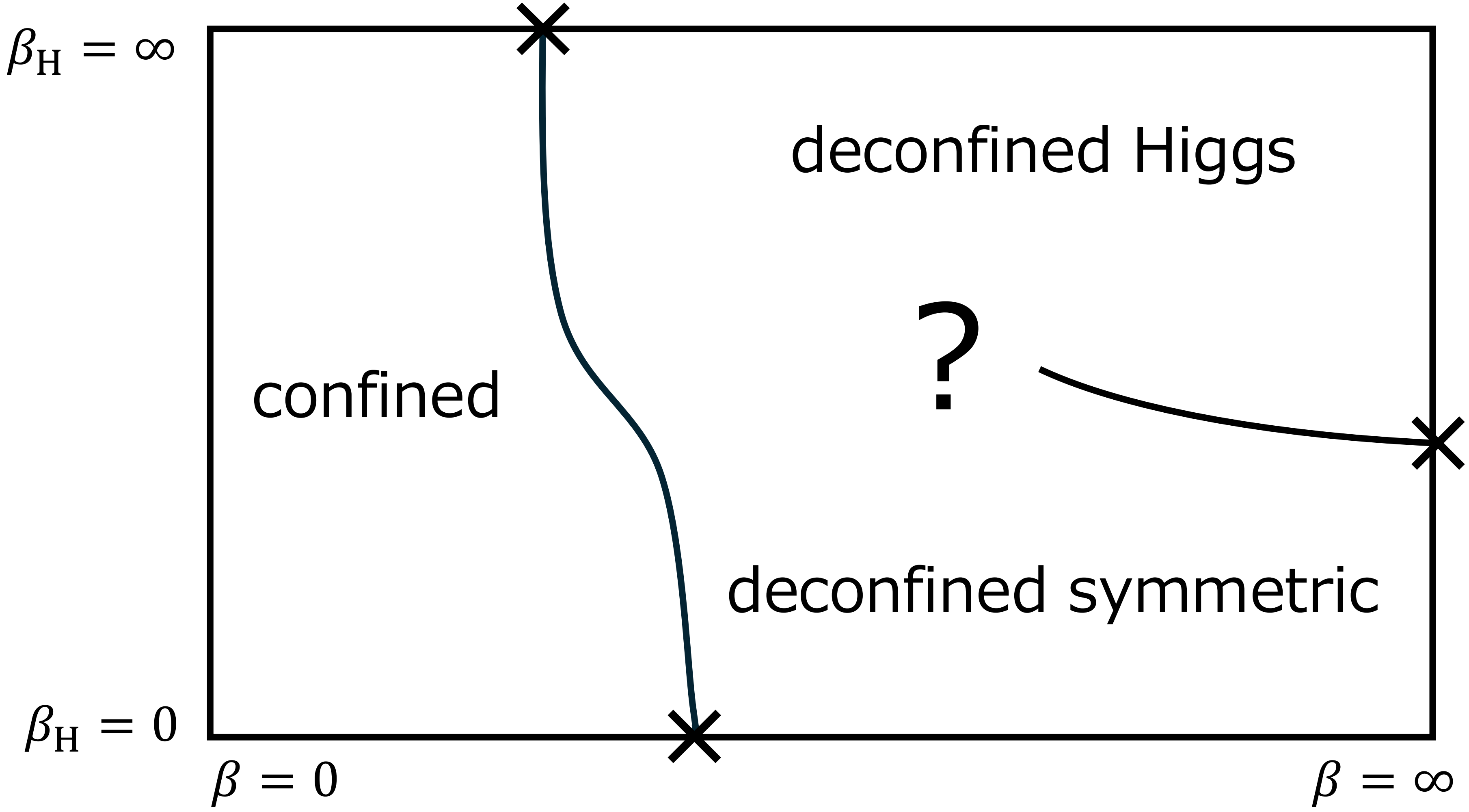


$$S[U,\phi] = \frac{\beta}{2} S_{\text{Plaquette}}[U] - \frac{\beta_{\text{H}}}{2} \sum_{x,\mu} \text{tr}[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y]$$



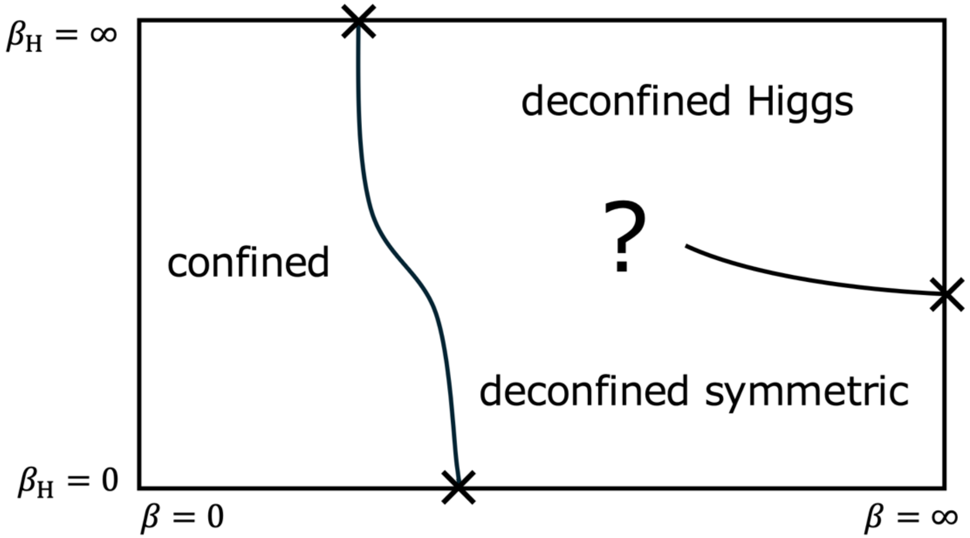
confined

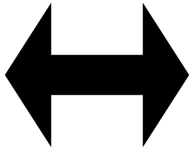
$$S[U,\phi] = \frac{\beta}{2} S_{\mathrm{Plaquette}}[U] - \frac{\beta_{\mathrm{H}}}{2} \sum_{x,\mu} \mathrm{tr}\left[U_\mu(x)\sigma^y U_\mu^\dagger(x)\sigma^y\right]$$



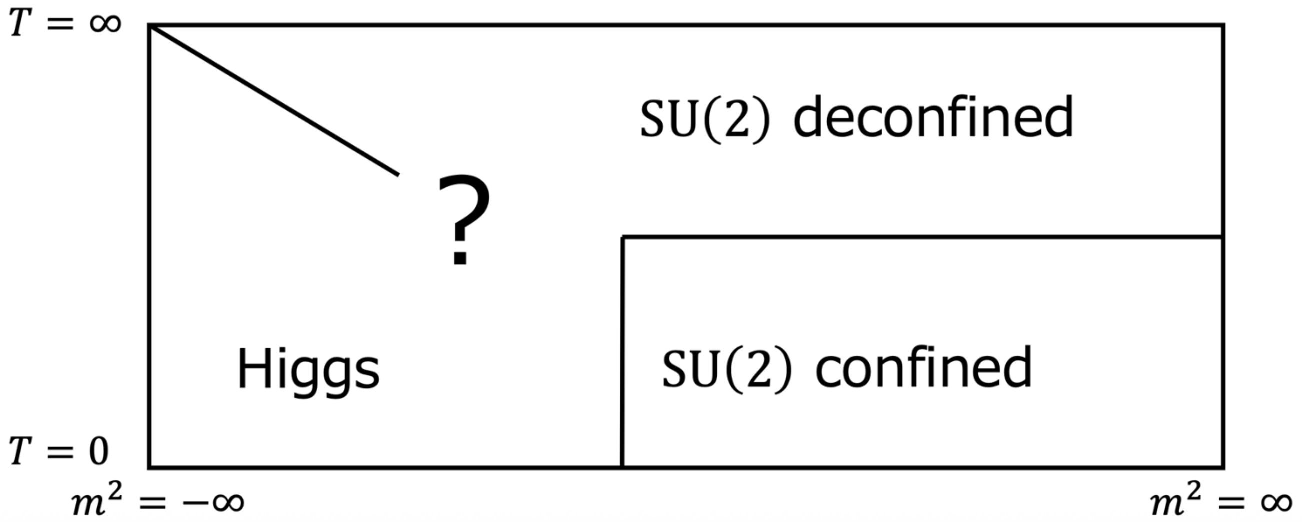
We qualitatively expect the correspondence

the phase diagram of
this lattice model





the phase diagram of
the original adjoint Higgs theory



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Center-destabilizing deformation

$$S'[U,\phi] = S[U,\phi] - c \sum_{\vec{x}:\mathrm{spatial}} |\mathrm{tr}\, P(\vec{x})|^2$$

c : deformation parameter

Center-destabilizing deformation

$$S'[U,\phi] = S[U,\phi] - c \sum_{\vec{x}:\mathrm{spatial}} |\mathrm{tr}\, P(\vec{x})|^2$$

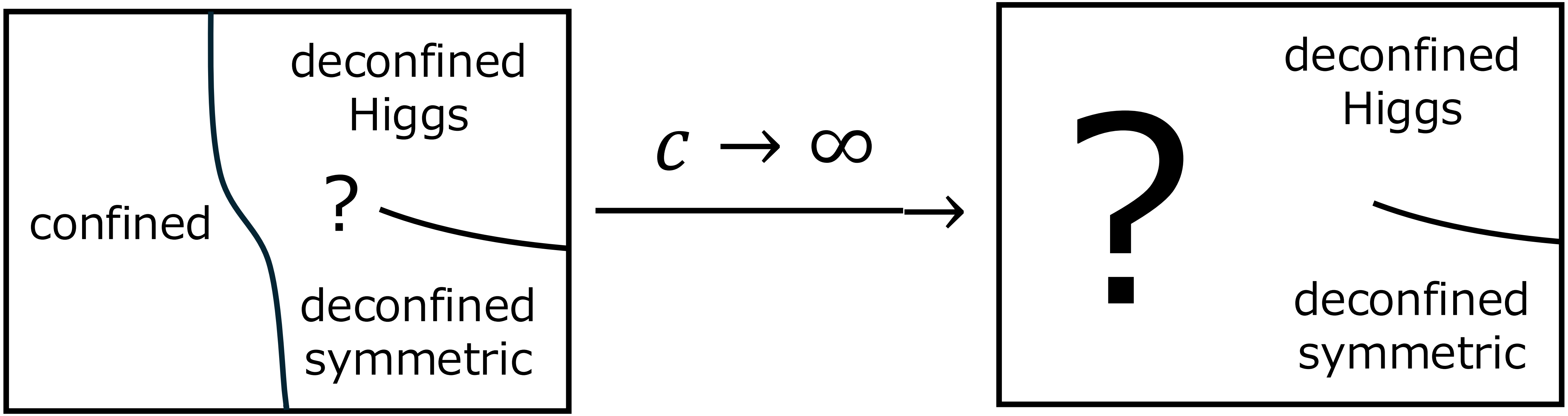
c : deformation parameter

$$c \to \infty \quad \Rightarrow \quad P \to \pm I$$

(center-destabilizing)

Assumption

No phase transition
in deconfined symmetric and deconfined Higgs phase
under center-destabilizing deformation



After a dimensional reduction (taking $N_{\mathrm{t}} = 1$), we have three kinds of fields.

- $U_m(\vec{x}) \in \mathrm{SU}(2)$ $\quad$ $m = 1,2,3$
- $U_4(\vec{x}) \in \mathbb{Z}_2$ (center-destabilizing) $\quad$ Polyakov loop $\mathrm{tr}(P) = \mathrm{tr}(U_4)$
- $\phi^i(\vec{x})$ $\quad$ $\sum_{i=1}^{3} (\phi^i)^2 = 1$

The three-dimensional model

$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S_{3\mathrm{d\ Plaquette}}[U]$$

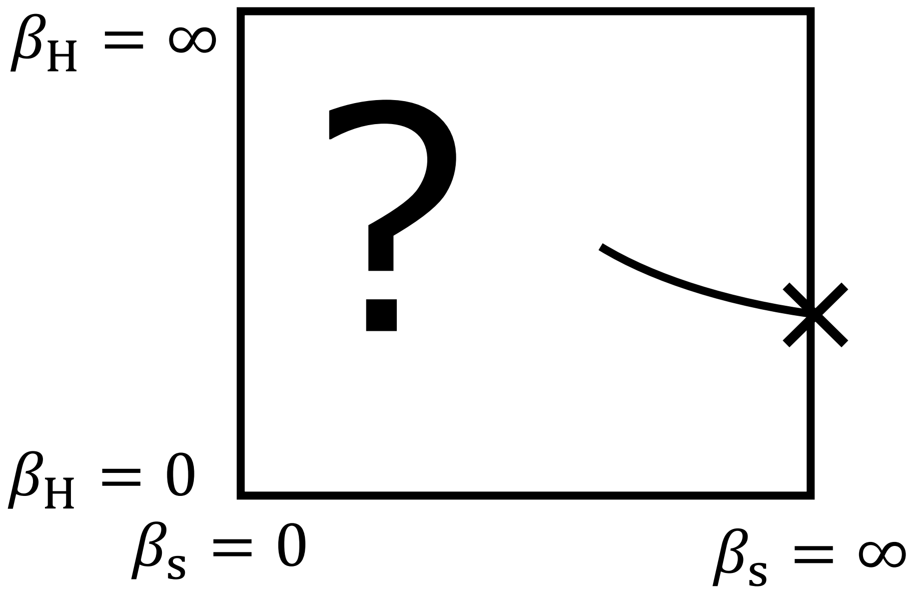
$$- \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

$$- \frac{\beta_\mathrm{H}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\, \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$

We keep β_t large so that $\langle \mathrm{tr}(U_4) \rangle \neq 0$.

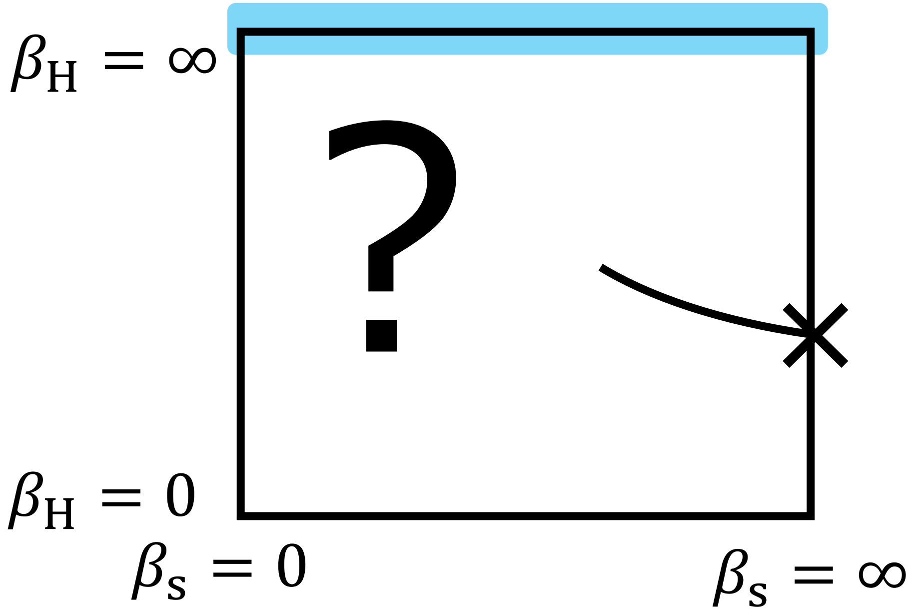
$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

$$- \frac{\beta_\mathrm{H}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\, \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$



$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x} + \hat{e}_m)]$$

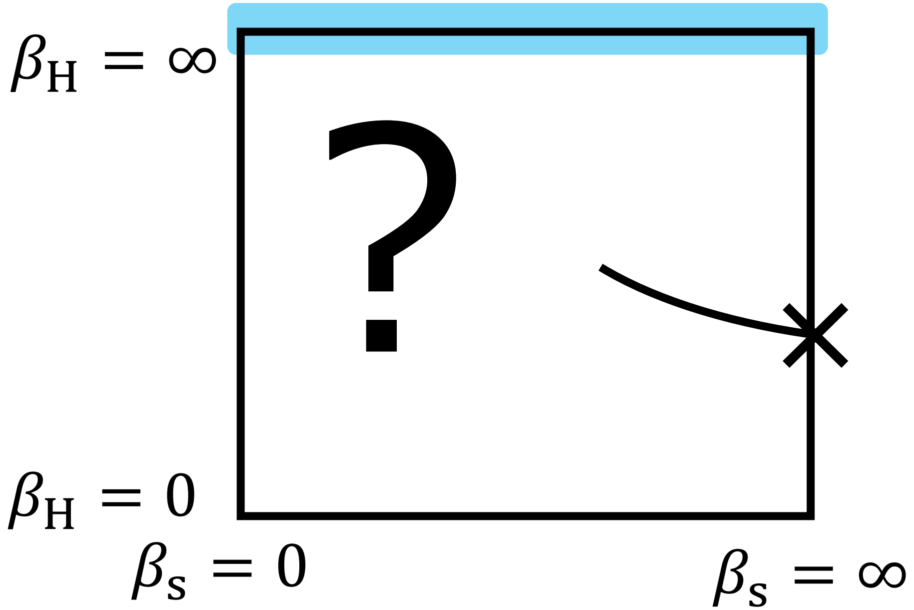
$$- \frac{\beta_\mathrm{H}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x} + \hat{e}_m)\ \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$



$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S^{\mathrm{U}(1)}_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x} + \hat{e}_m)]$$

$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

$$- \frac{\beta_\mathrm{H}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\, \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$

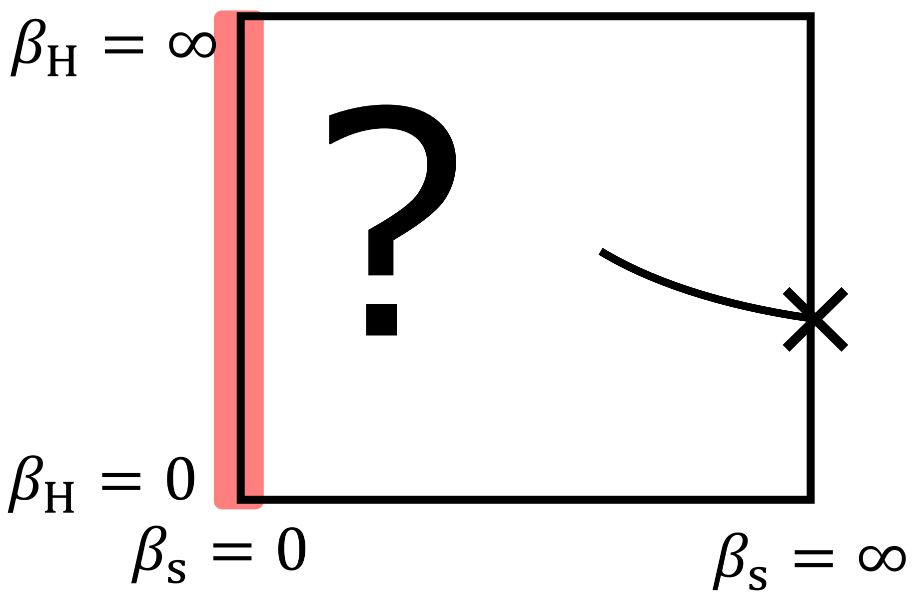


$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S^{\mathrm{U}(1)}_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

- No phase transition

$$S_{\rm 3d}[U,\phi] = \frac{\beta_{\rm s}}{2} S_{\rm 3d\ Plaquette}[U] - \frac{\beta_{\rm t}}{2}\sum_{\vec{x},m} {\rm tr}[U_4(\vec{x})U_4(\vec{x}+\hat{e}_m)]$$

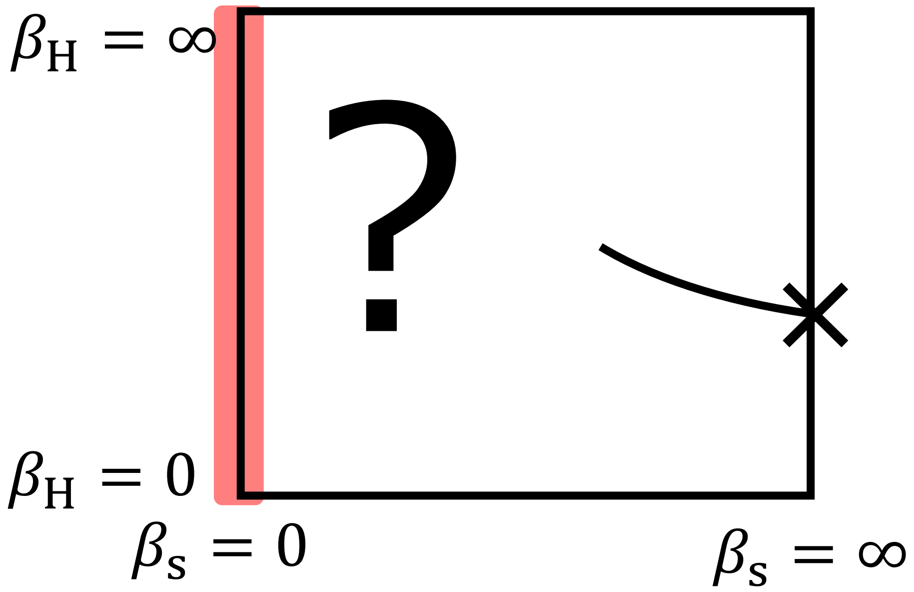
$$-\frac{\beta_{\rm H}}{2}\sum_{\vec{x},m} \phi^i(\vec{x})\phi^j(\vec{x}+\hat{e}_m)\ {\rm tr}\left[U_m(\vec{x})\sigma^i U_m^\dagger(\vec{x})\sigma^j\right]$$



$$S_{\rm 3d}[U,\phi] = -\frac{\beta_{\rm t}}{2}\sum_{\vec{x},m} {\rm tr}[U_4(\vec{x})U_4(\vec{x}+\hat{e}_m)] - \frac{\beta_{\rm H}}{2}\sum_{\vec{x},m} \phi^i(\vec{x})\phi^j(\vec{x}+\hat{e}_m)\ {\rm tr}\left[U_m(\vec{x})\sigma^i U_m^\dagger(\vec{x})\sigma^j\right]$$

$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_{\mathrm{s}}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_{\mathrm{t}}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

$$- \frac{\beta_{\mathrm{H}}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\ \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$

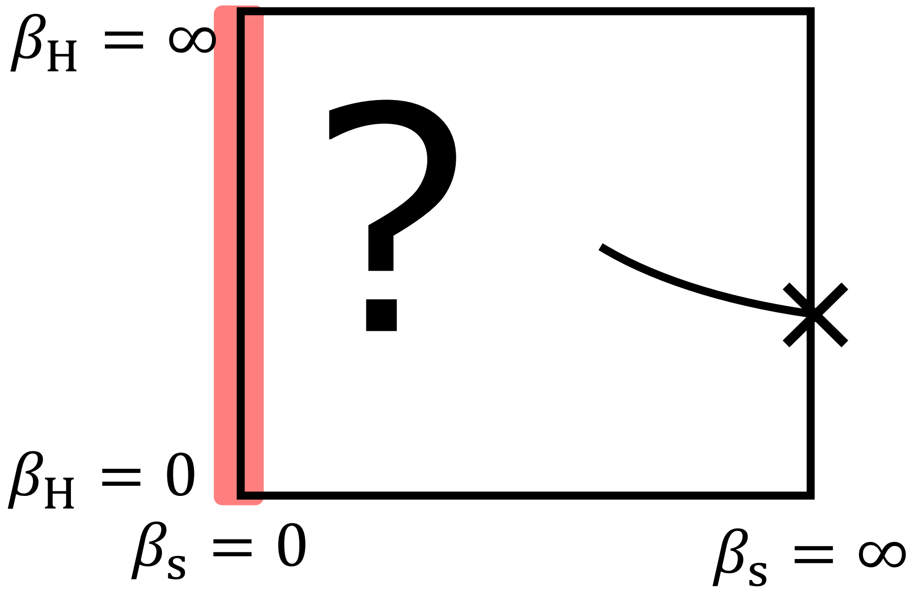


$$S_{3\mathrm{d}}[U,\phi] = -\frac{\beta_{\mathrm{t}}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)] - \frac{\beta_{\mathrm{H}}}{2} \sum_{\vec{x},m} \underline{\phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\ \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]}$$

$$\rightarrow \mathrm{tr}\left[U_m(\vec{x}) \sigma^y U_m^\dagger(\vec{x}) \sigma^y\right]$$

$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_{\mathrm{s}}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_{\mathrm{t}}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

$$- \frac{\beta_{\mathrm{H}}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\, \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$



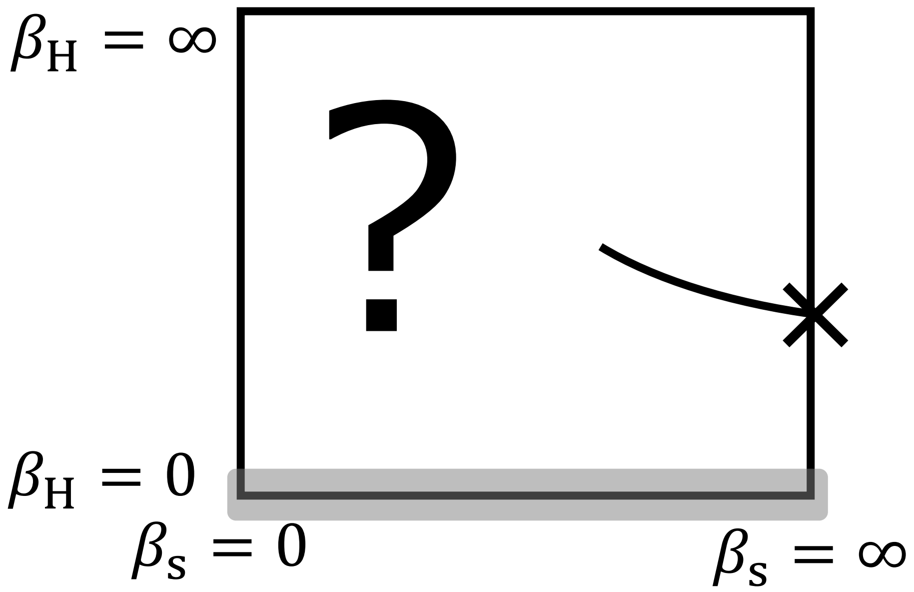
$$S_{3\mathrm{d}}[U,\phi] = -\frac{\beta_{\mathrm{t}}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)] - \frac{\beta_{\mathrm{H}}}{2} \sum_{\vec{x},m} \underline{\phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\, \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]}$$

$\rightarrow \mathrm{tr}\left[U_m(\vec{x}) \sigma^y U_m^\dagger(\vec{x}) \sigma^y\right]$

▶ No phase transition

$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

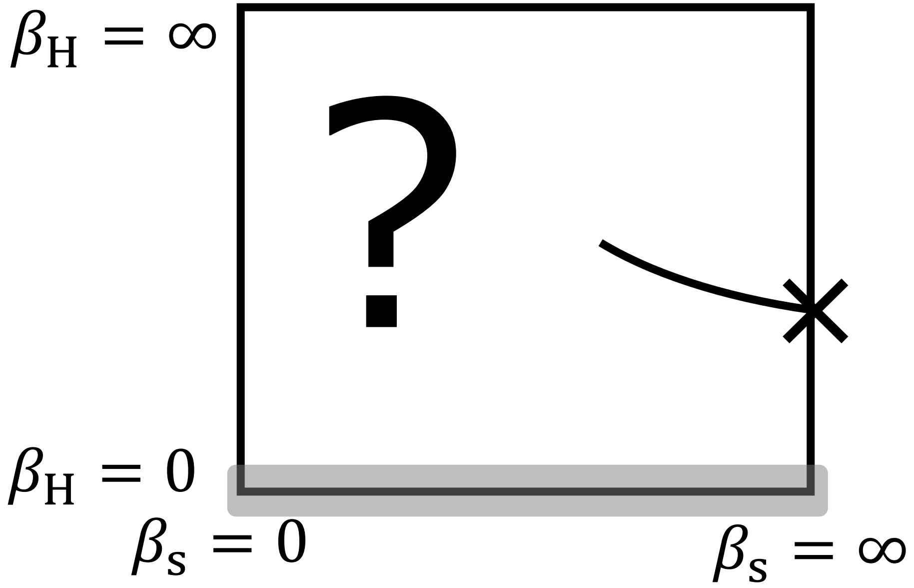
$$- \frac{\beta_\mathrm{H}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\ \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$



$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

$$S_{3d}[U,\phi] = \frac{\beta_s}{2} S_{3d\ \mathrm{Plaquette}}[U] - \frac{\beta_t}{2}\sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x})U_4(\vec{x}+\hat{e}_m)]$$

$$-\frac{\beta_H}{2}\sum_{\vec{x},m} \phi^i(\vec{x})\phi^j(\vec{x}+\hat{e}_m)\ \mathrm{tr}\left[U_m(\vec{x})\sigma^i U_m^\dagger(\vec{x})\sigma^j\right]$$

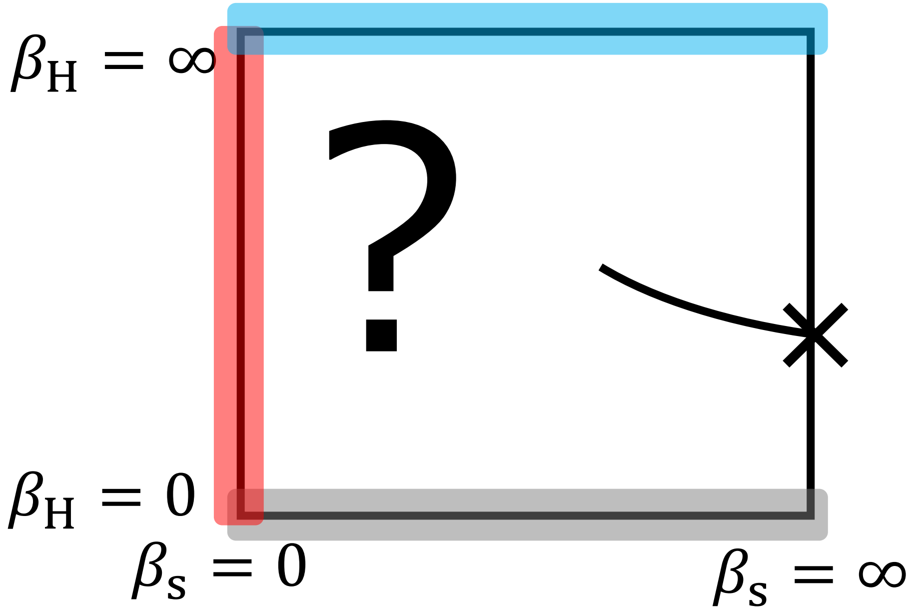


$$S_{3d}[U,\phi] = \frac{\beta_s}{2} S_{3d\ \mathrm{Plaquette}}[U] - \frac{\beta_t}{2}\sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x})U_4(\vec{x}+\hat{e}_m)]$$

▶ No phase transition

$$S_{\mathrm{3d}}[U,\phi] = \frac{\beta_{\mathrm{s}}}{2} S_{\mathrm{3d\ Plaquette}}[U] - \frac{\beta_{\mathrm{t}}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x} + \hat{e}_m)]$$

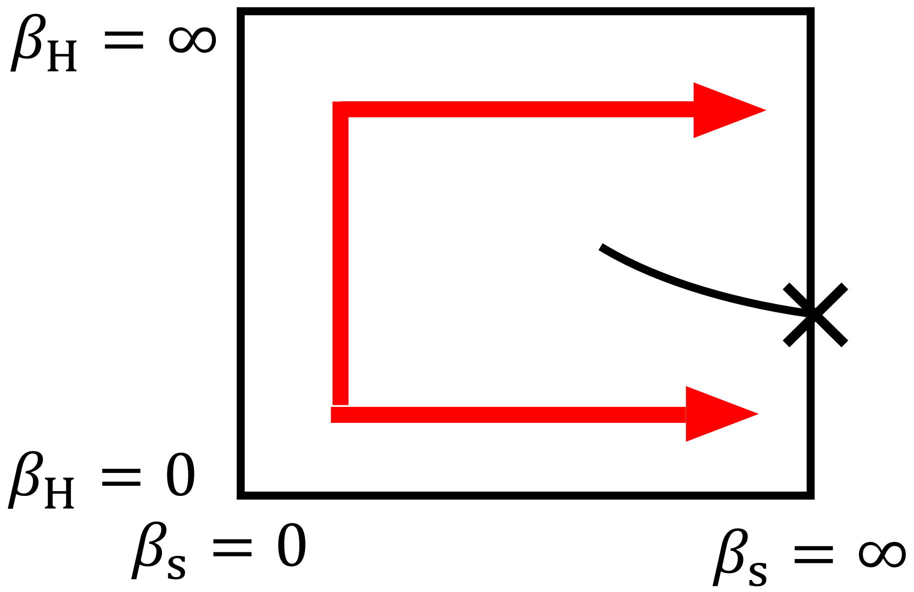
$$- \frac{\beta_{\mathrm{H}}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x} + \hat{e}_m)\, \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$



No phase transition

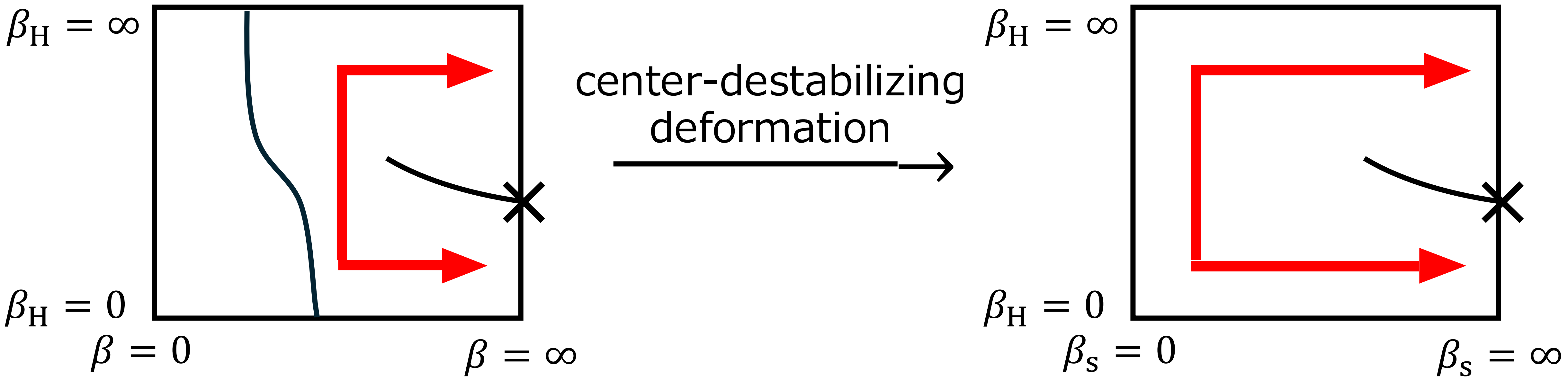
$$S_{3\mathrm{d}}[U,\phi] = \frac{\beta_\mathrm{s}}{2} S_{3\mathrm{d\ Plaquette}}[U] - \frac{\beta_\mathrm{t}}{2} \sum_{\vec{x},m} \mathrm{tr}[U_4(\vec{x}) U_4(\vec{x}+\hat{e}_m)]$$

$$- \frac{\beta_\mathrm{H}}{2} \sum_{\vec{x},m} \phi^i(\vec{x}) \phi^j(\vec{x}+\hat{e}_m)\, \mathrm{tr}\left[U_m(\vec{x}) \sigma^i U_m^\dagger(\vec{x}) \sigma^j\right]$$



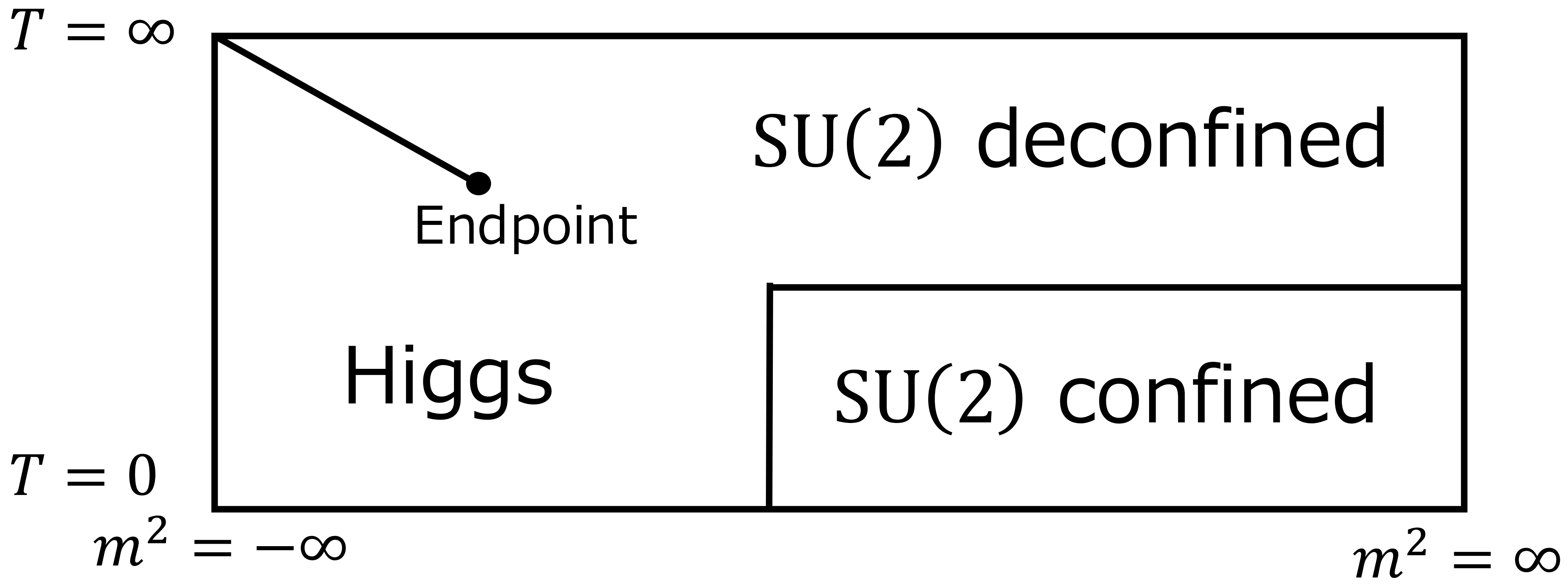
Continuity

If no phase transition occurs under center-destabilization, it means the continuity in the original phase diagram.



- Motivation
- Our setup and proposal
- Lattice model and its schematic phase diagram
- Center-destabilizing deformation
- Summary and Discussion

In this talk, I discussed the possibility of deconfinement-Higgs continuity.



However, the center-destabilizing deformation
ignores the temporal dynamics.

Thus, an analysis with full dynamics
is ultimately required.

We also performed a preliminary Monte Carlo analysis,
which is currently consistent with this continuity.

However, several issues remain,
such as evaluating the finite-volume scaling.