Broken symmetry

I. Mass and interaction range

II. Spontaneous breaking of a global symmetry

III. The BEH mechanism

IV. The quest for unified laws of nature

24 February 2011, CERN

I. Mass and interaction range

Relativity: massive and massless particles

c is the maximal causal velocity

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The mass m of a particle of rest mass m_0 increases with its velocity v

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Relativity: massive and massless particles

c is the maximal causal velocity

$\downarrow$

The mass m of a particle of rest mass m_0 increases with its velocity v

$$E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\Downarrow$$

$$\swarrow \qquad \searrow$$

$$m_0 \neq 0 \qquad\qquad m_0 = 0$$

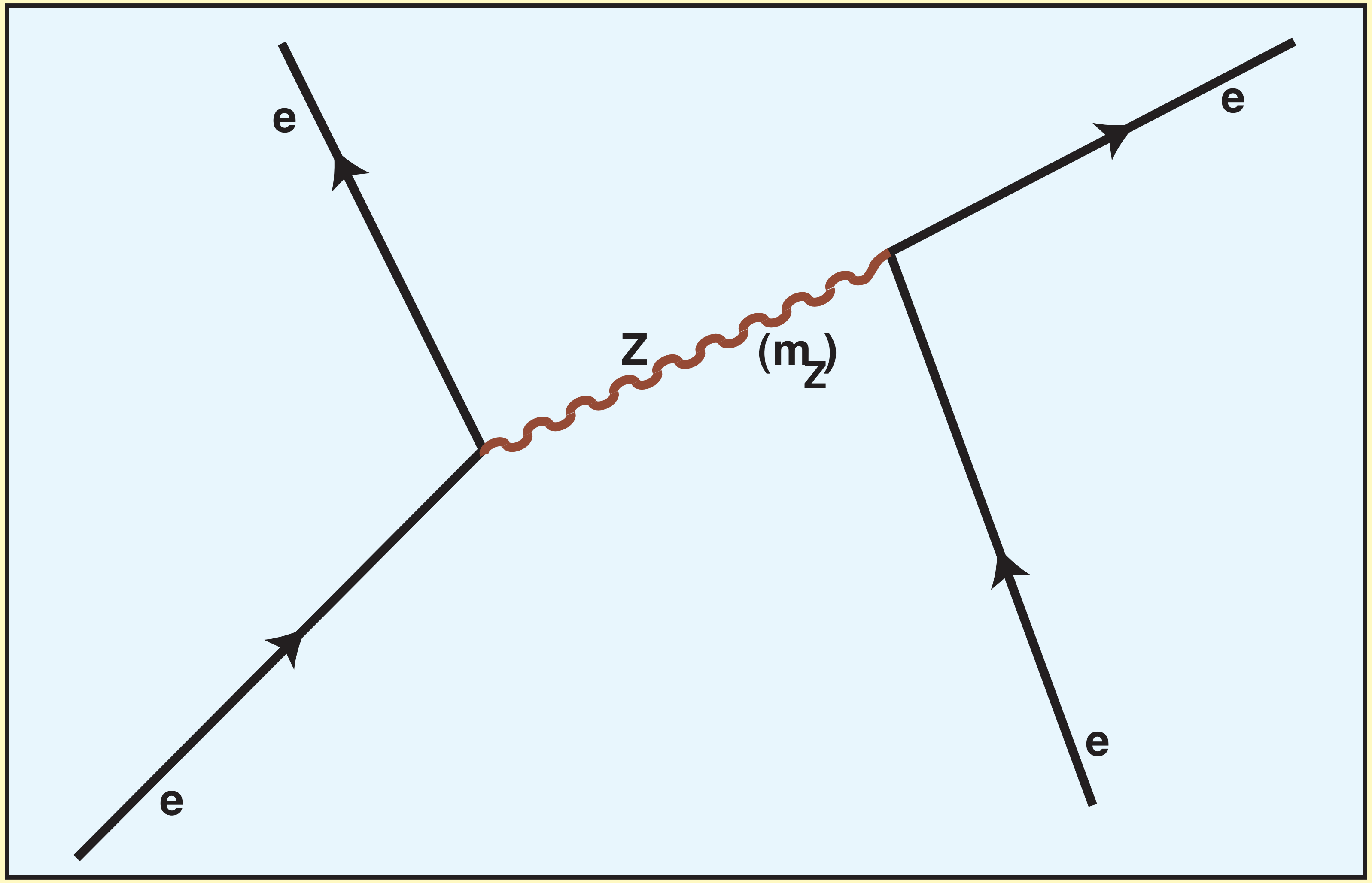
$$\downarrow \qquad\qquad \downarrow$$

The particle never reaches the velocity c	*The particle always moves with velocity c*

Quantum mechanics: long and short range forces

Interactions between particles are described by particle exchange

time



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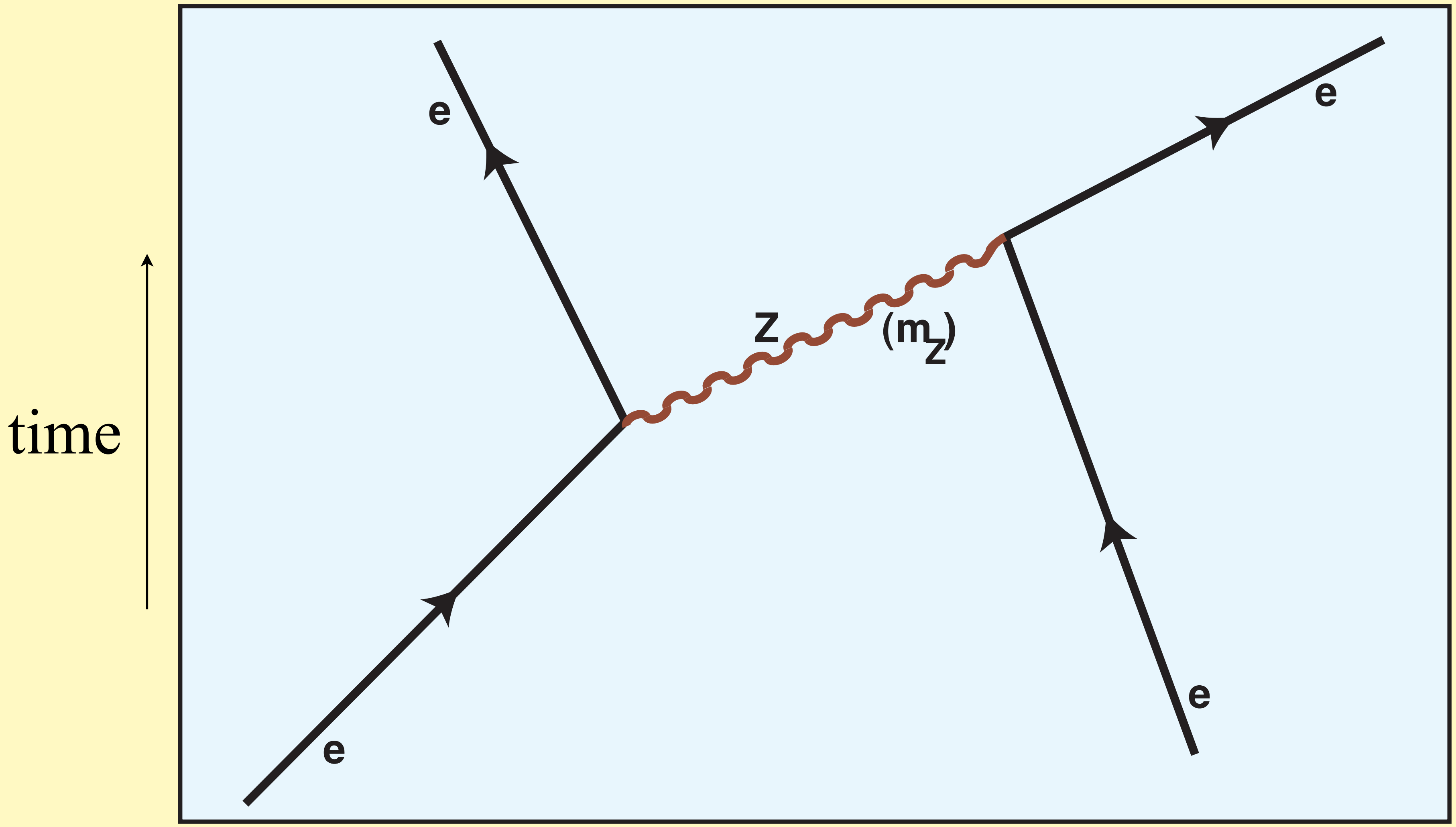

Energy is conserved in the limit of large time intervals

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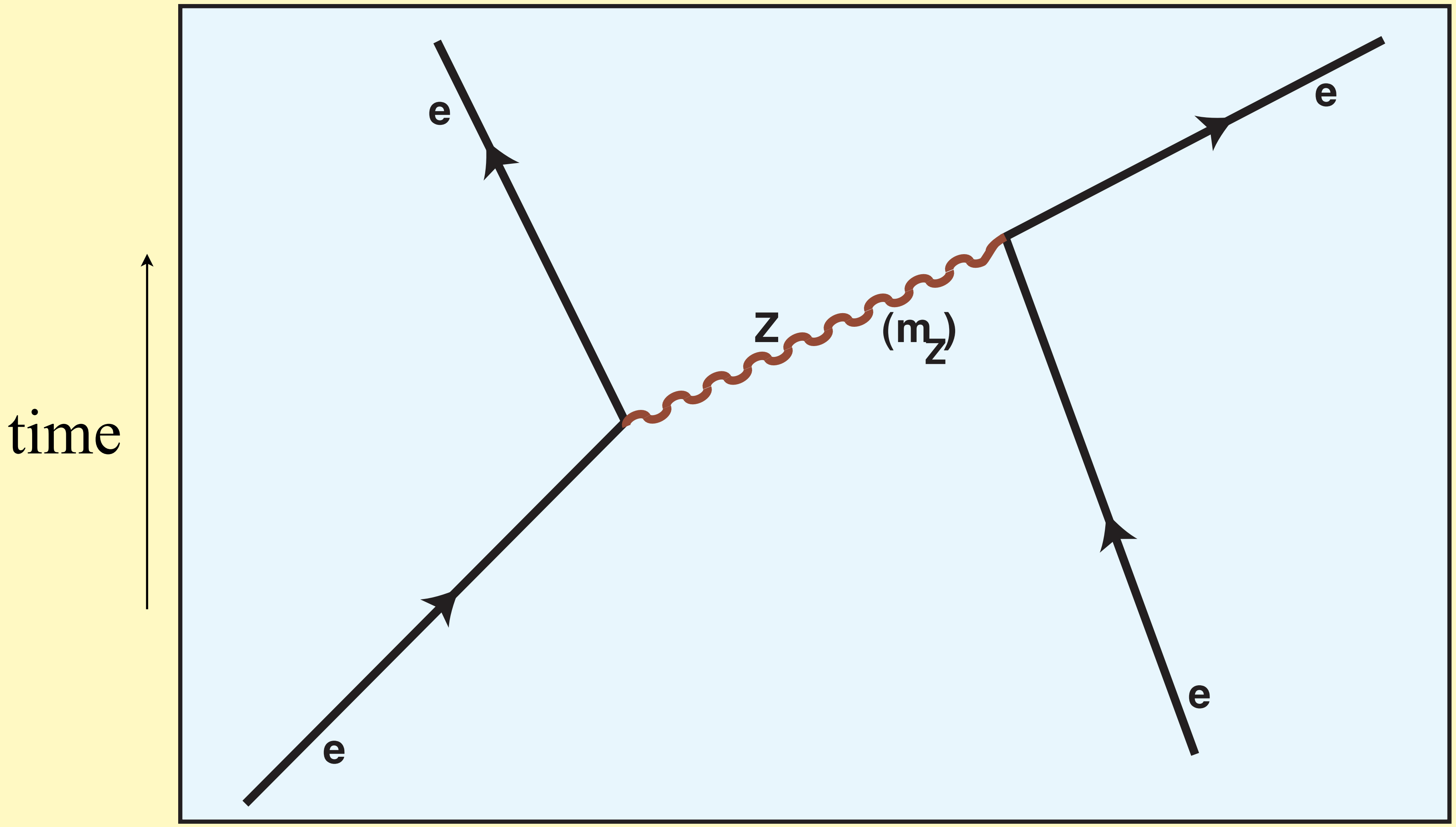

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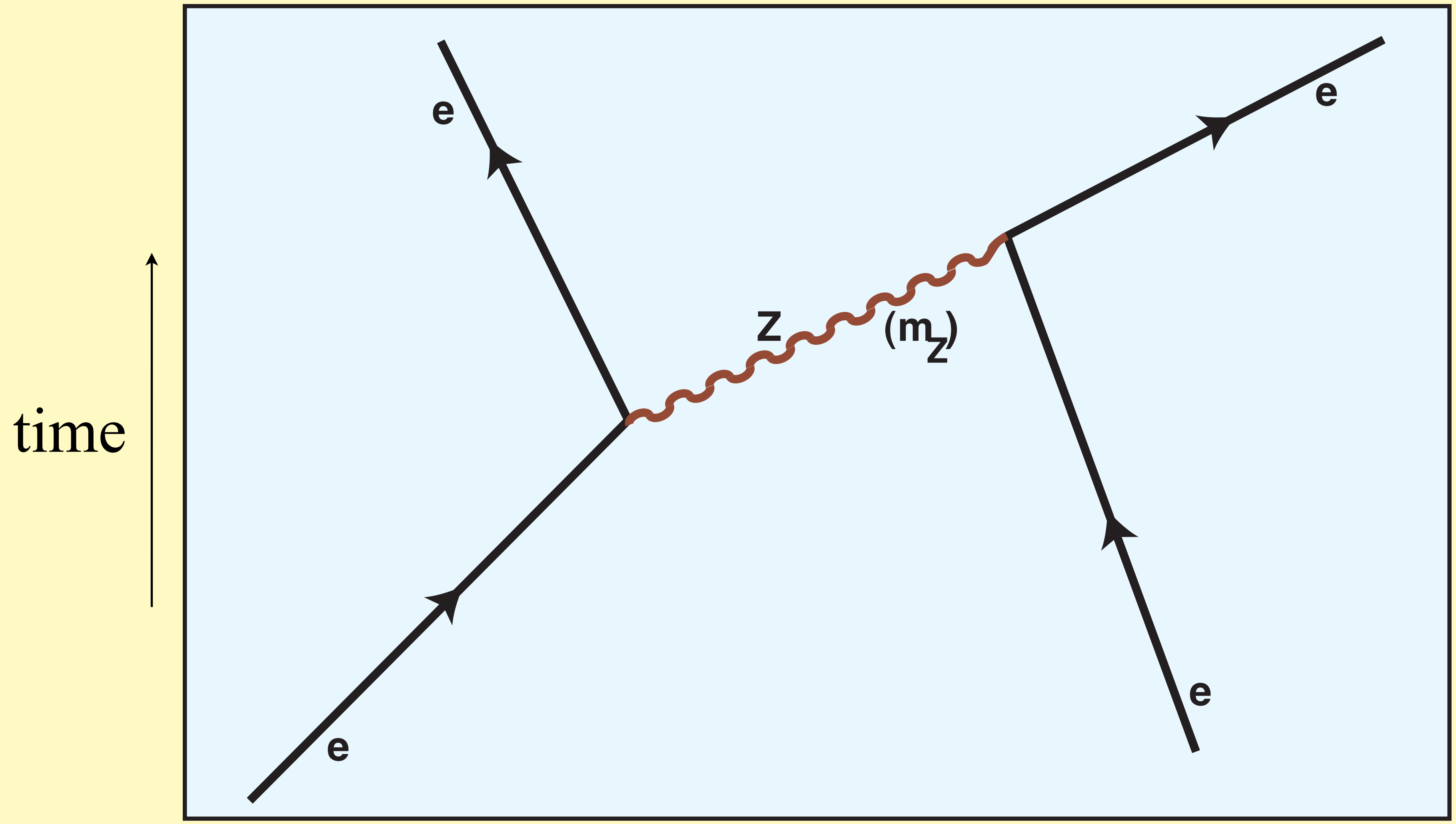

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Massless particle exchange generates long range forces

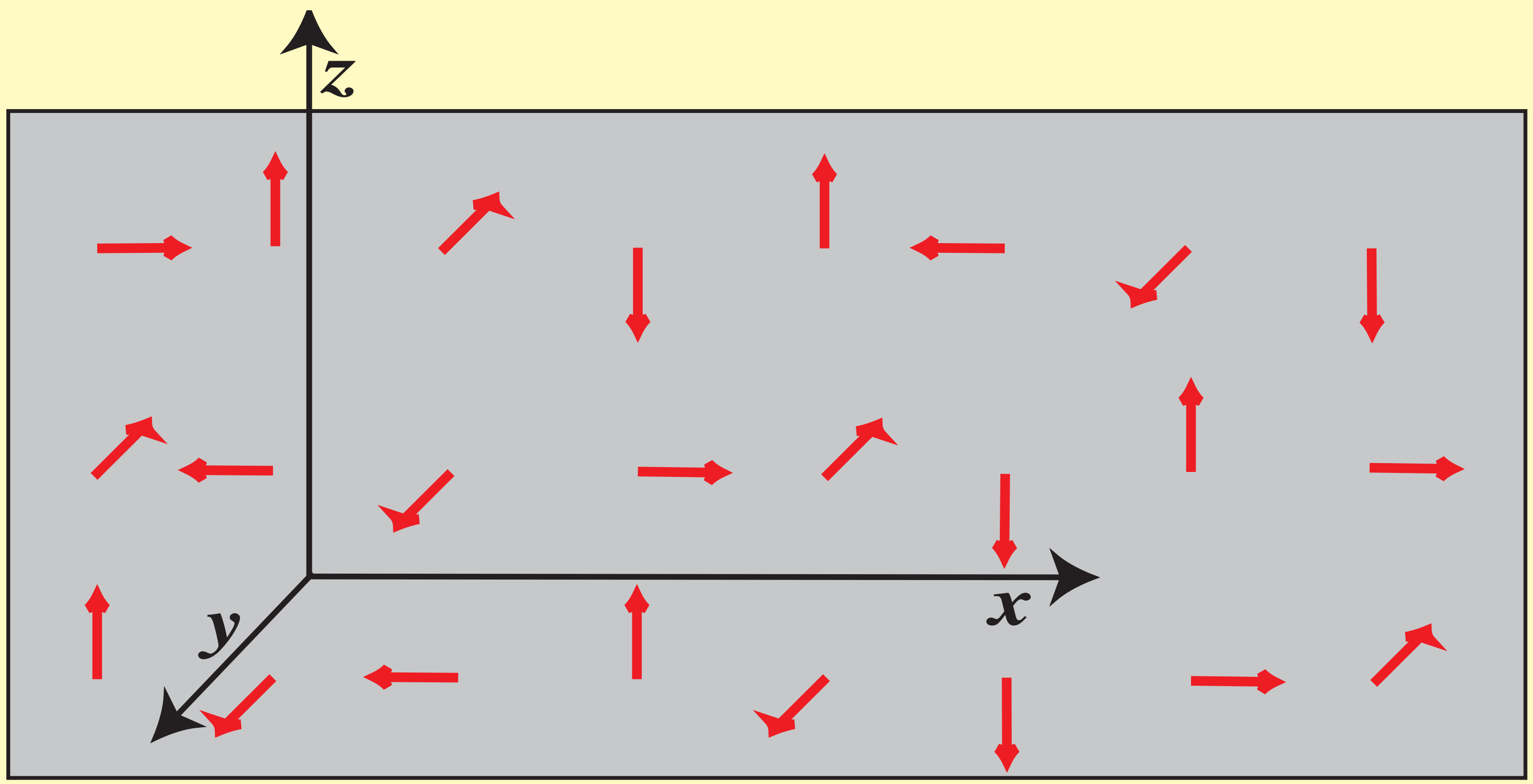
Massive particle exchange generates short range forces

II. Spontaneous breaking of a global symmetry

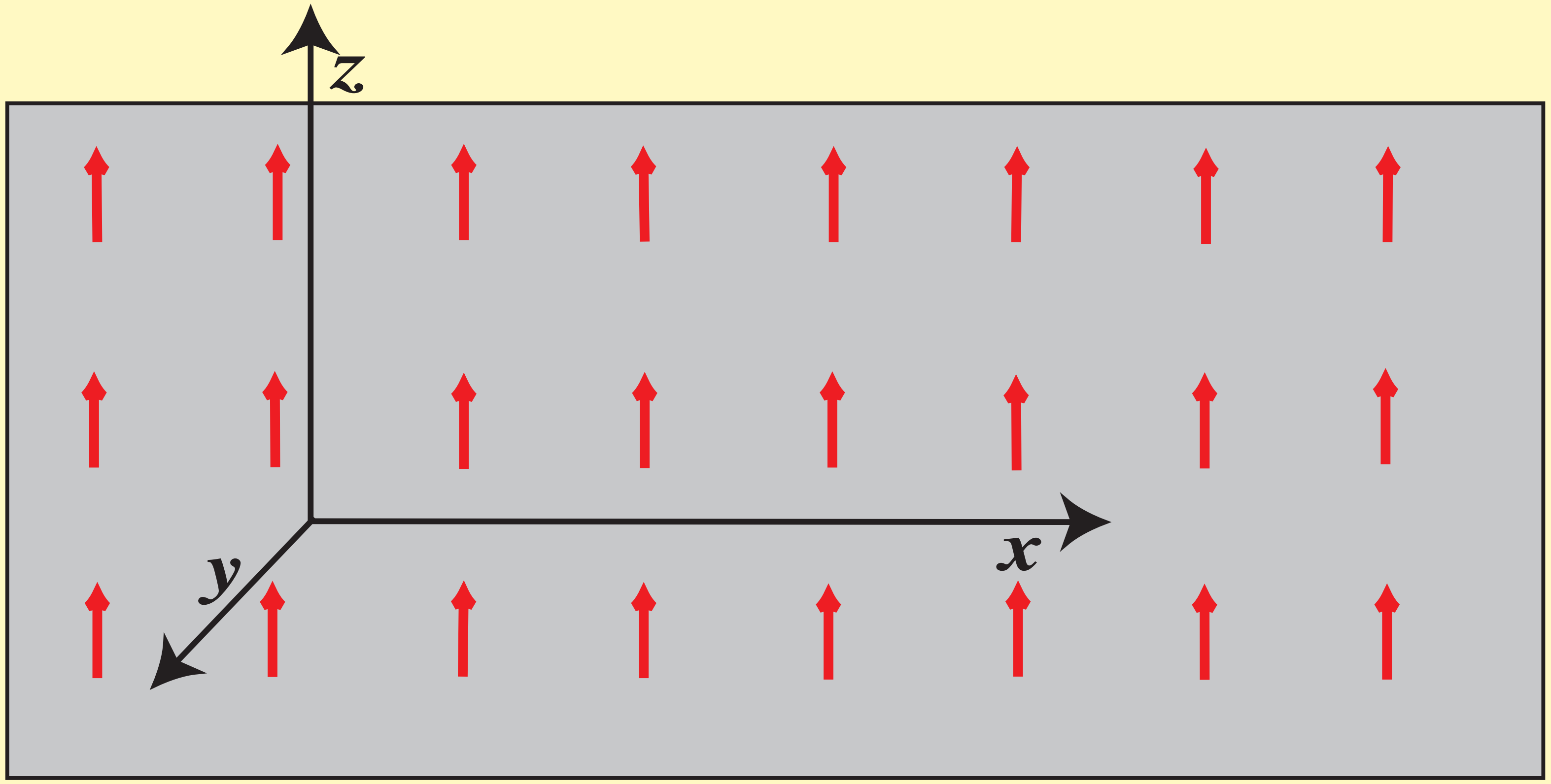
1. Spontaneous symmetry breaking in phase transitions

L.D. Landau, Phys. Z. Sowjet. **11** (1937) 26 [JETP **7** (1937) 19].

Ferromagnetism : the phase transition

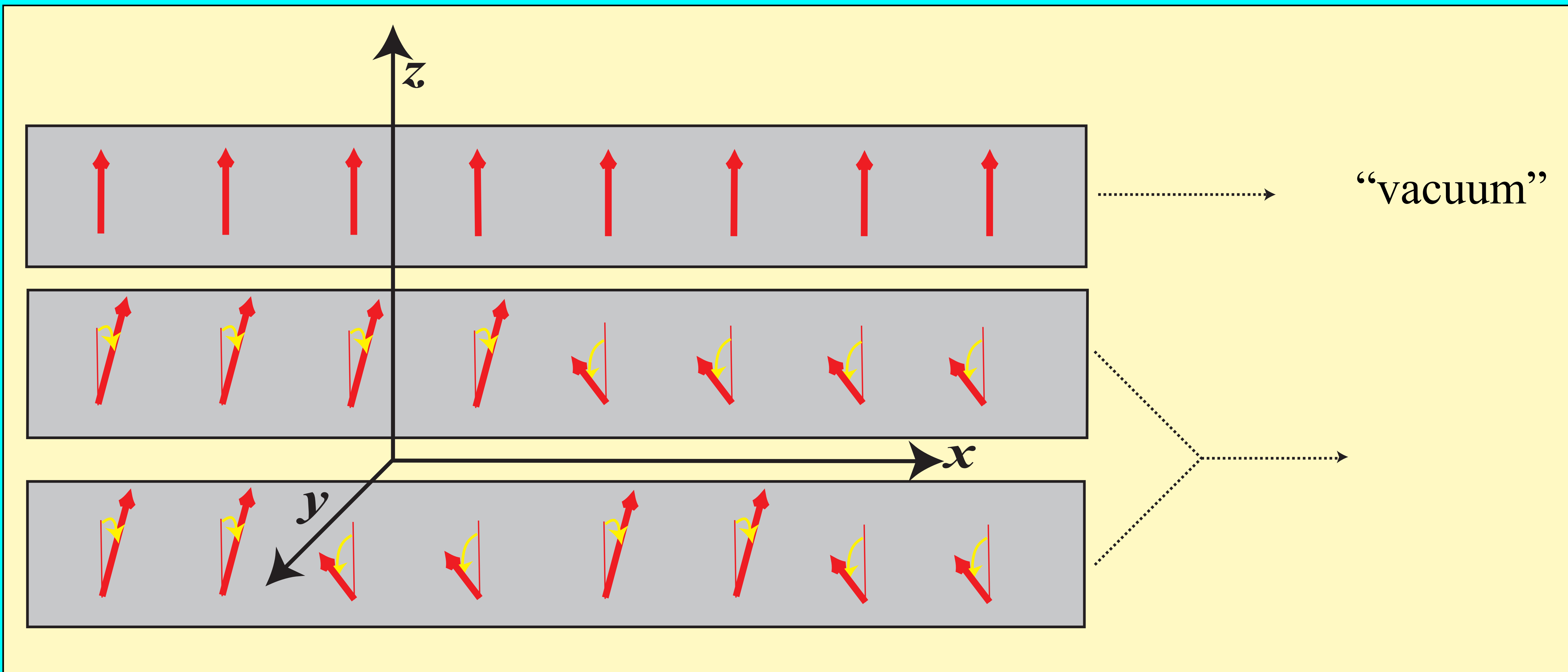


Disordered phase at high temperature



Ordered phase at low temperature

Ferromagnetism : the "massless" boson



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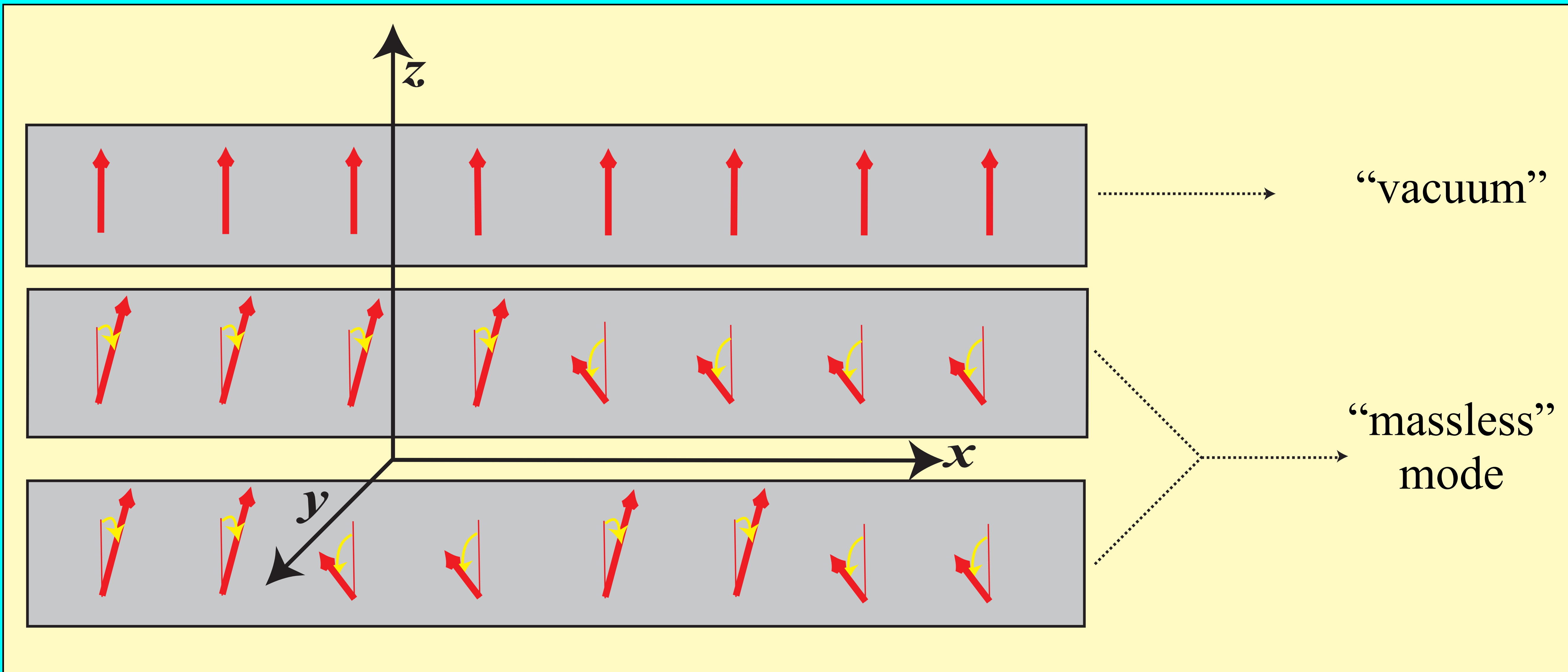

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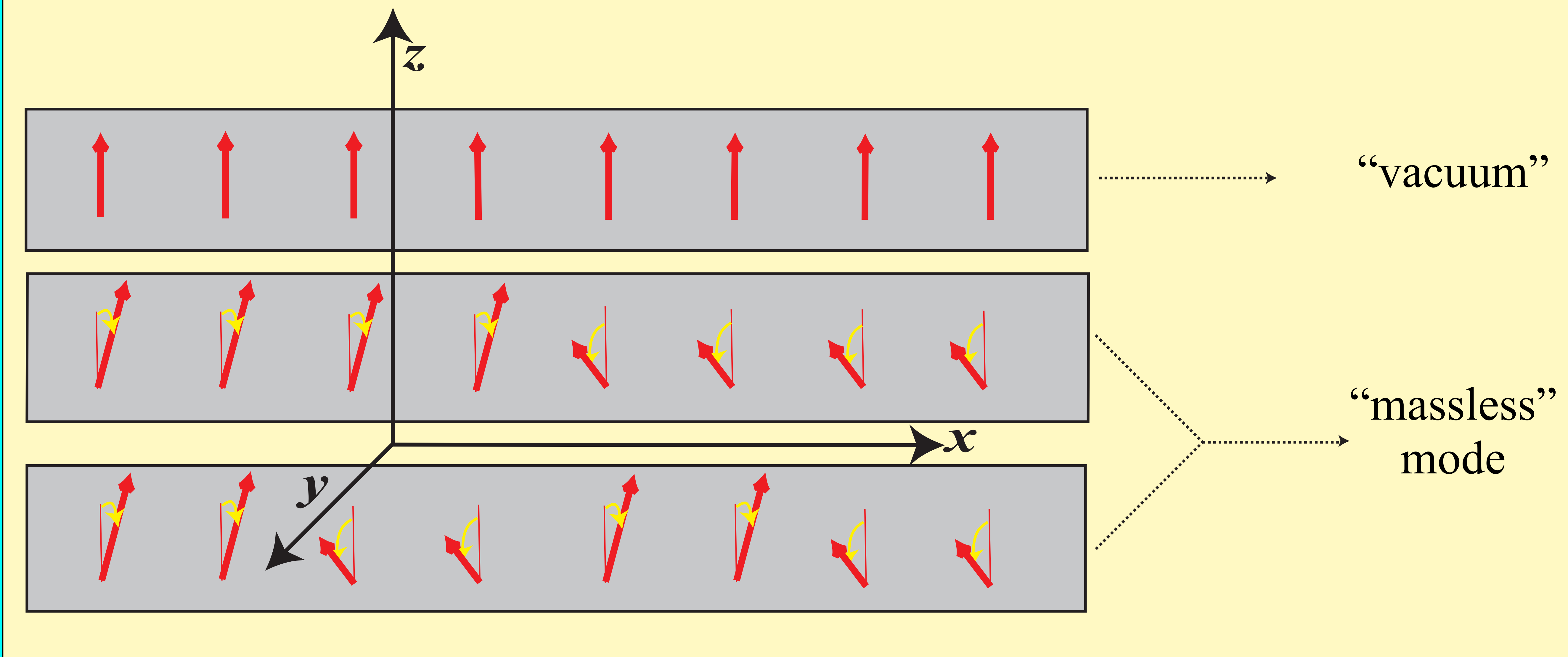
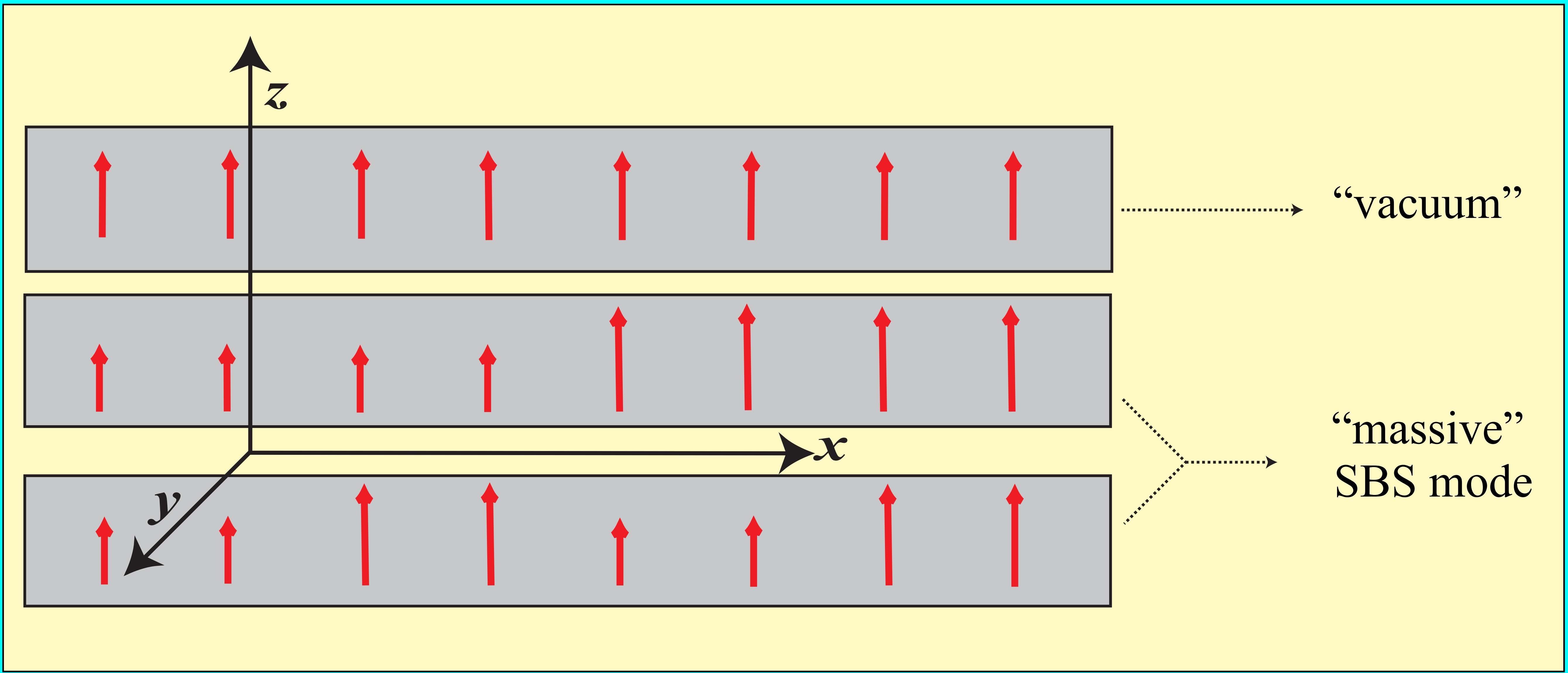


The "massless" mode characterizes a continuous SBS

It is the ancestor of the massless Nambu-Goldstone boson

Ferromagnetism : the “massive” SBS boson



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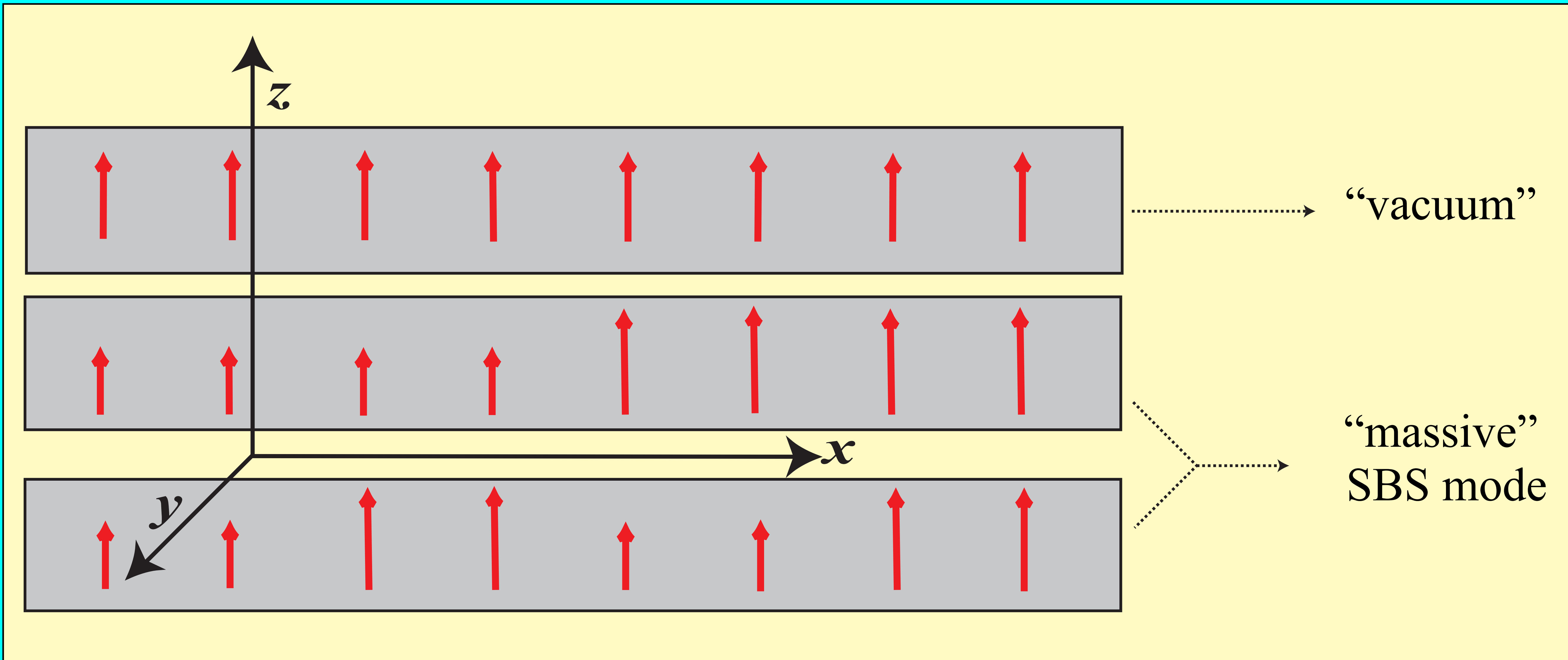
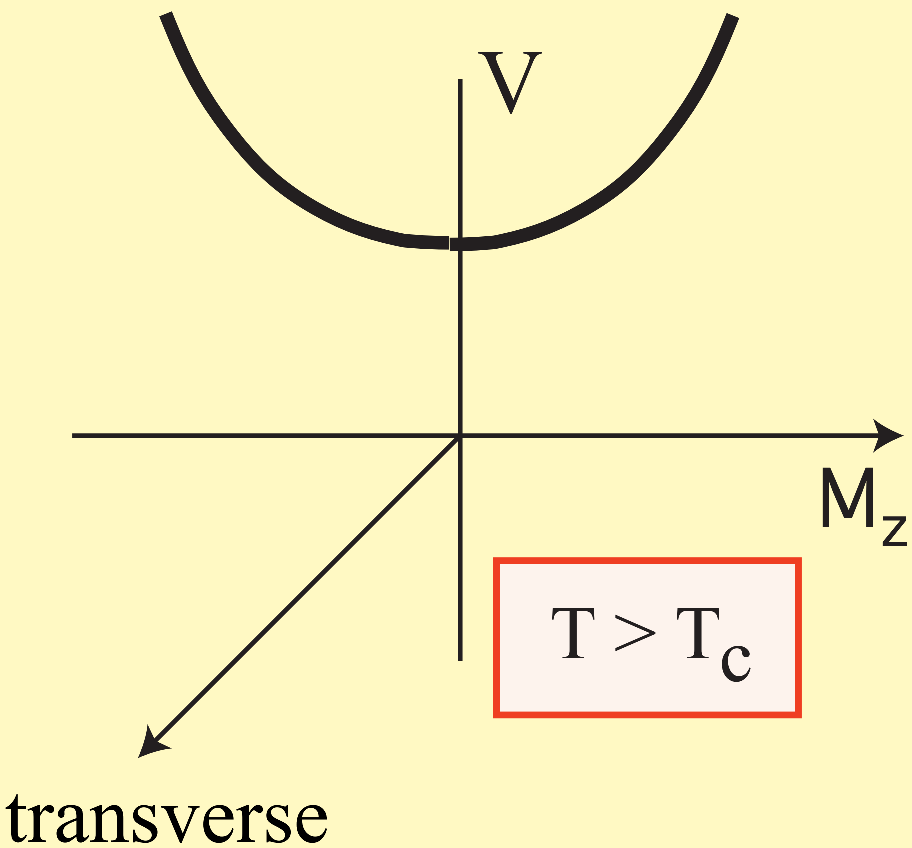


The "massive" SBS mode measures the rigidity of the SBS phase

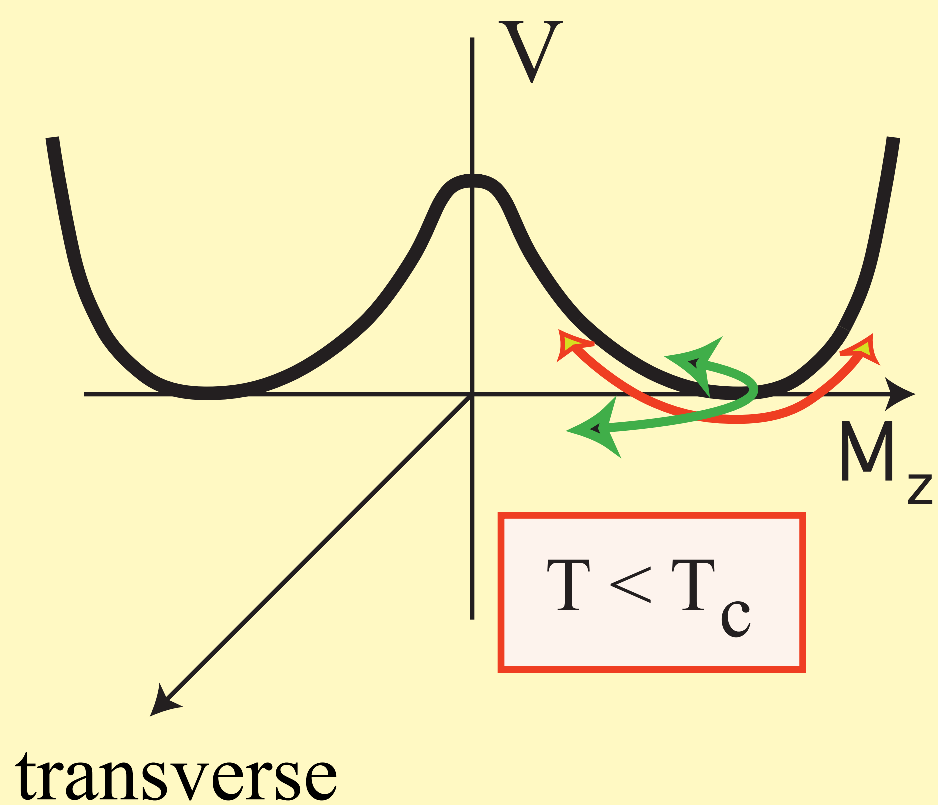
It is the ancestor of the massive SBS scalar boson

Ferromagnetism : the quantitative description

$$V = \lim_{N \to \infty} G / N$$



$\vec{M} = 0$



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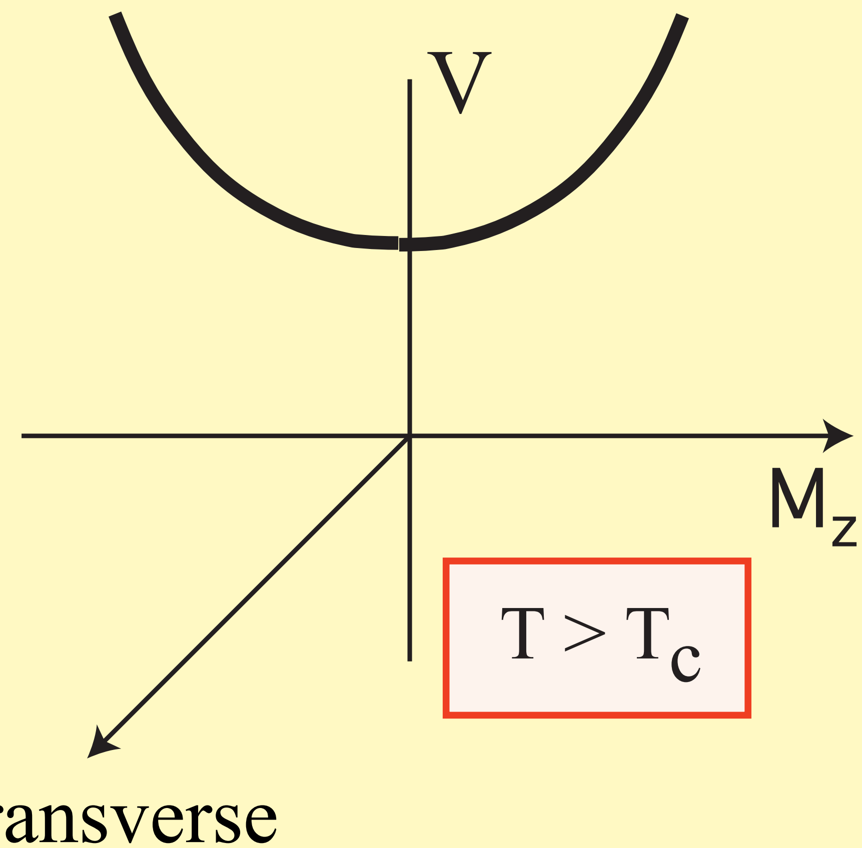

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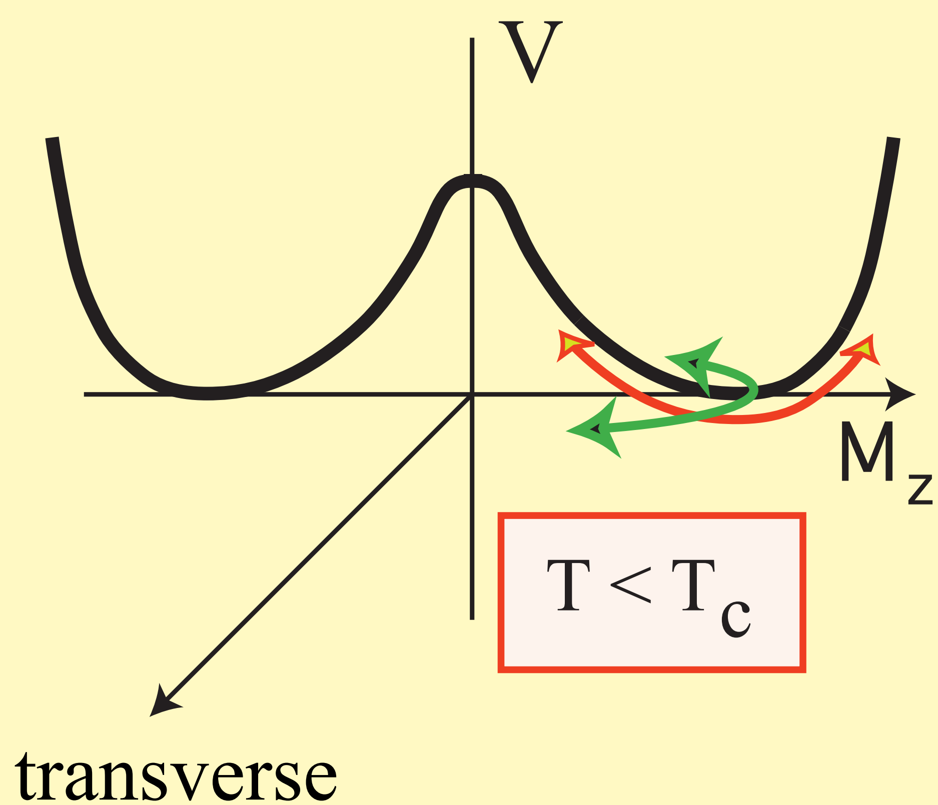

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"massless" mode   "massive" mode

Superconductivity ?

P.W. Anderson, Phys. Rev. **112** (1958) 1900; Y. Nambu, Phys.Rev. **117** (1960) 648.

2. Spontaneous symmetry breaking of the vacuum

Y. Nambu, Phys. Rev. Lett. **4** (1960) 380; Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122** (1961) 345, Phys. Rev. **124** (1961) 246;
J. Goldstone, Il Nuovo Cimento **19** (1961) 154; J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. **127** (1962) 965.

Chiral symmetry breaking

Massless fermions $\equiv \{\nu_R \; \nu_L\} \longrightarrow$ *(chiral)* $U(1)$ *invariance*

Chiral invariant interactions preserve masslessness

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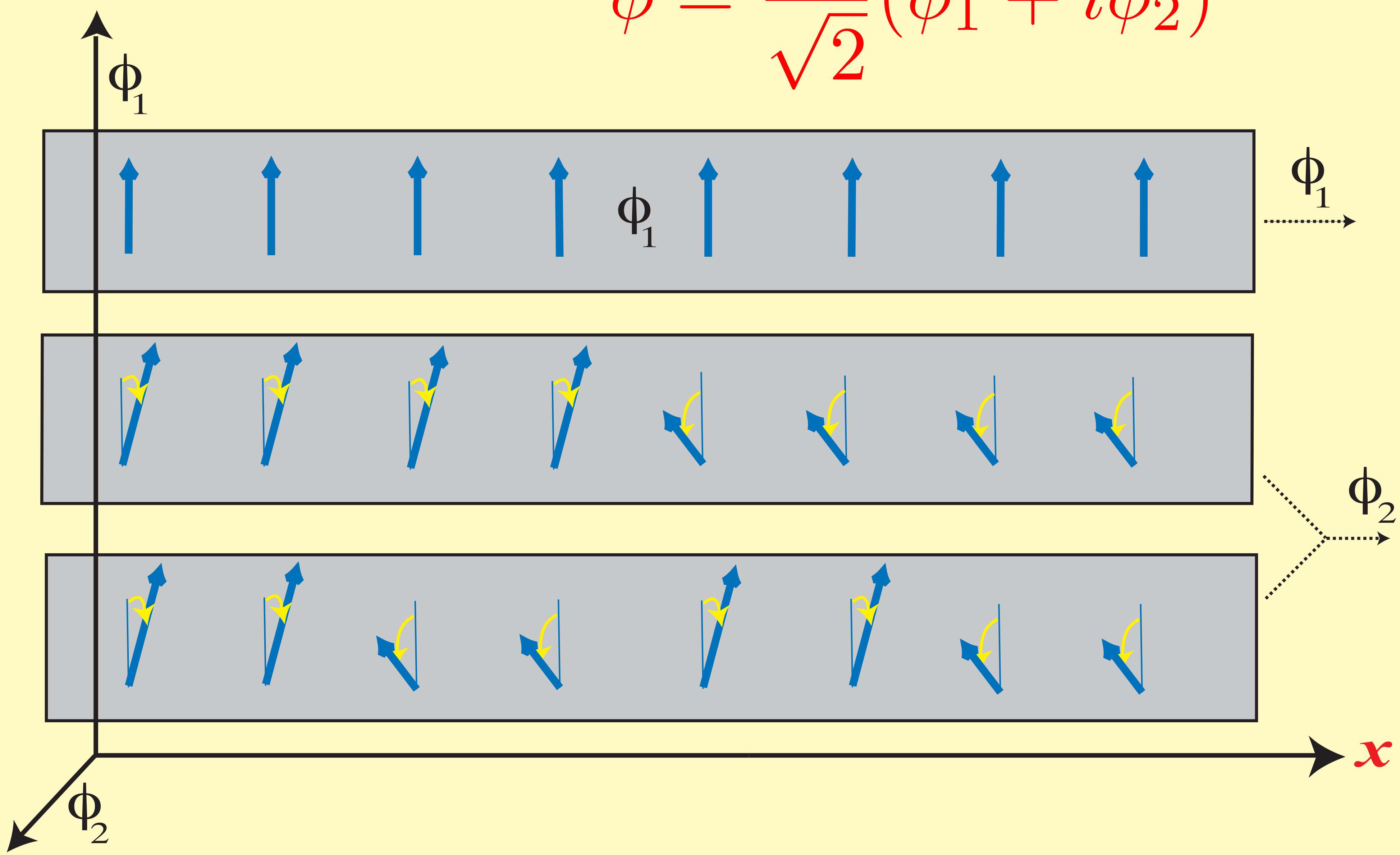
massive SBS scalar boson

A simple model : the Nambu-Goldstone boson

$U(1)$ *symmetry* $\phi \rightarrow e^{i\alpha}\phi$ *of a complex scalar is broken by* $|\phi| \neq 0$

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$



structured vacuum

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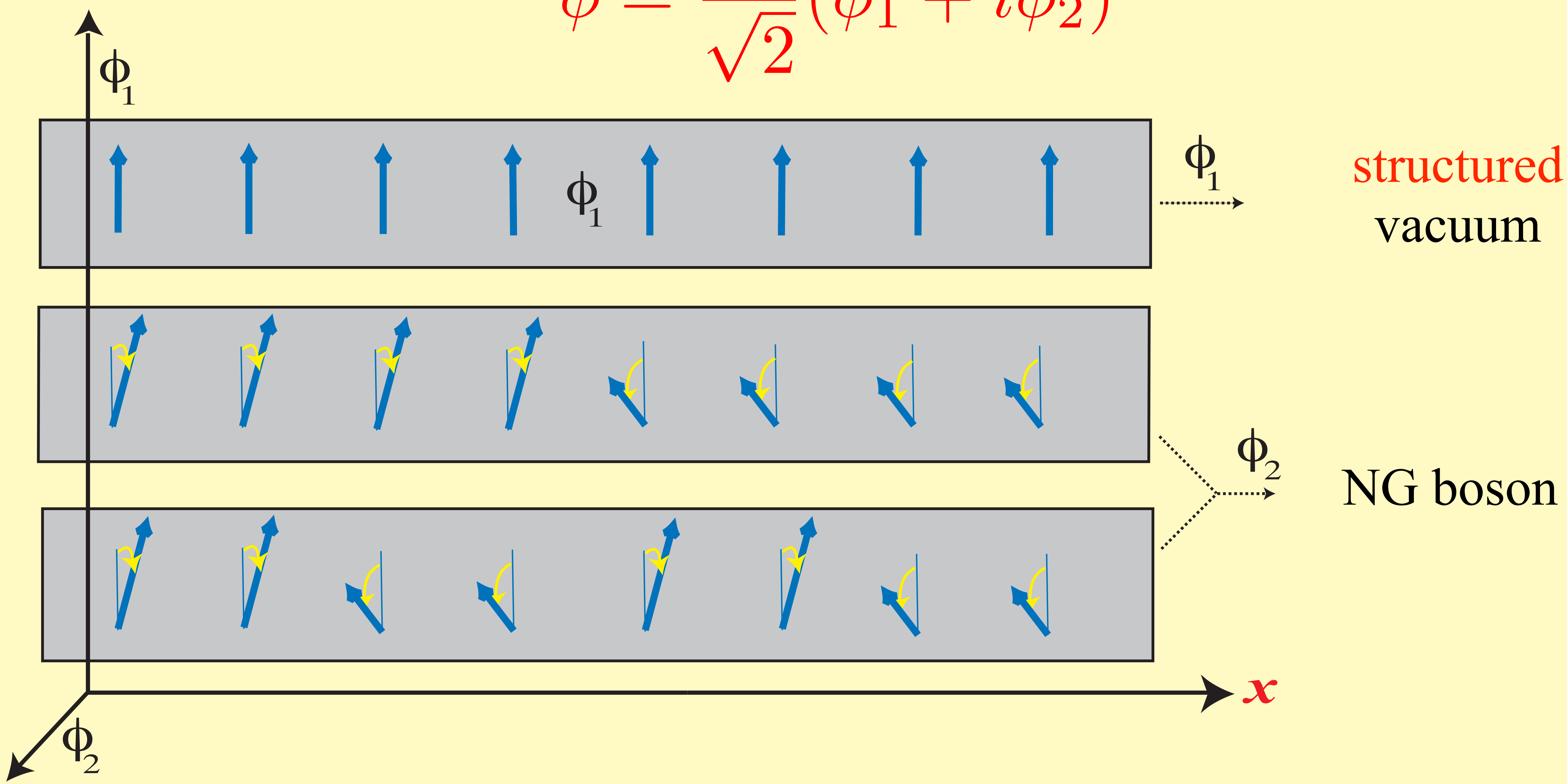

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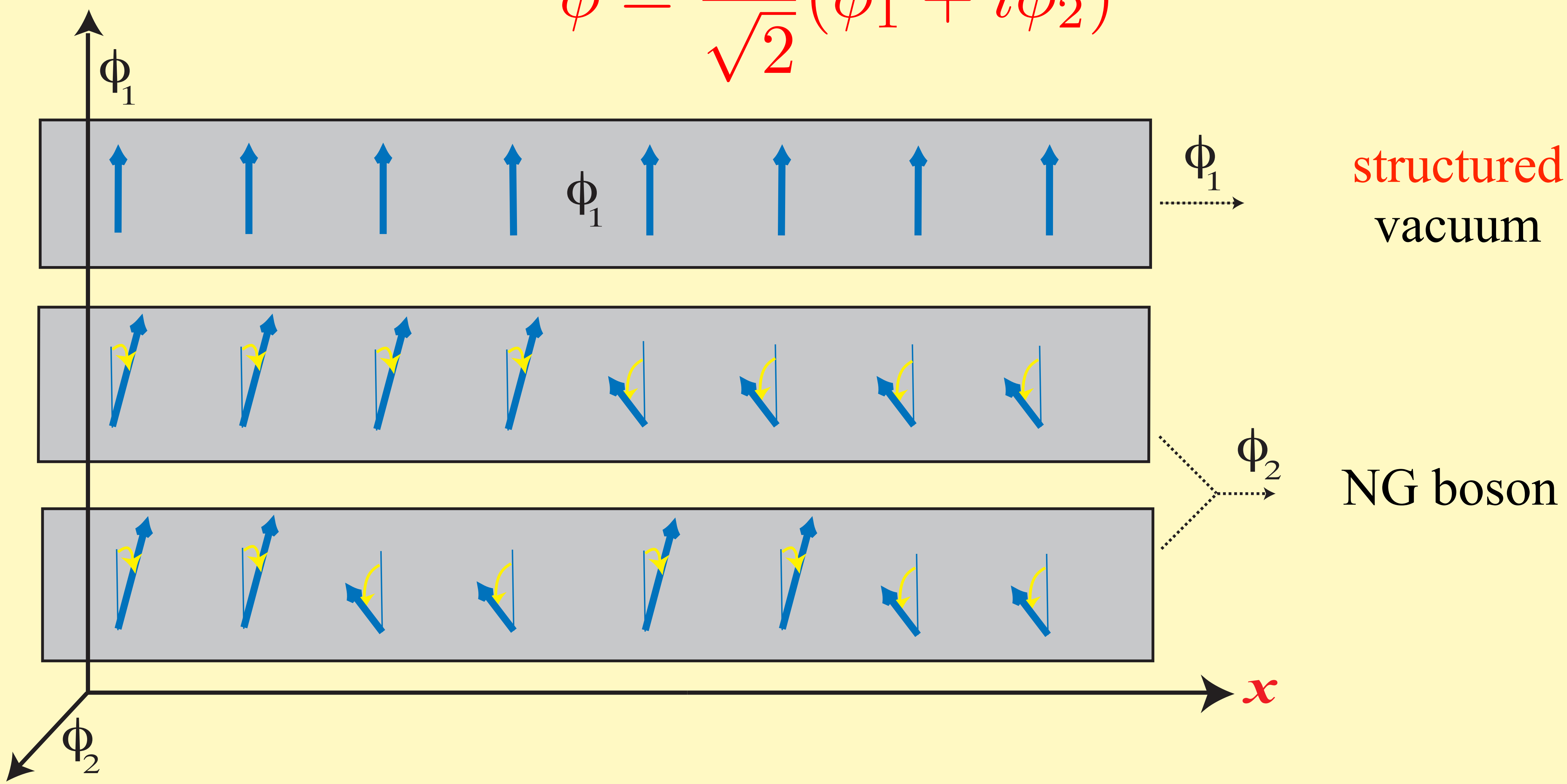

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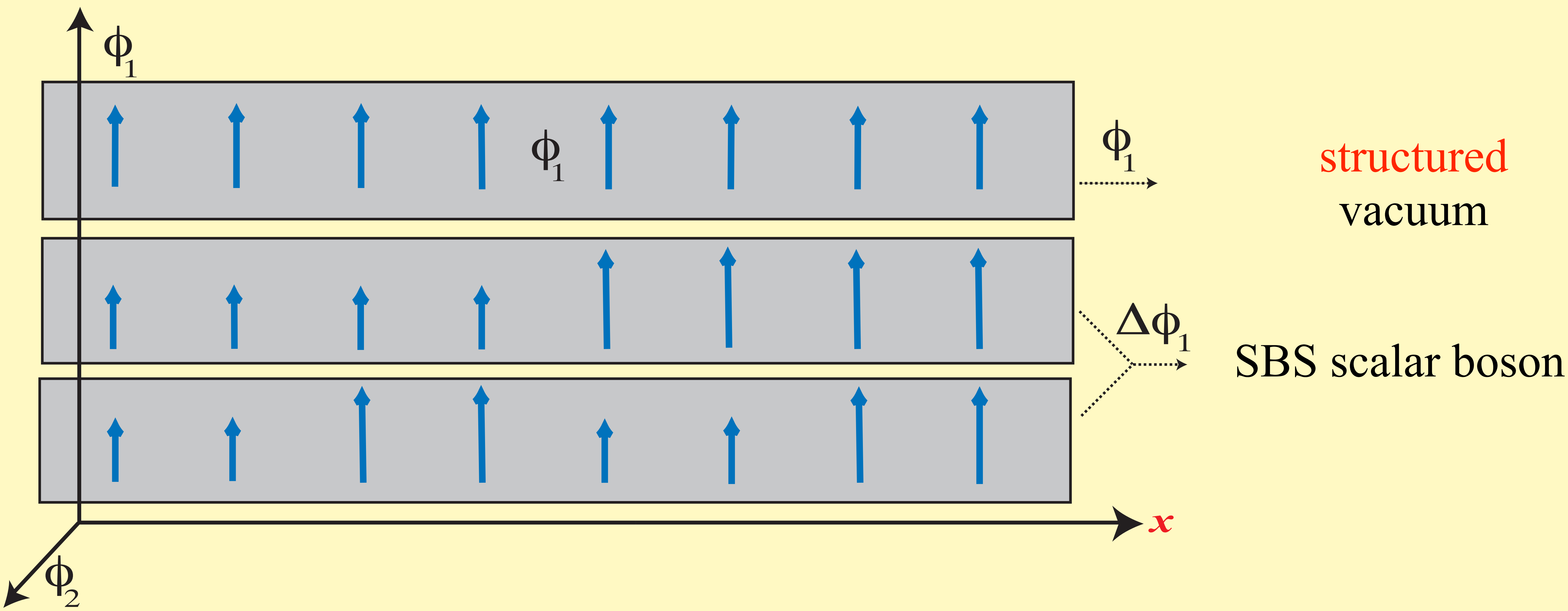

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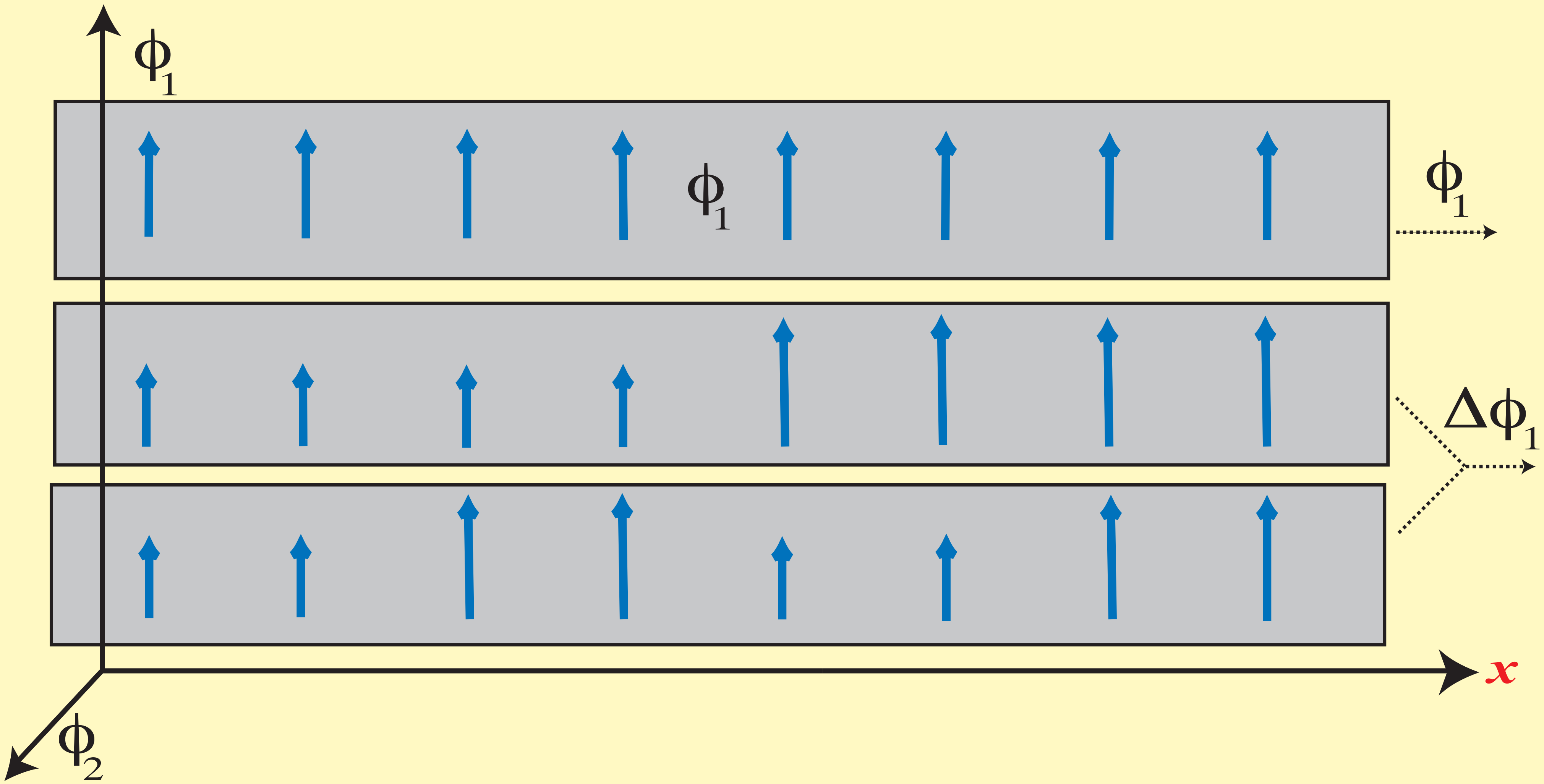


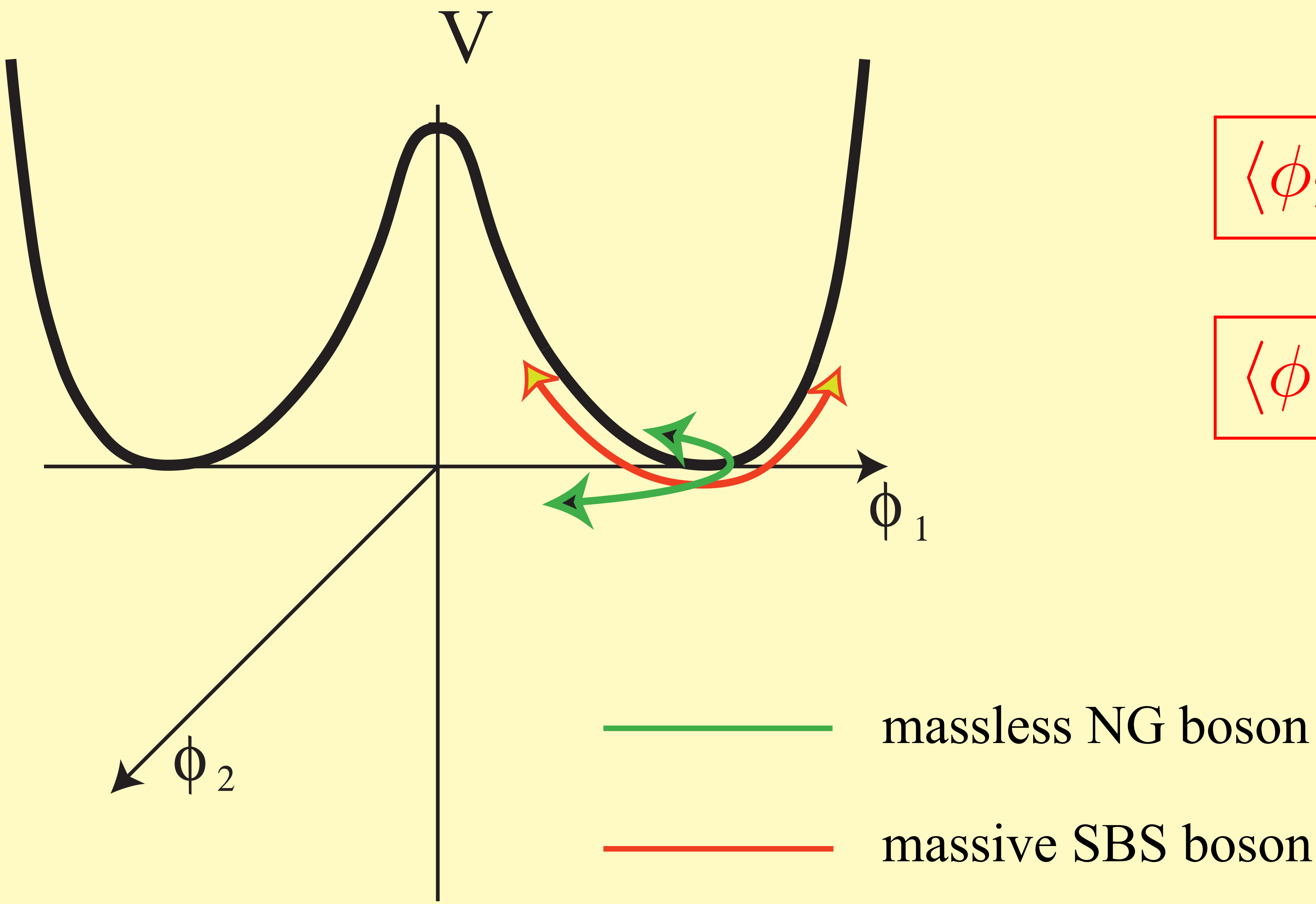
structured vacuum

SBS scalar boson

The massive SBS scalar boson measures the rigidity of the vacuum

A simple model : the quantitative description

$$\mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi - V(\phi^* \phi) \qquad V(\phi^* \phi) = -\mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$



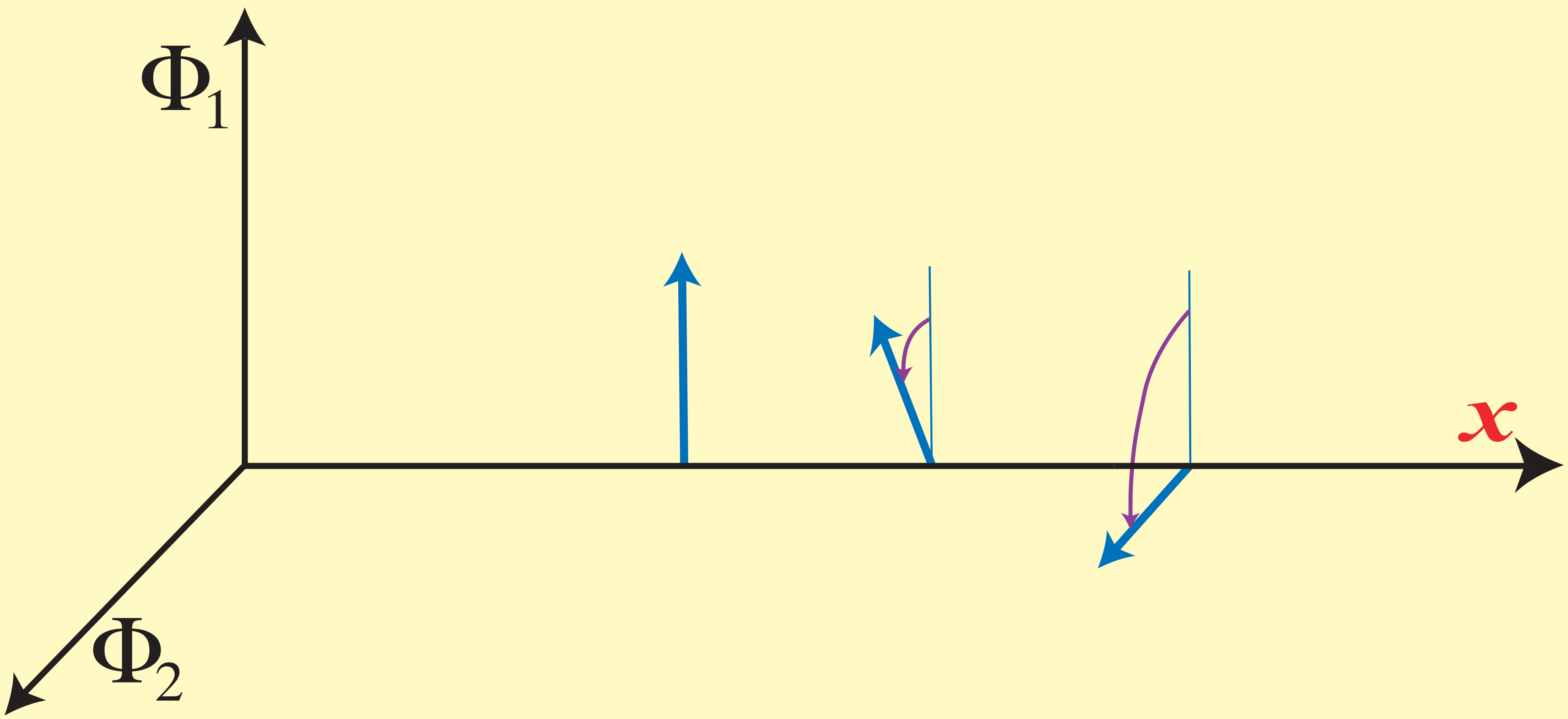
$$\langle \phi_2 \rangle = 0$$

$$\langle \phi_1 \rangle \neq 0$$

III. The BEH mechanism

1. From global to local symmetry

Example: "abelian" local symmetry



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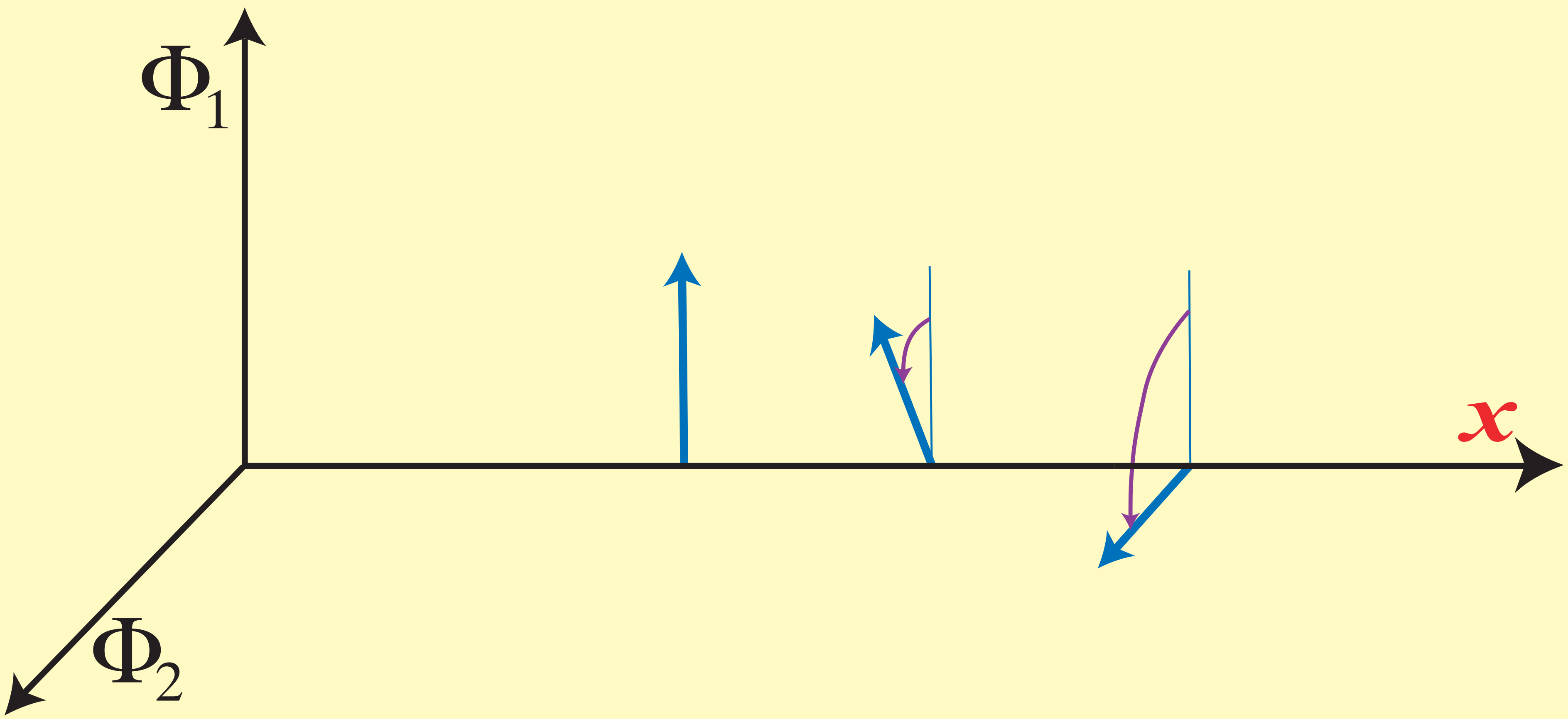

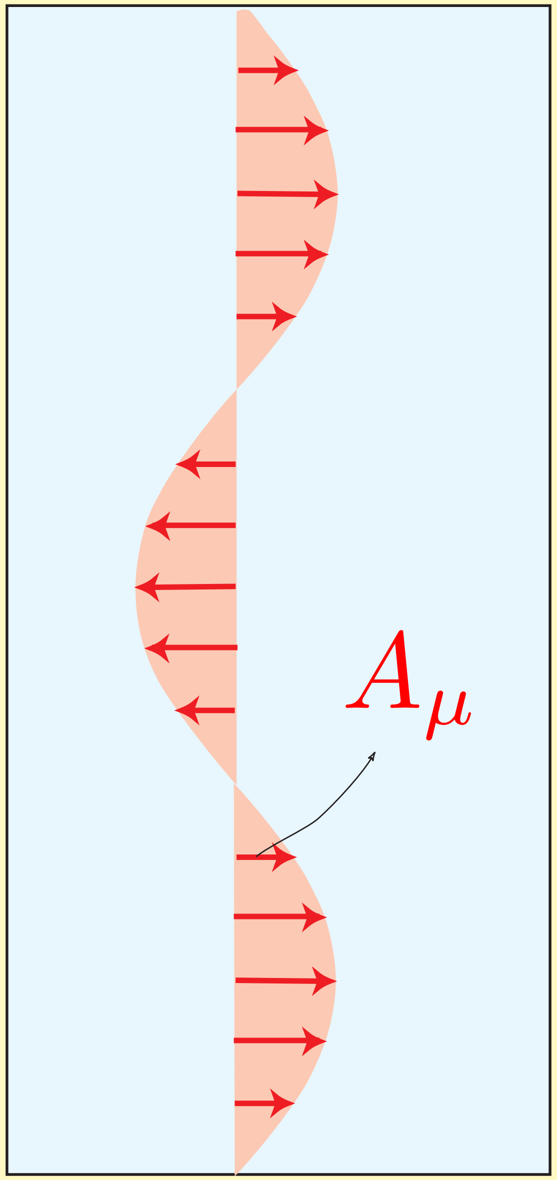

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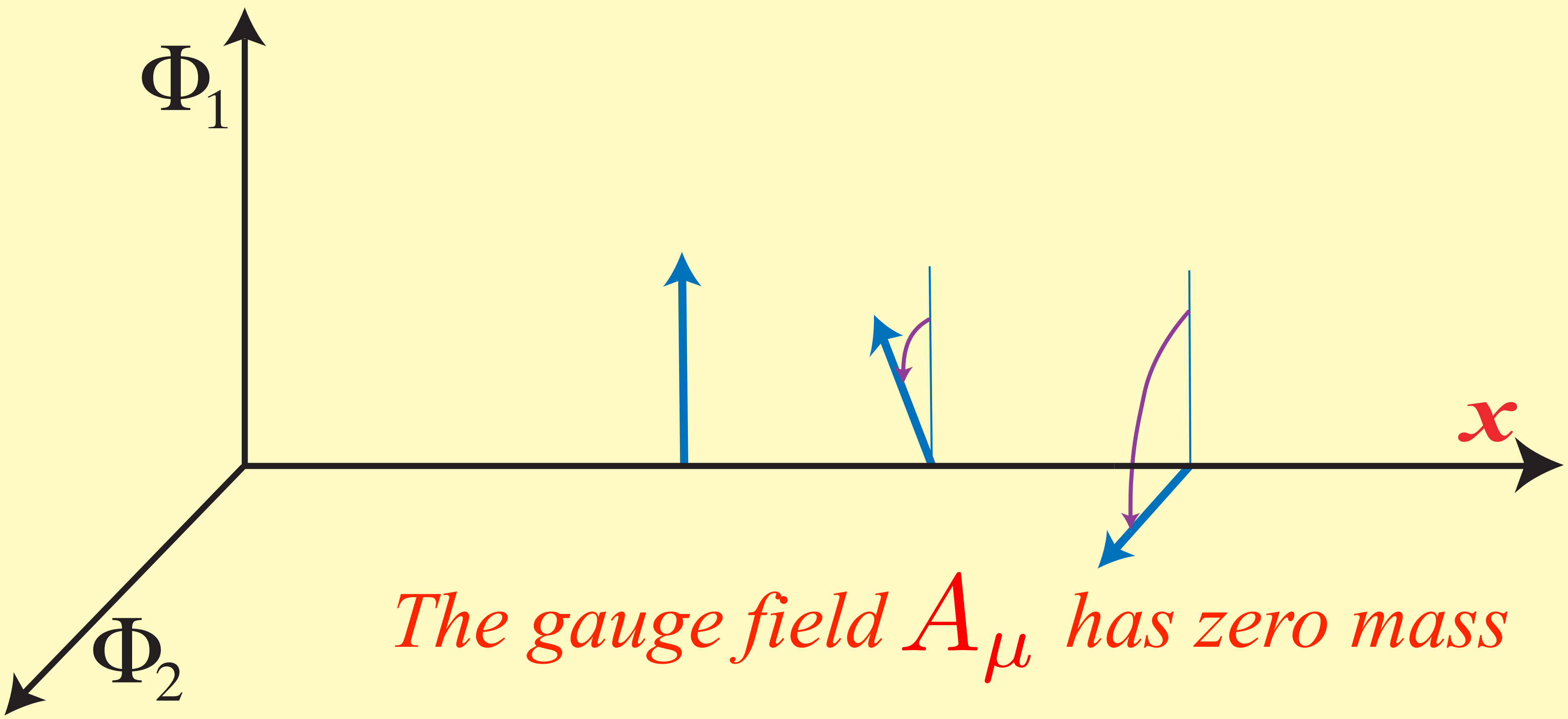
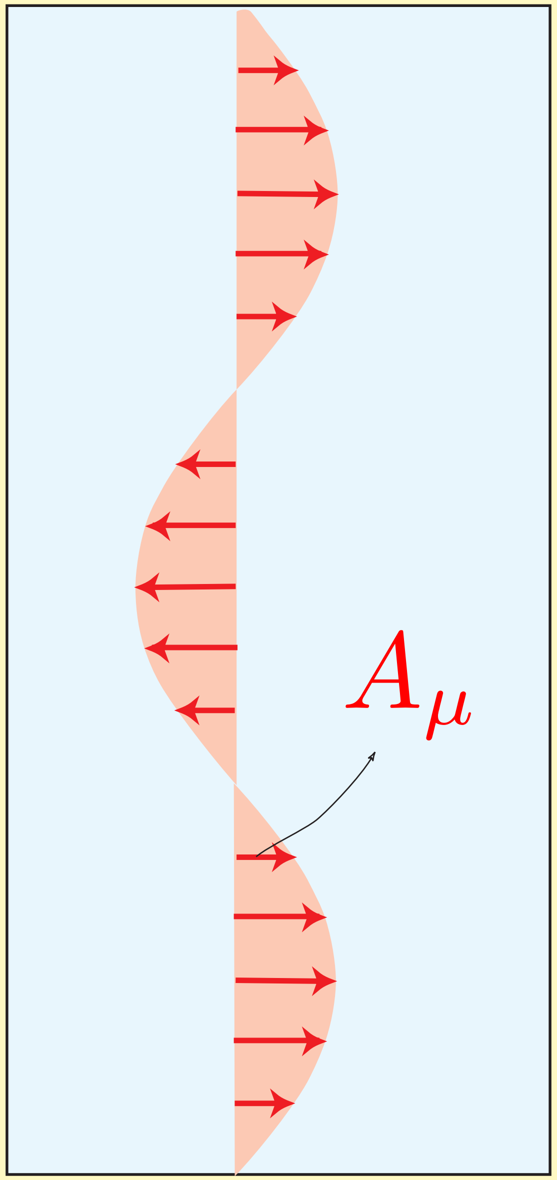


The gauge field A_μ has zero mass



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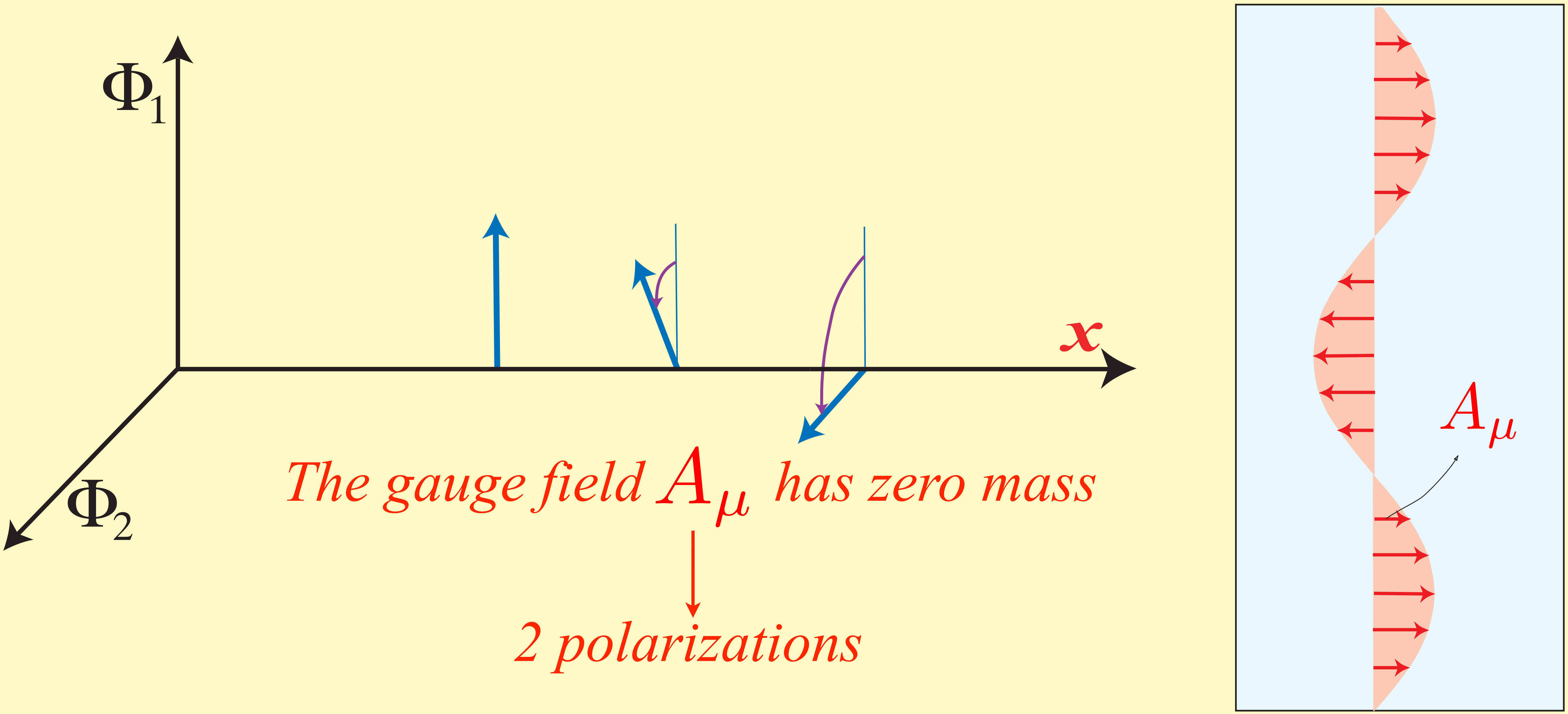

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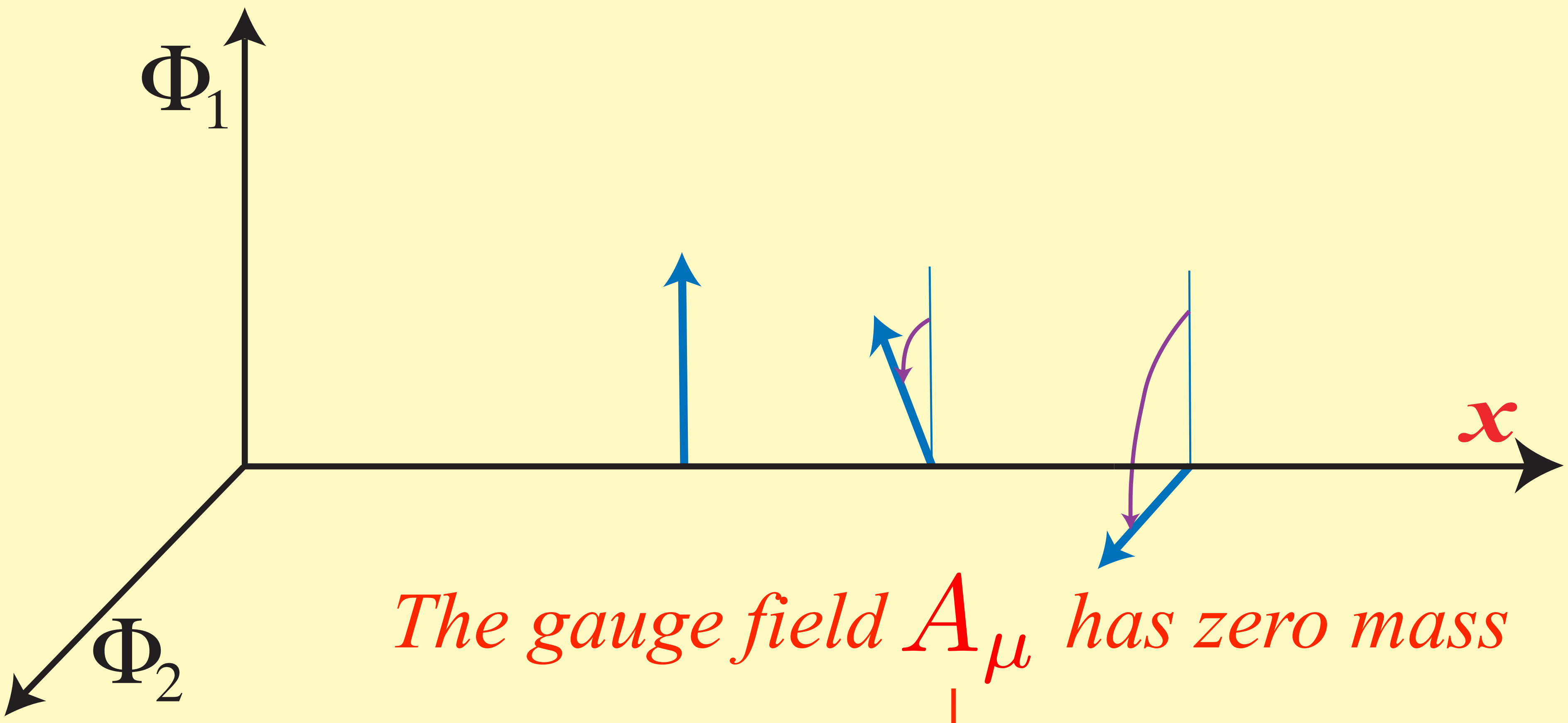

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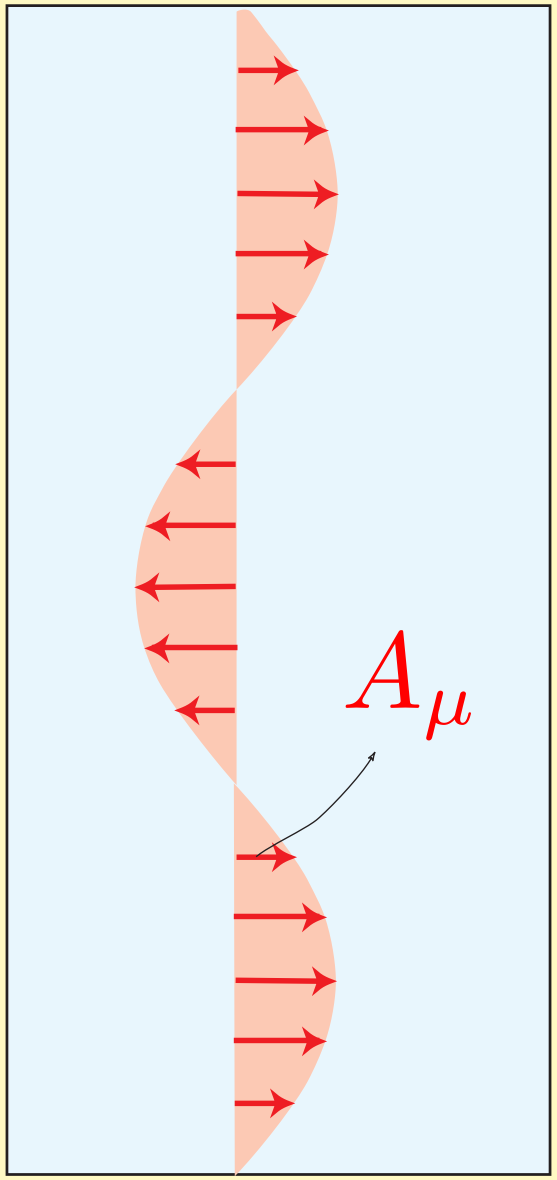
↓

2 polarizations



This is electromagnetism!

Global abelian symmetry

$$\phi \rightarrow e^{i\alpha}\phi \qquad \mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi - V(\phi^* \phi)$$

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Local abelian symmetry

$$\phi \to e^{i\alpha(x)}\phi \qquad A_\mu \to A_\mu + \partial_\mu \alpha$$

$$\mathcal{L} = D^\mu \phi^* D_\mu \phi - V(\phi^*\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$D_\mu \phi = \partial_\mu \phi - ieA_\mu \phi \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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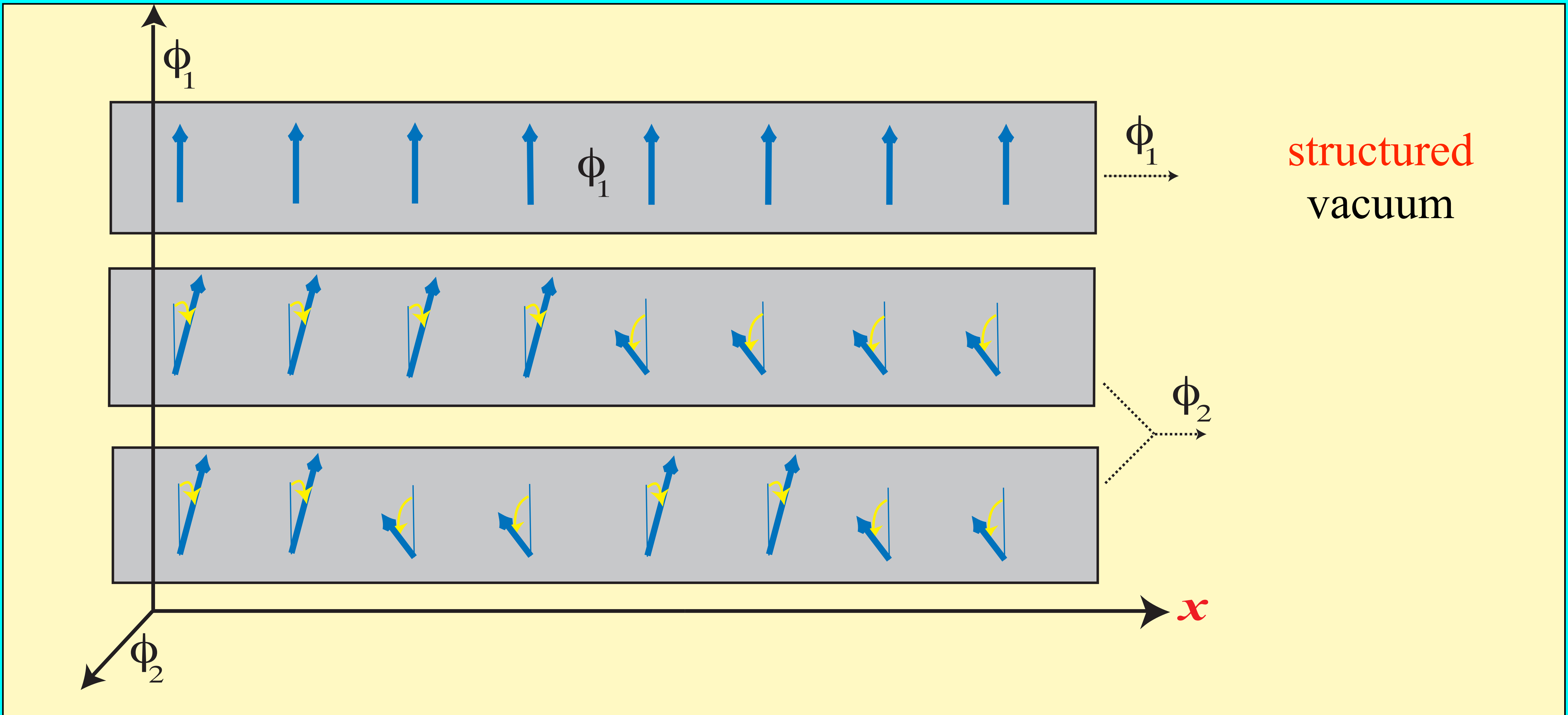
Local non-abelian symmetry

$$\begin{aligned} (D_\mu \phi)^A &= \partial_\mu \phi^A - eA^a_\mu T^{a\,AB}\phi^B \\ F^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + ef^{abc}A^b_\mu A^c_\nu \end{aligned}$$

2. Conceptual issues in SBS for local symmetries

The fate of the Nambu-Goldstone boson (a simple model)



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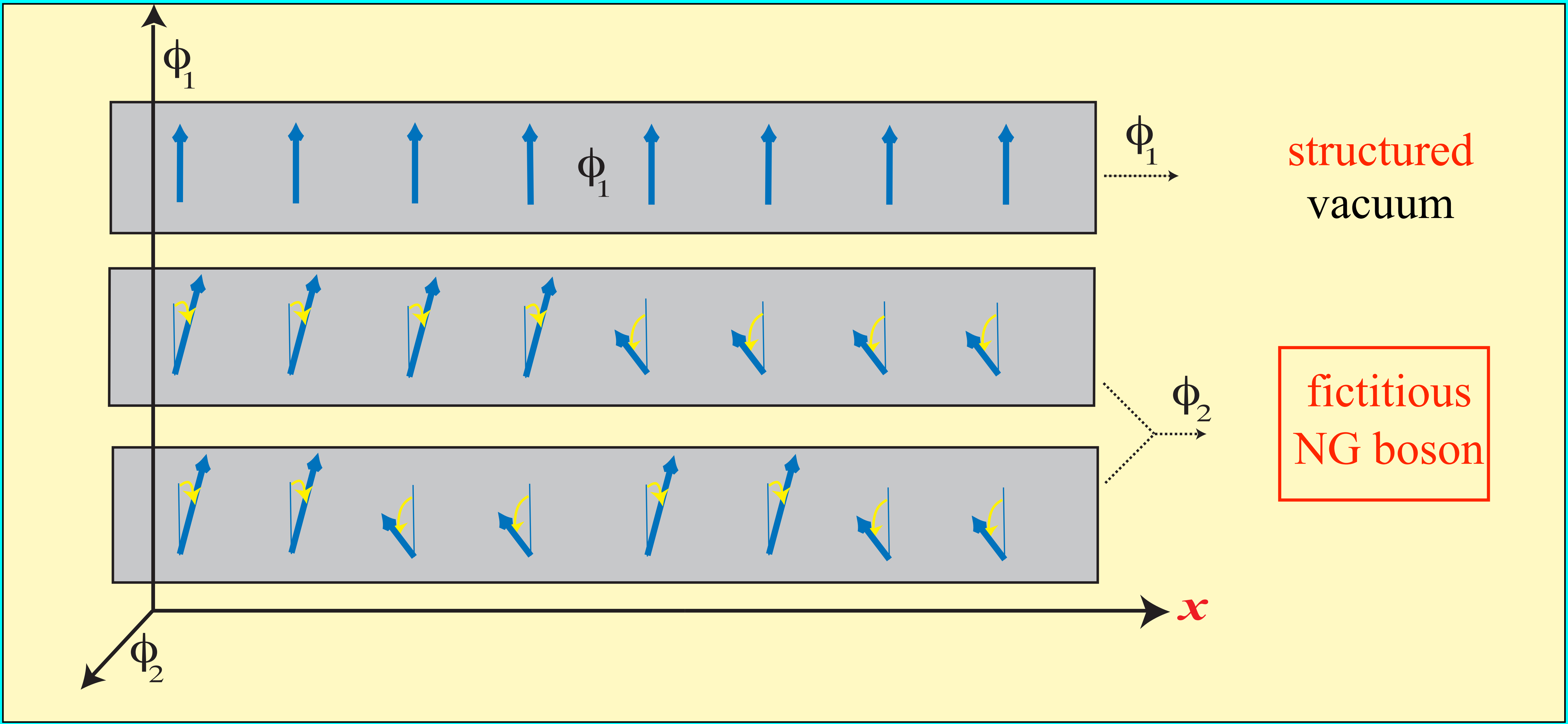

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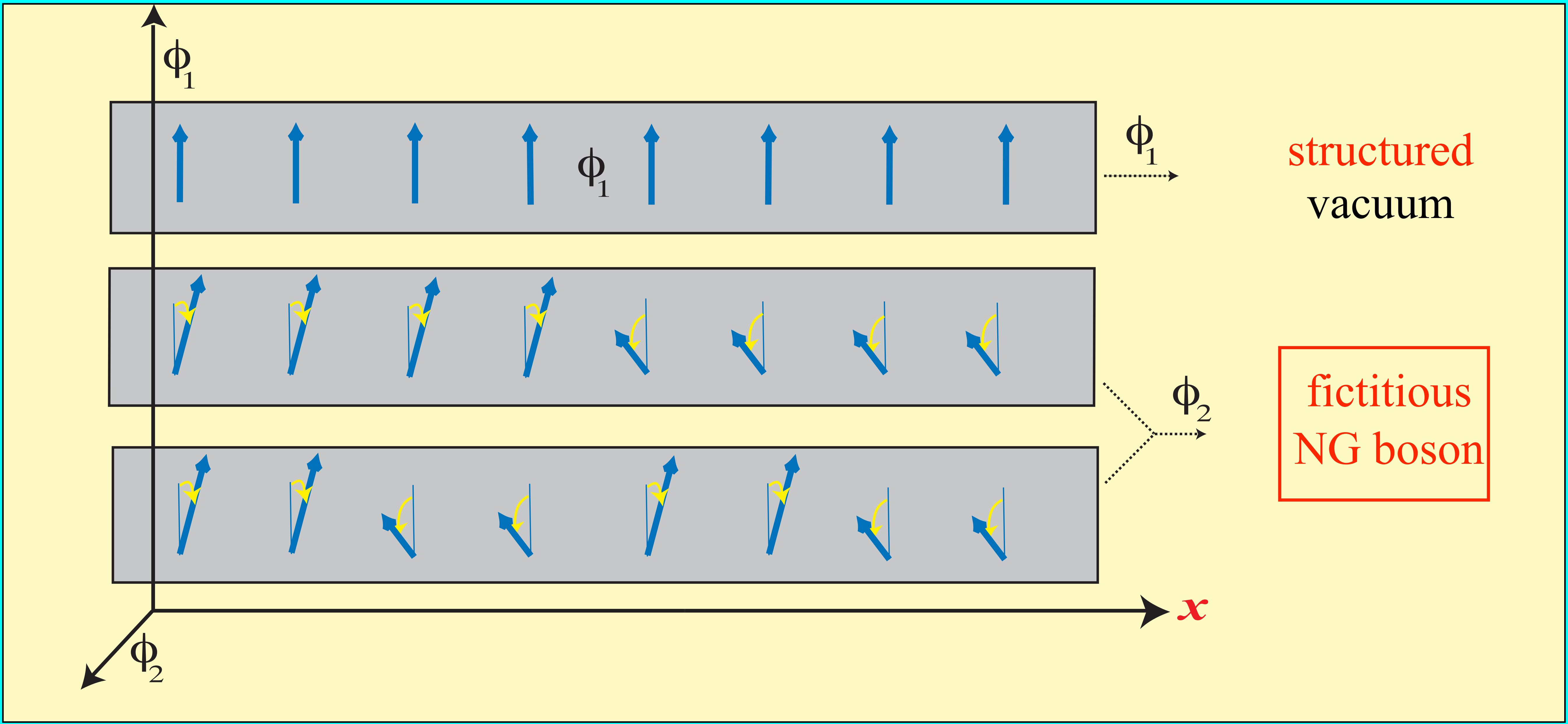

cf. P.W. Higgs, Phys. Letters **12** (1964) 132; G.S. Guralnik, C.R. Hagen and T.W. Kibble, Phys;Rev.Lett. **13** (1964) 585.

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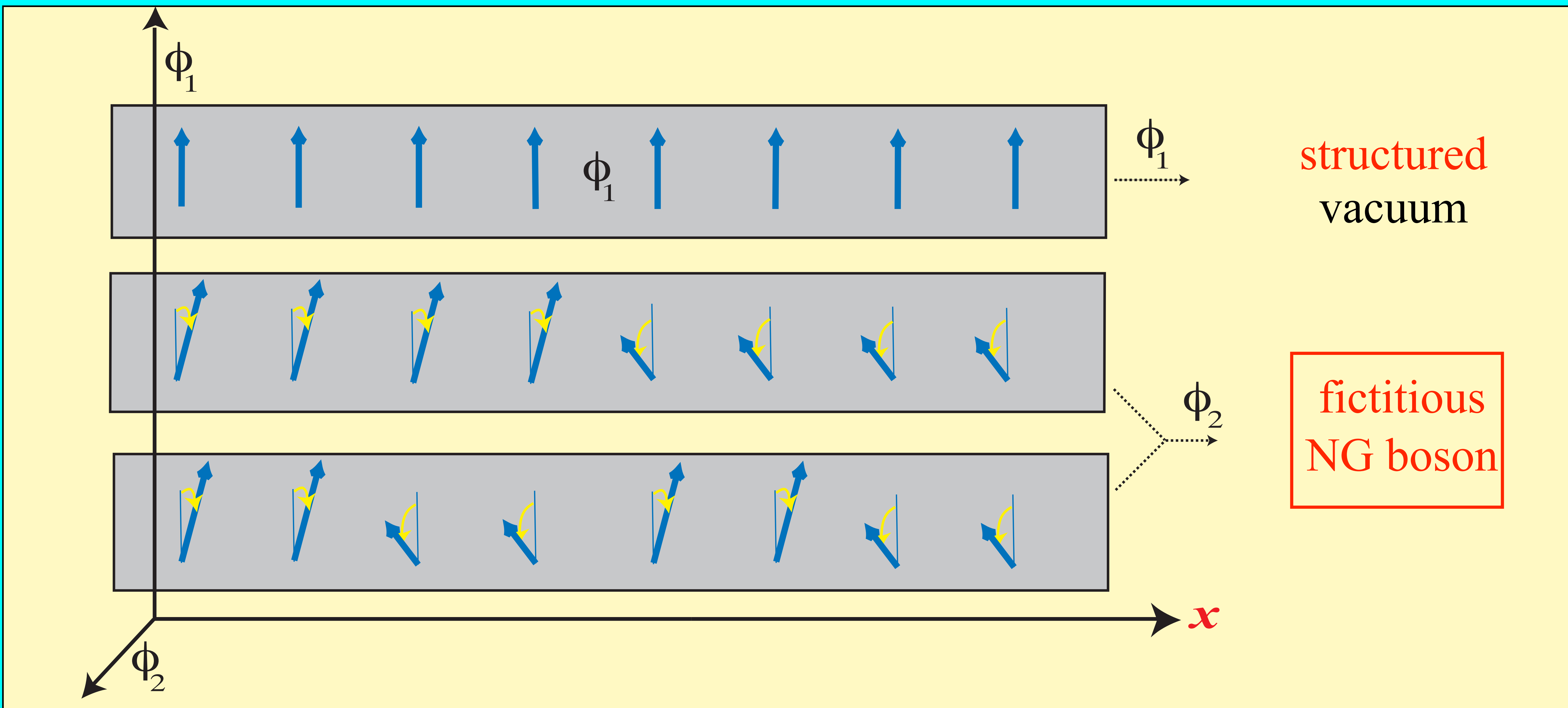

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  Apparent breaking is with respect to a preferred orientation

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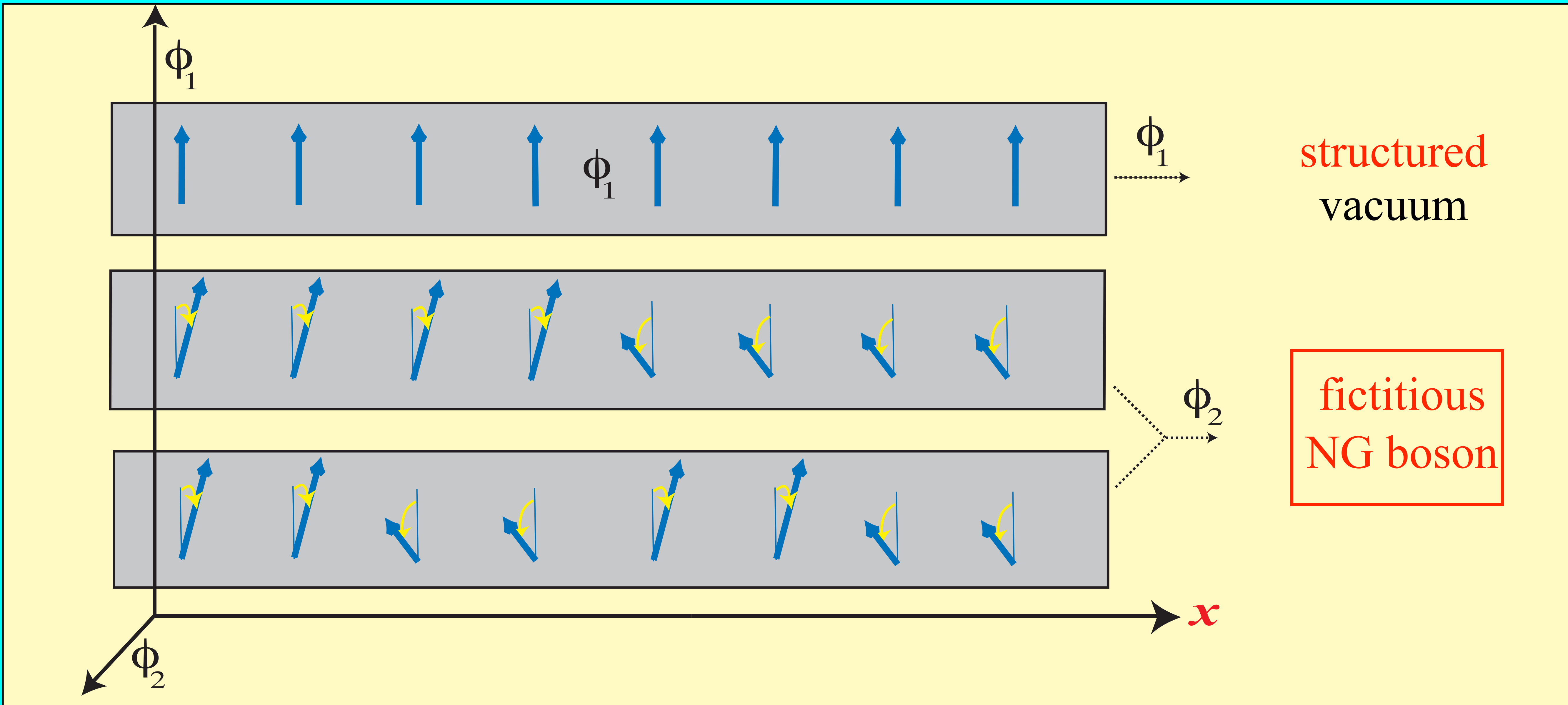

- *The local symmetry is unbroken !*
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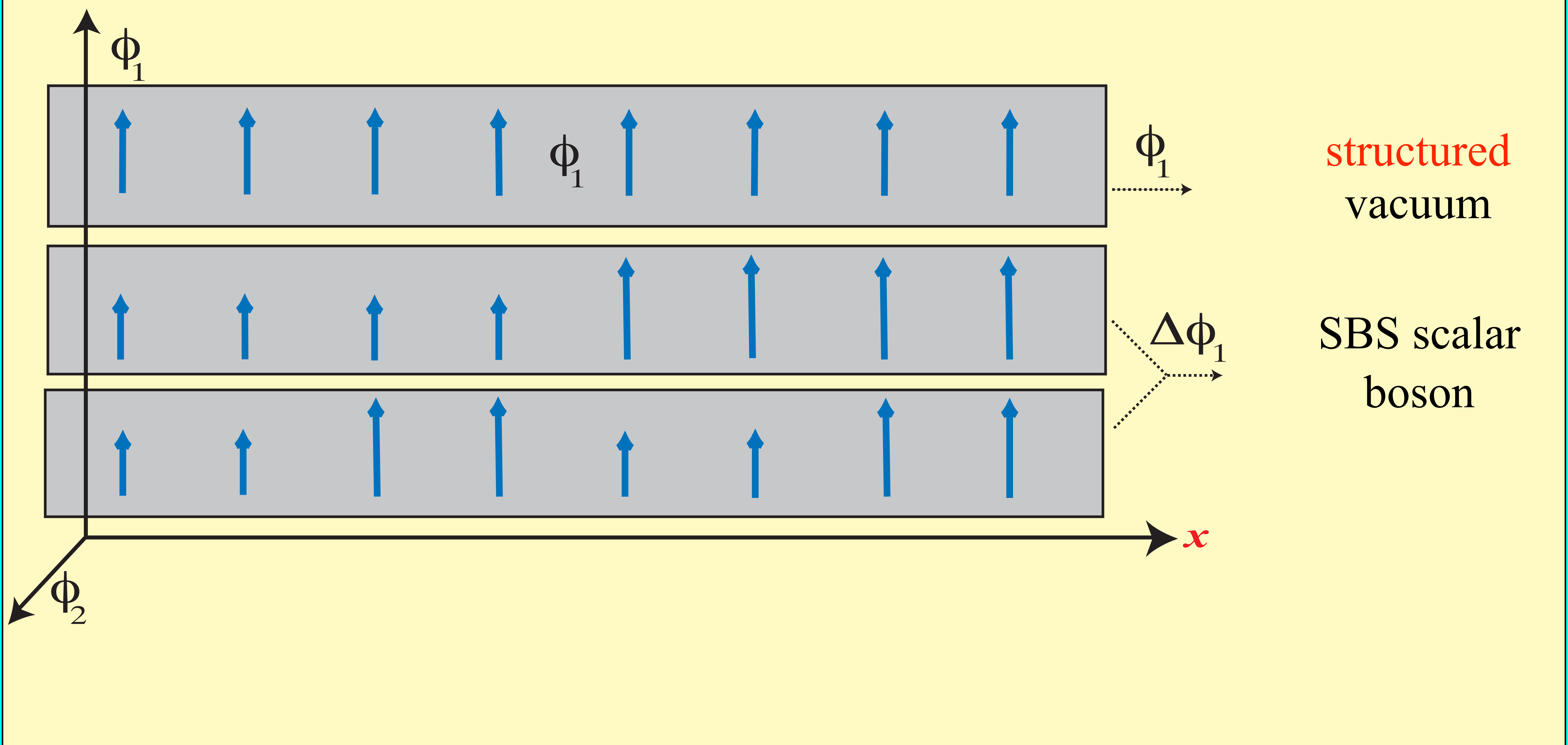
- *The NG boson → the third polarization of a massive gauge boson*

The fate of the SBS scalar boson (a simple model)



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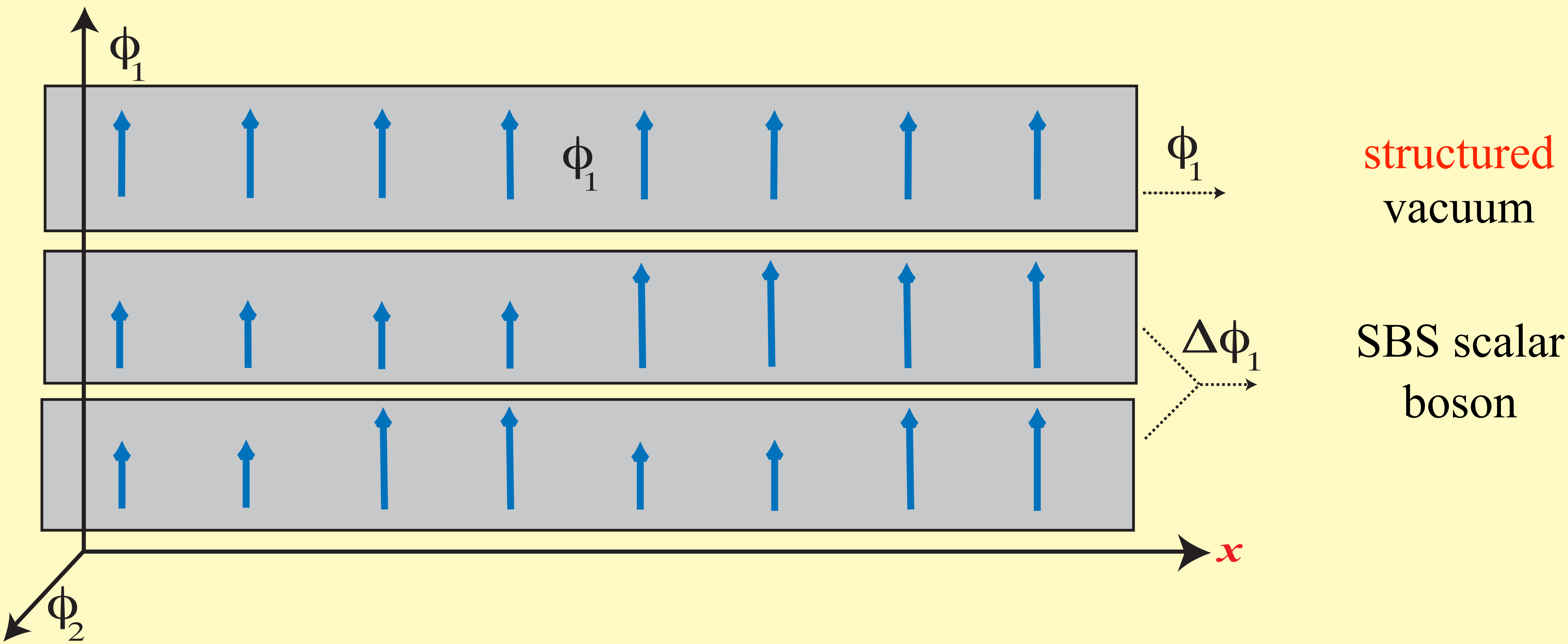
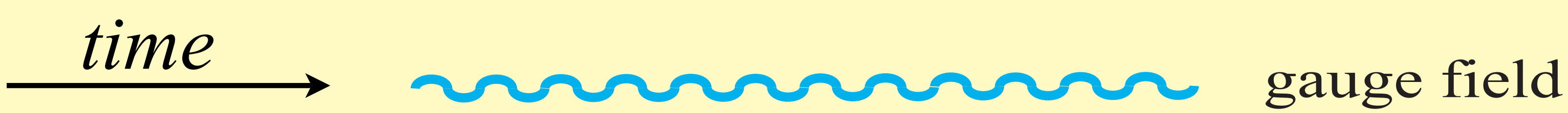


The SBS scalar boson is not affected by the gauging

3. The field-theoretic approach

F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321.

Breaking by scalar fields: the abelian case



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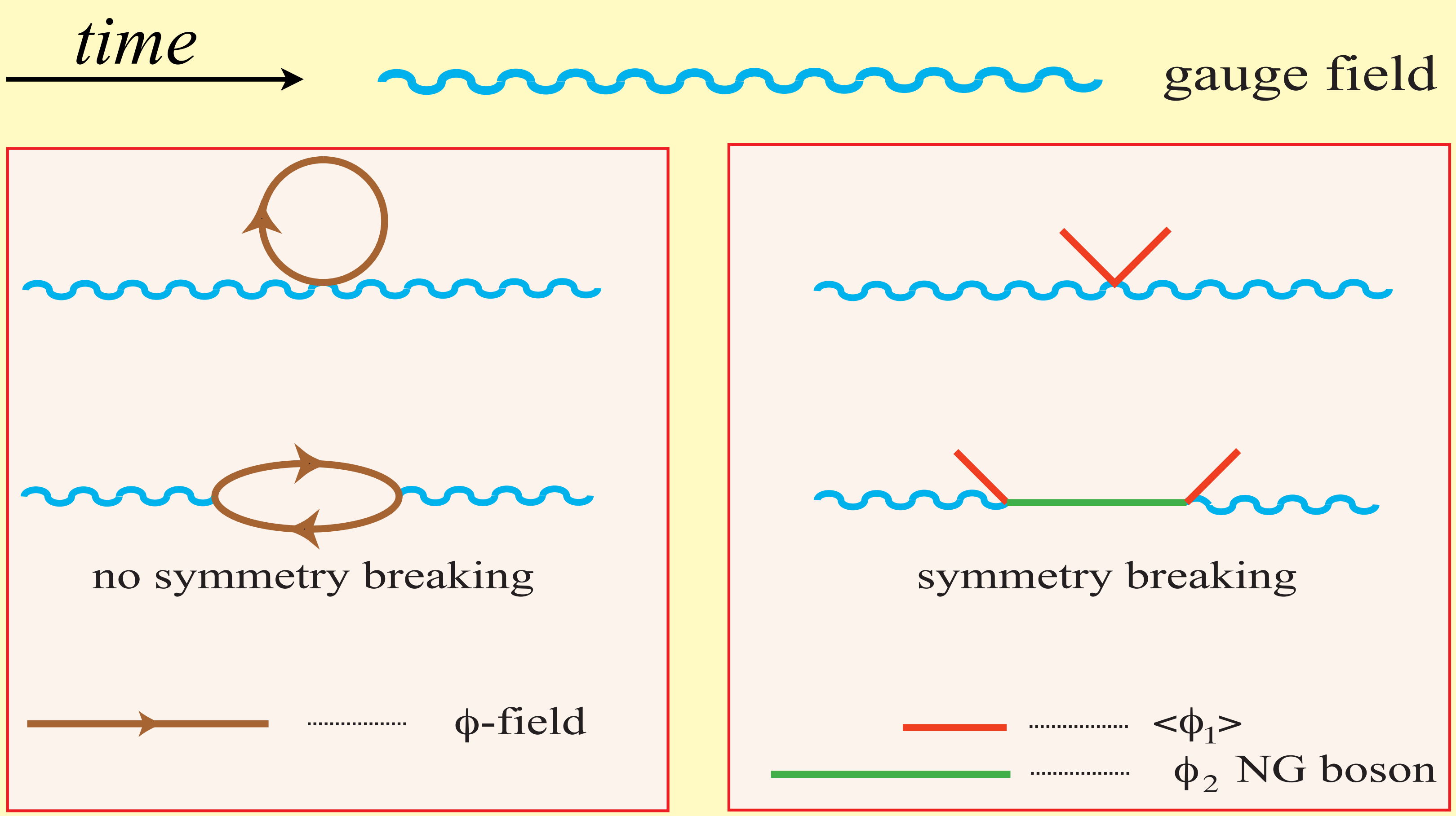

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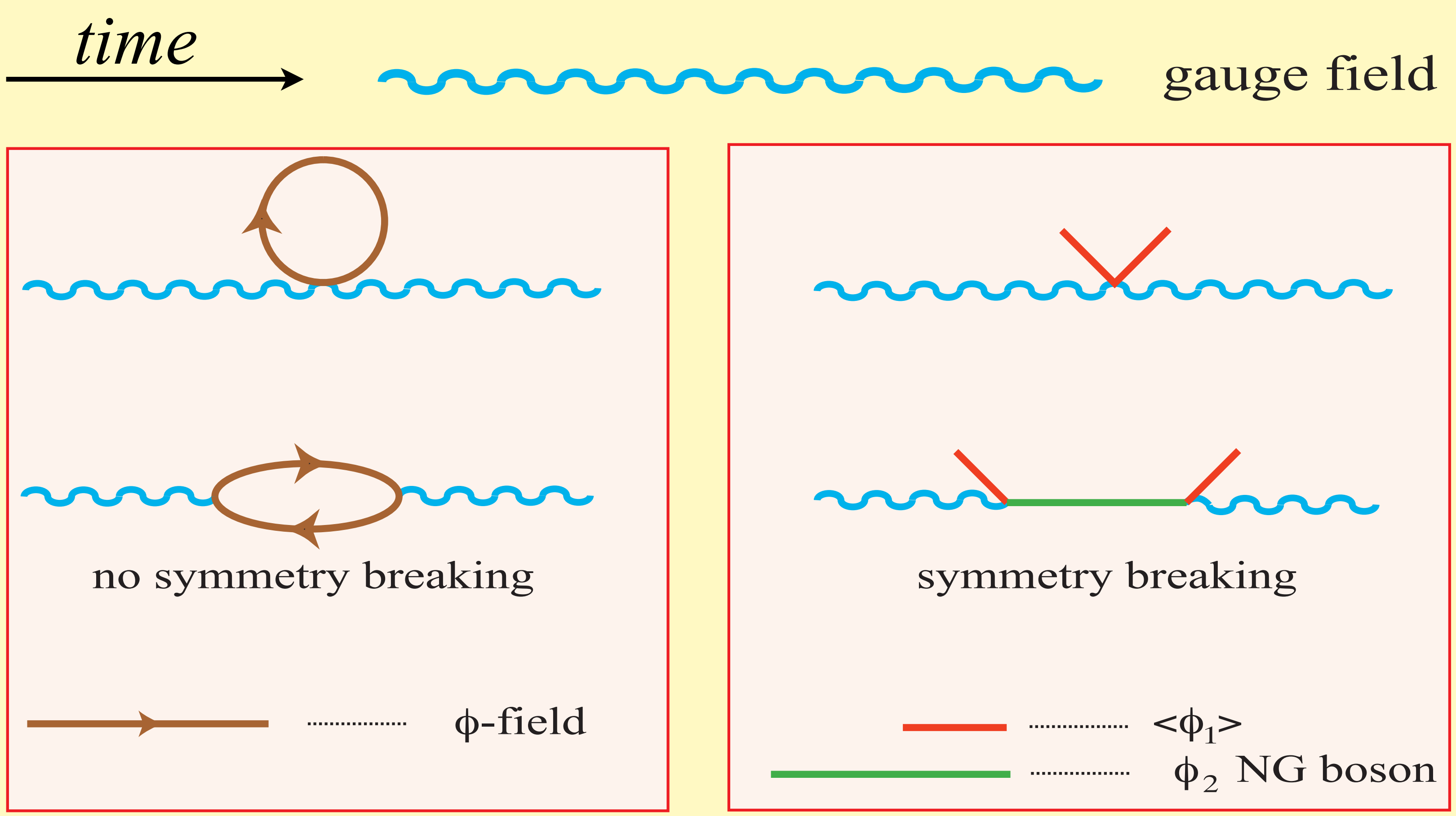

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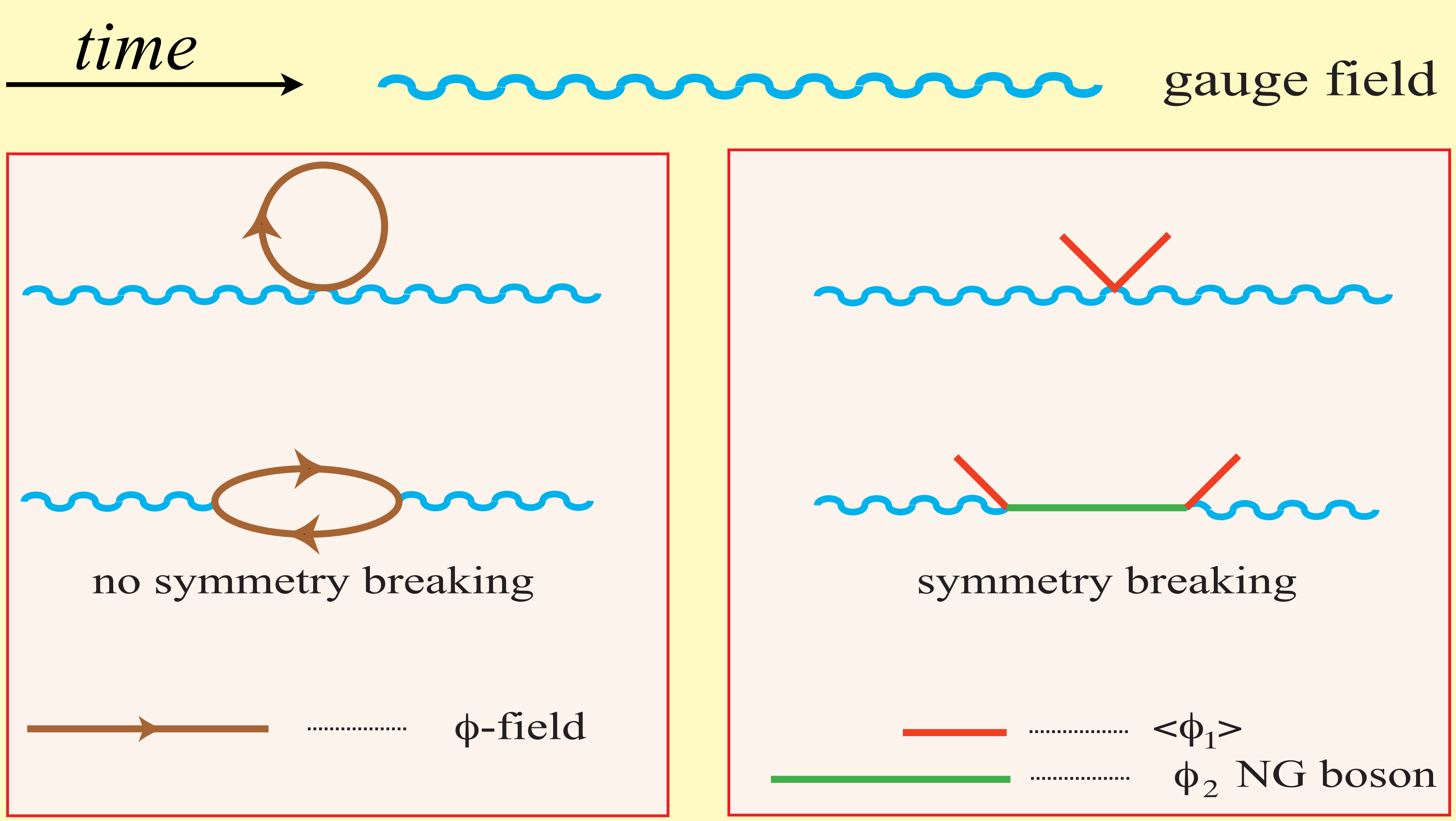

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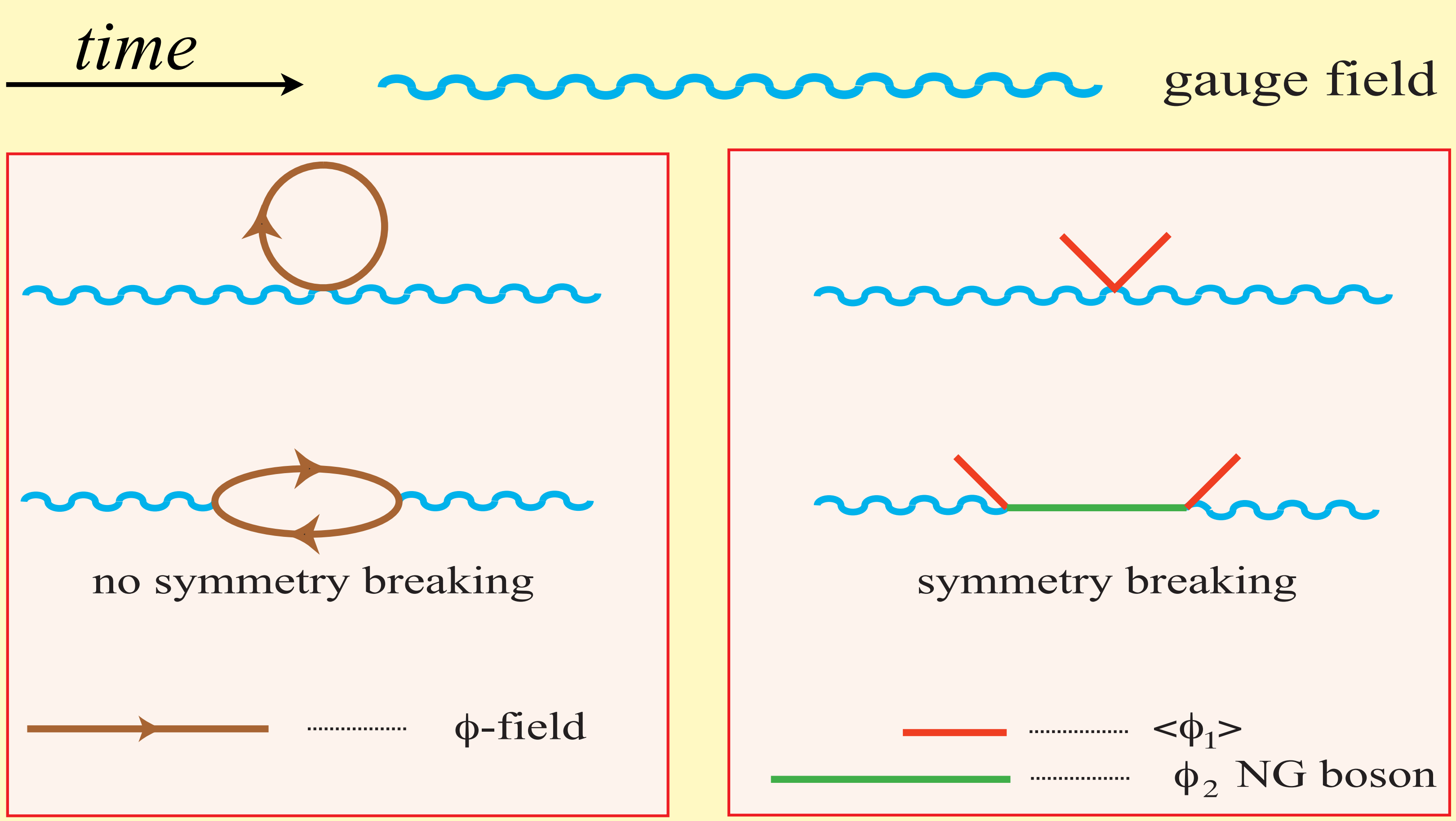

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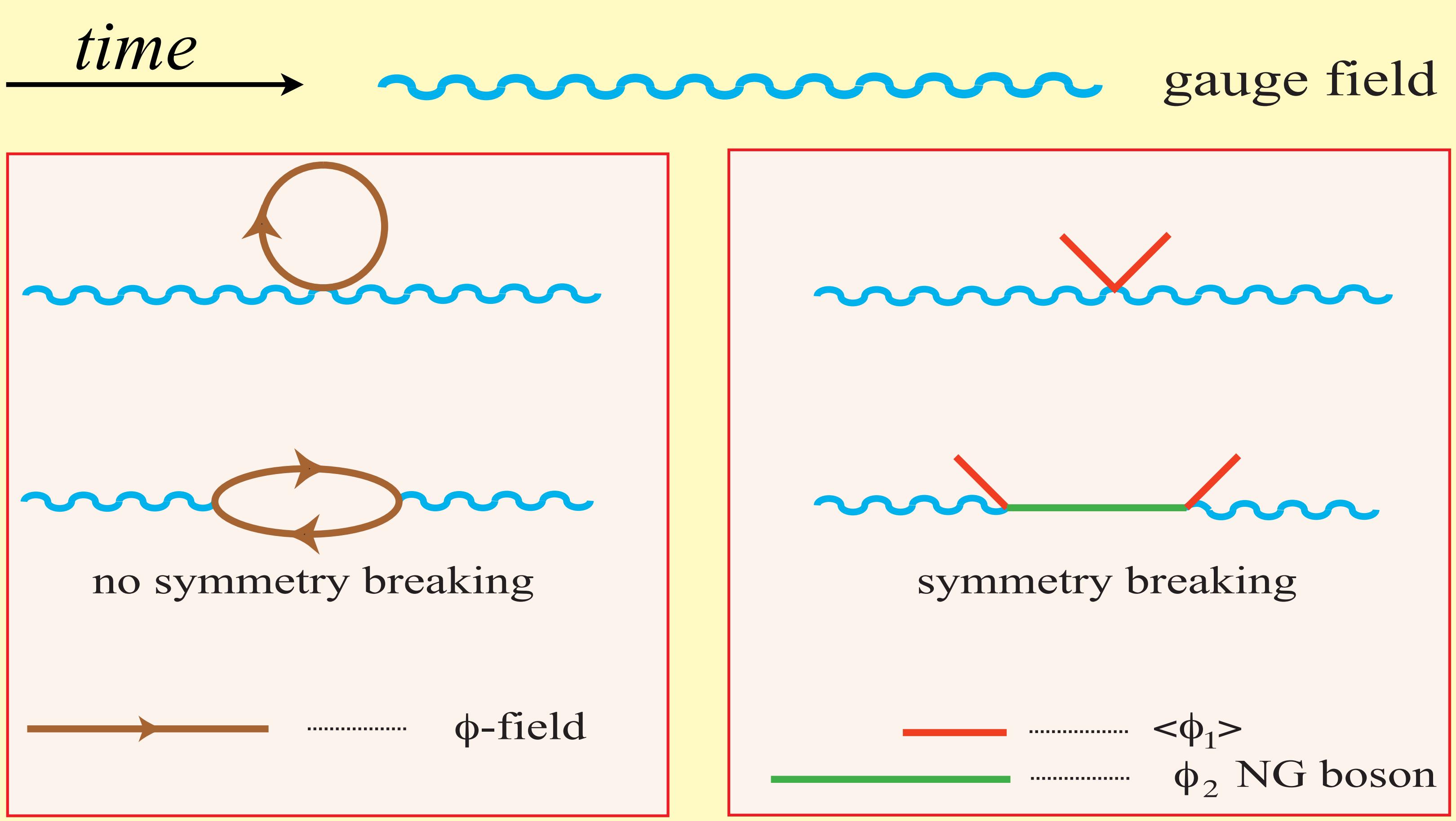

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$$\boxed{\mu^2 = e^2 \langle \phi_1 \rangle^2}$$

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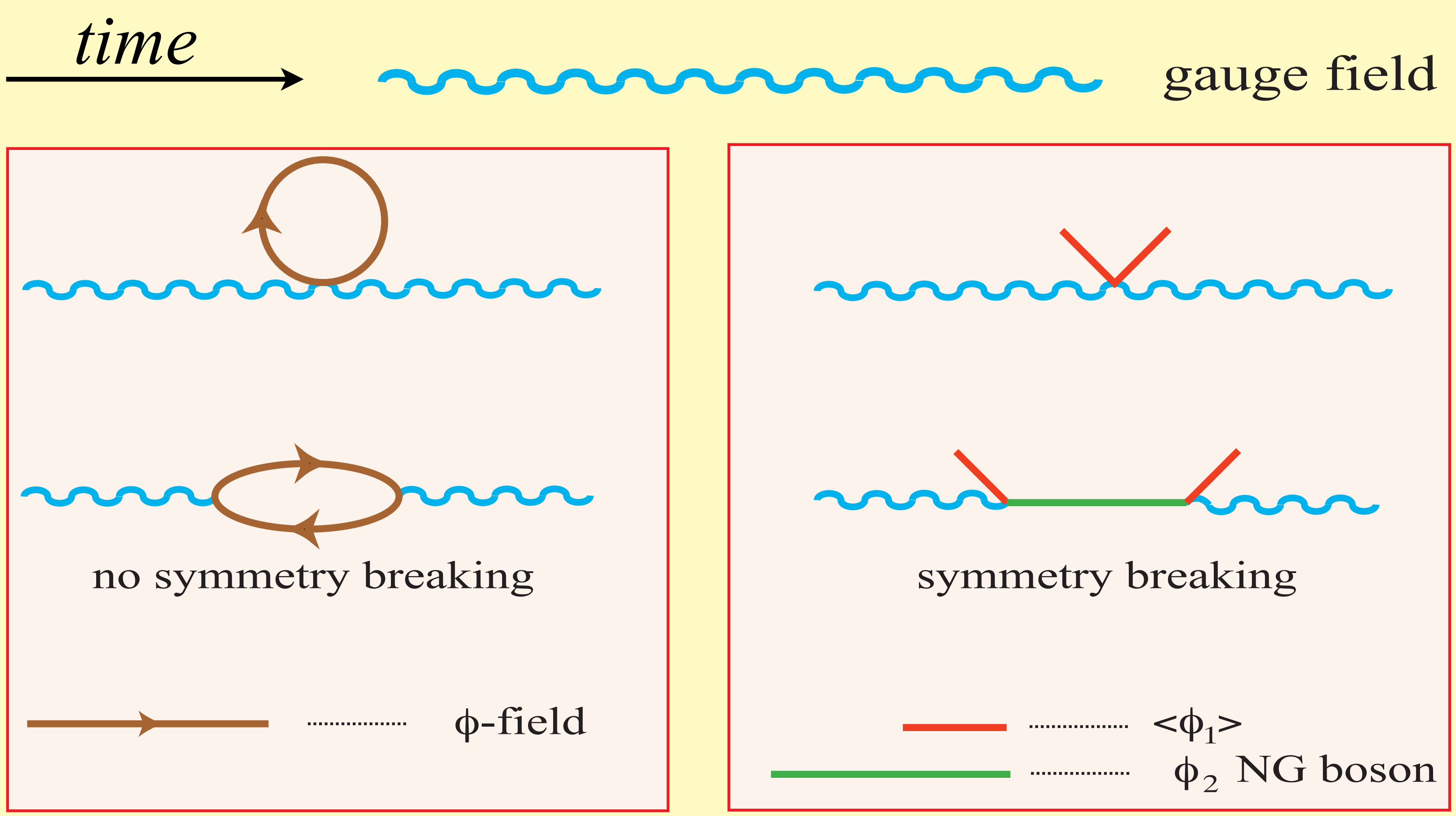
Breaking by scalar fields: the abelian case



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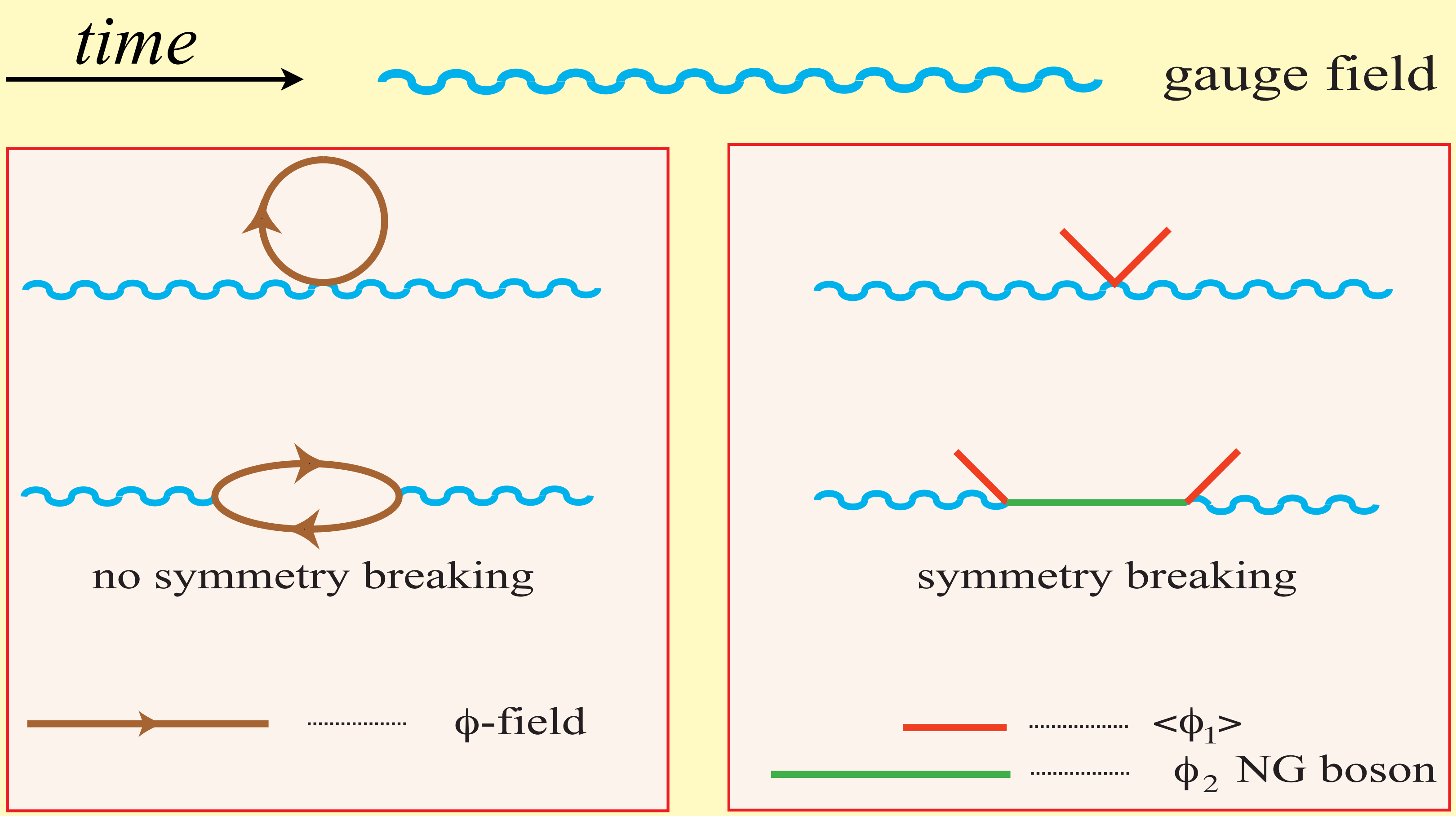

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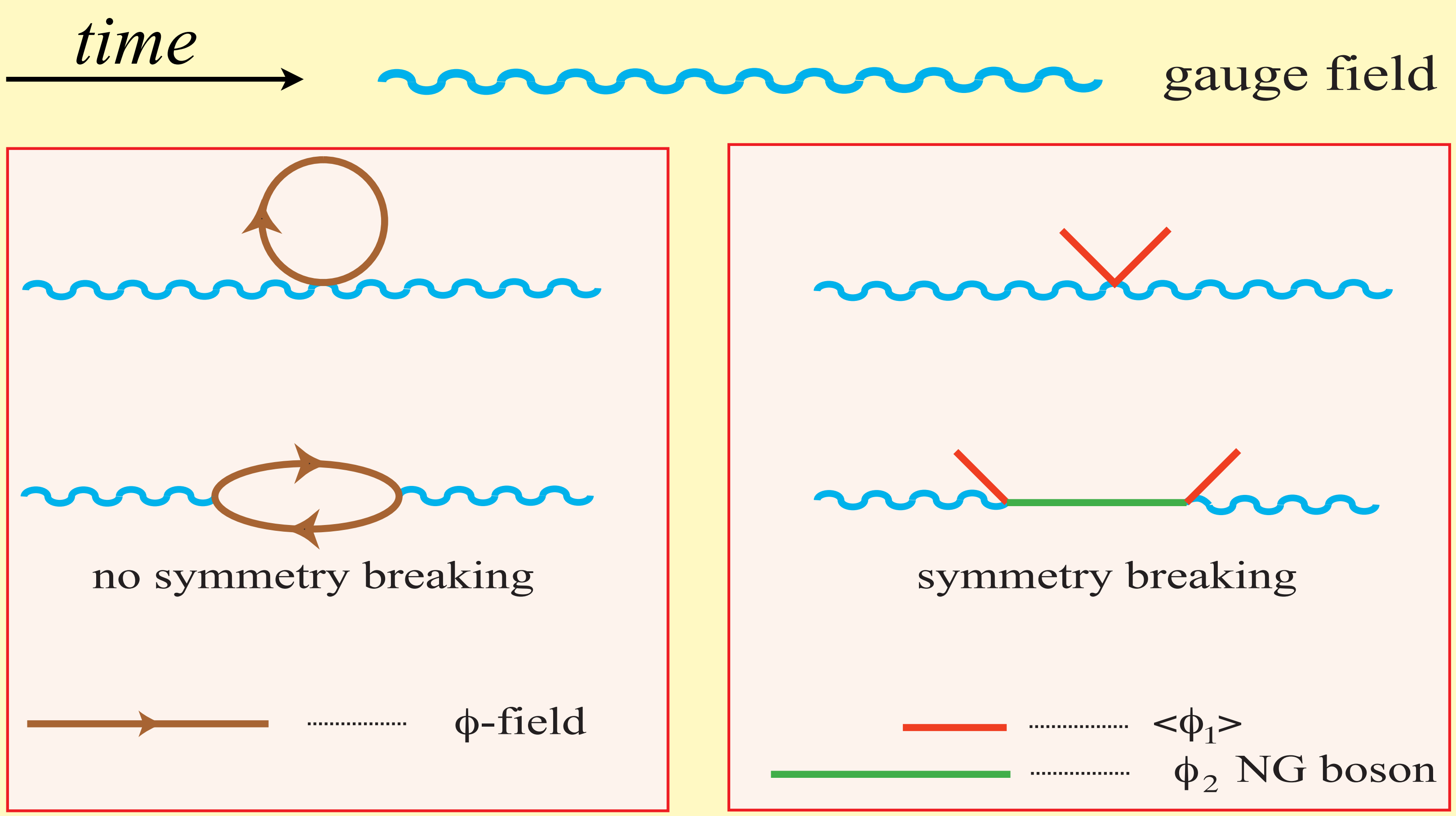

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The absorption of the NG boson yields a massive vector boson

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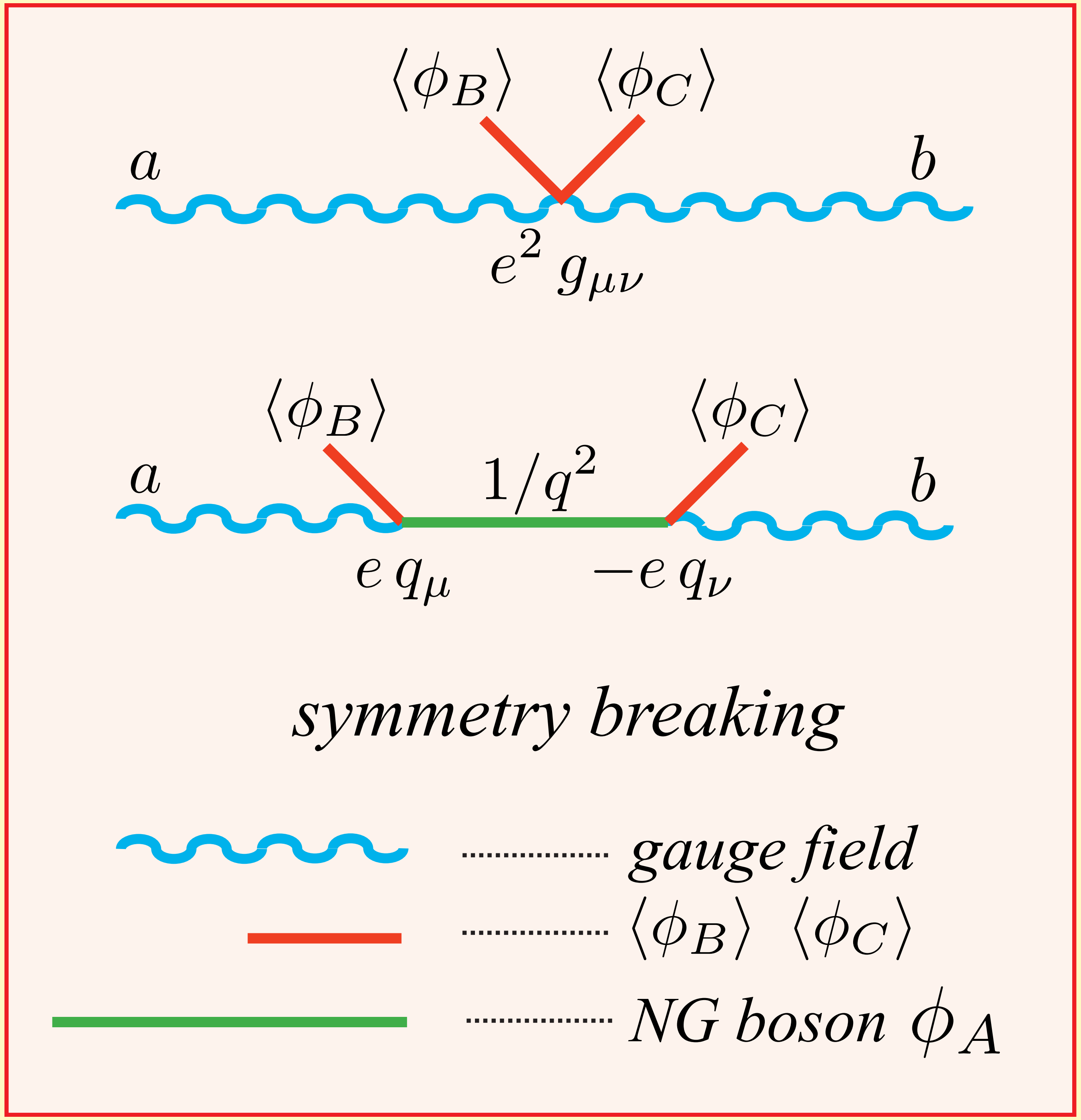
The SBS scalar boson decouples from $D_{\mu\nu}$

Breaking by scalar fields: the "non-abelian" generalization



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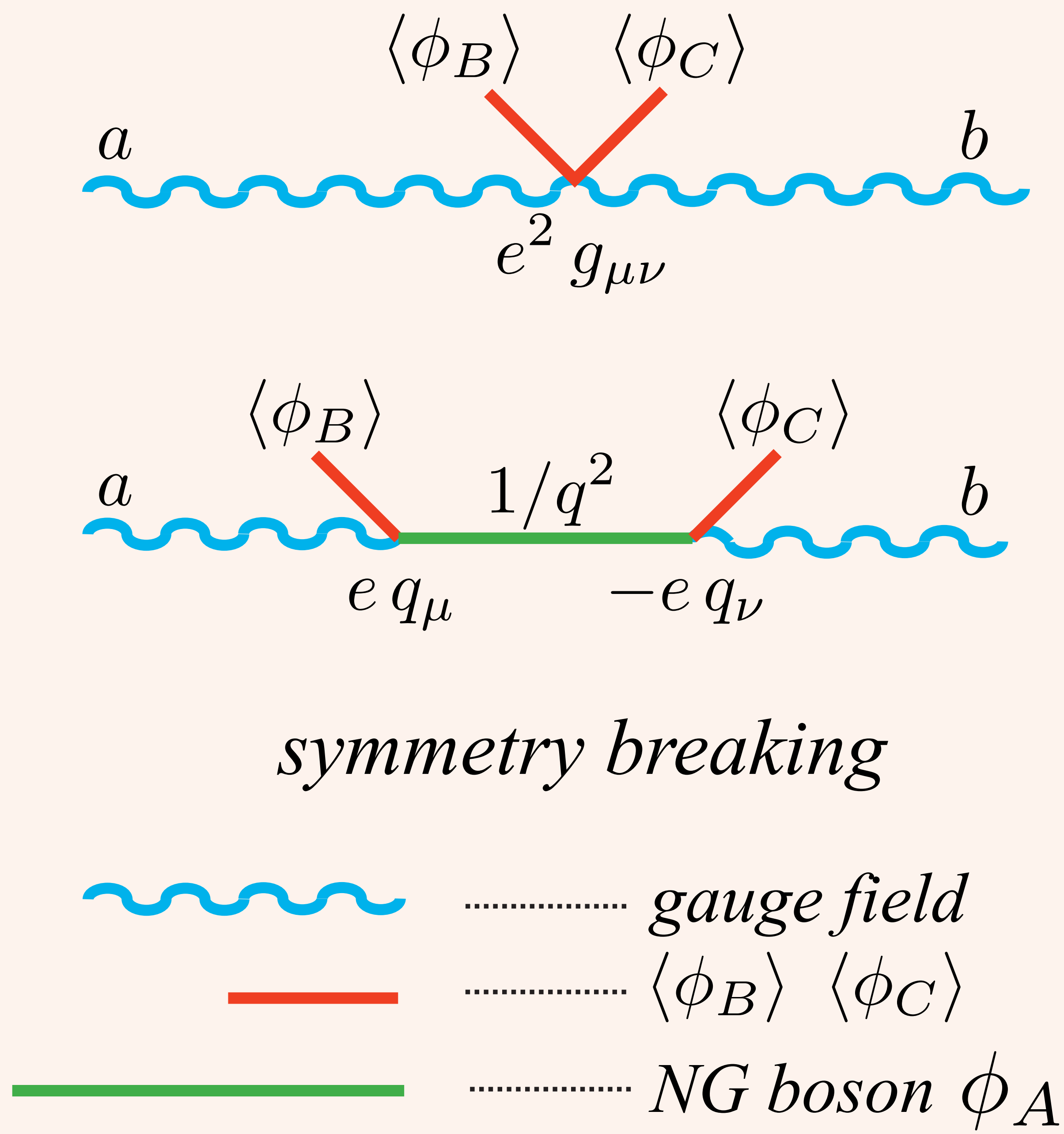

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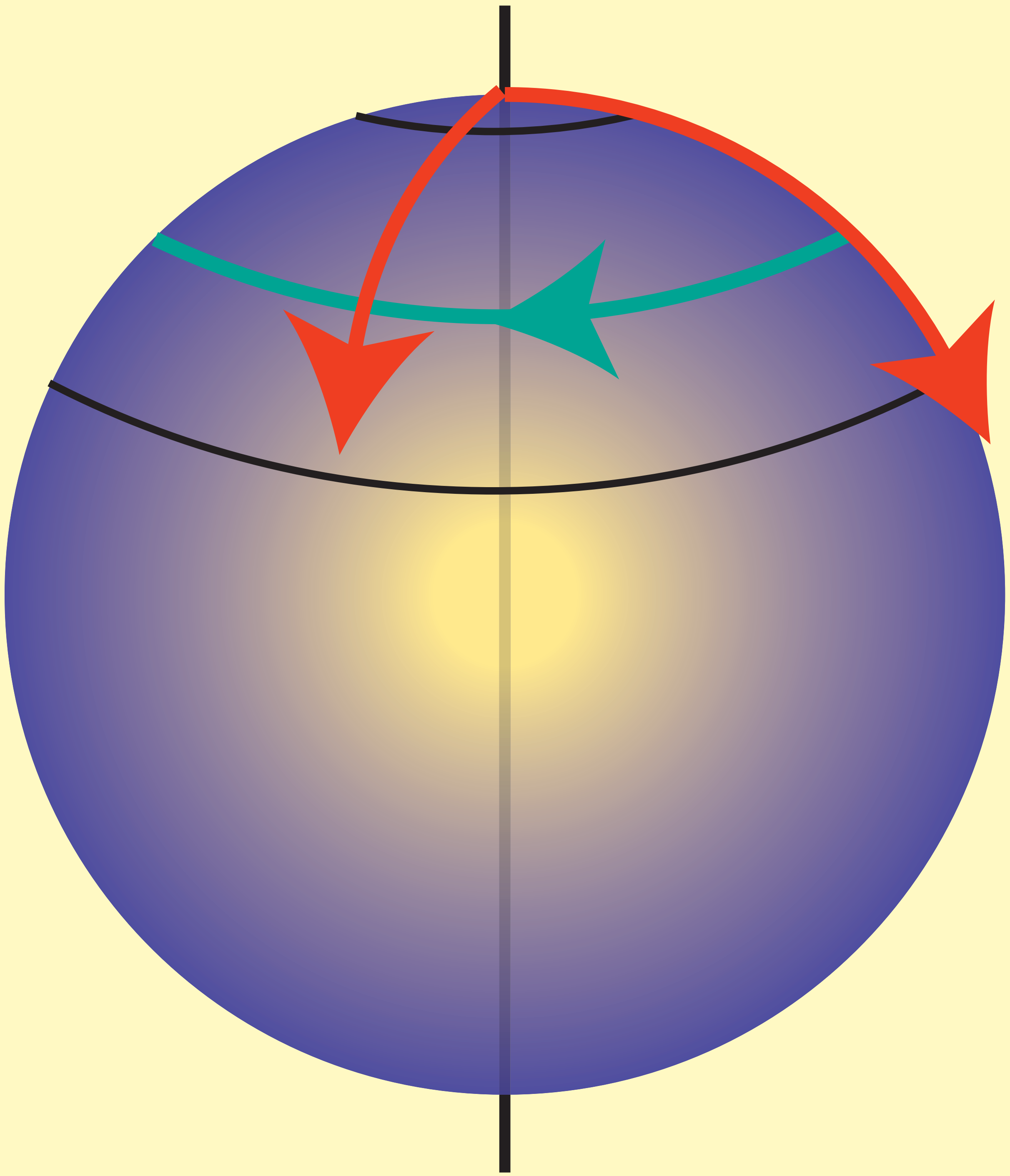
Each fictitious NG boson yields a massive gauge field

Example $SO(3)/U(1)$



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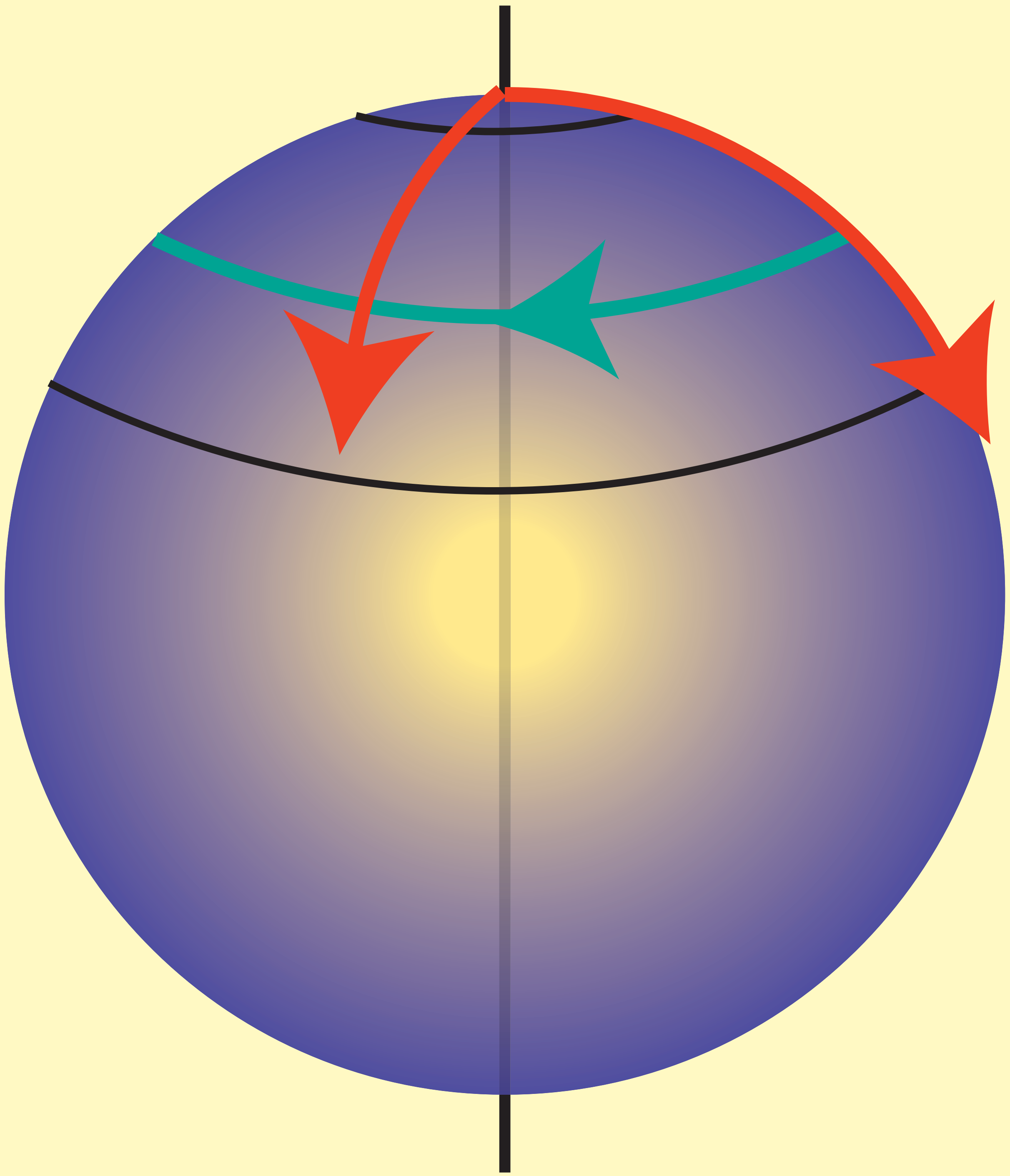
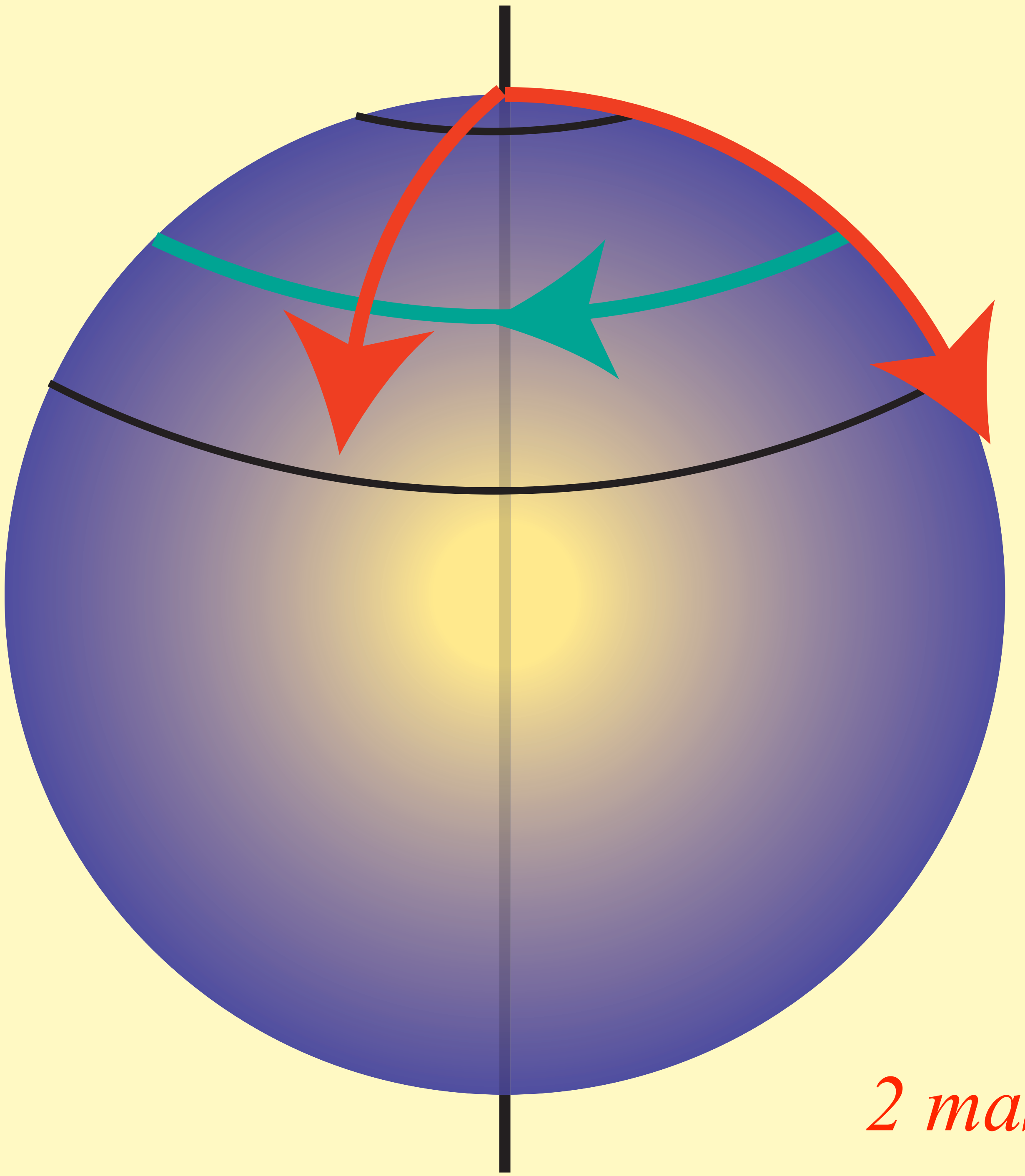


2 fictitious NG bosons

Example $SO(3)/U(1)$



2 fictitious NG bosons

↓

2 massive and 1 massless gauge boson

Dynamical symmetry breaking

$$U(1) \times U(1)$$

$$\mathcal{L} = \mathcal{L}_0^F - e_V\,\bar{\psi}\gamma_\mu\psi V_\mu - e_A\,\bar{\psi}\gamma_\mu\gamma_5\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}(V) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}(A)$$

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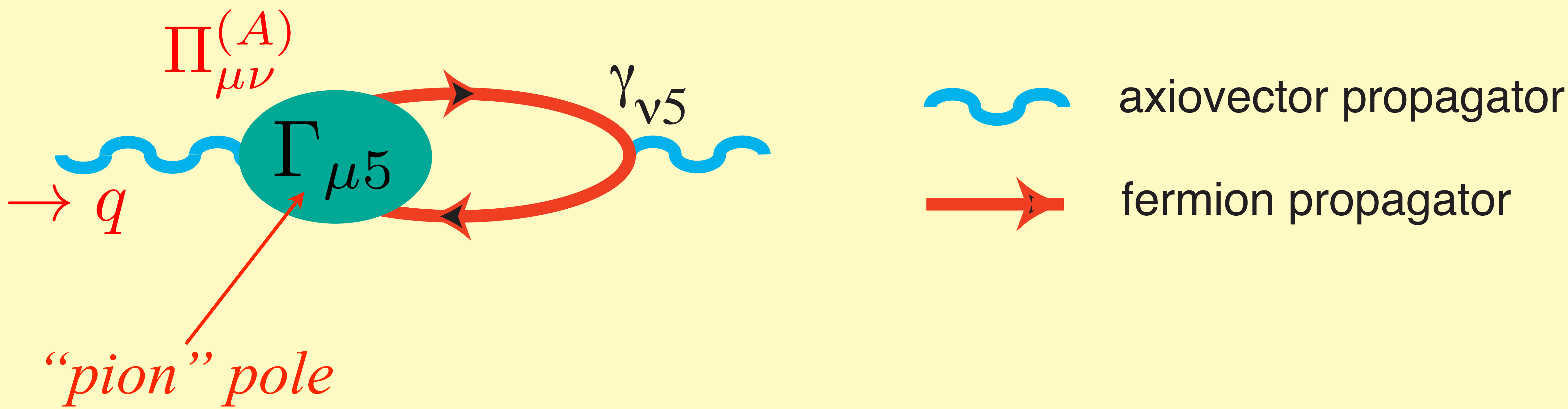

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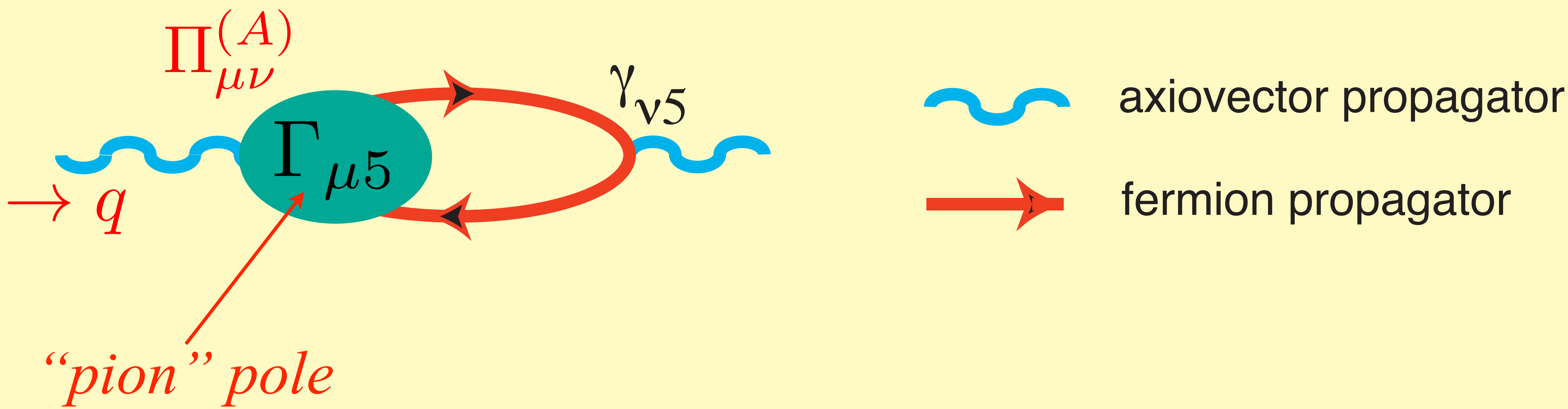

$$\Pi^{(A)}_{\mu\nu} = e_A^2(g_{\mu\nu}q^2 - q_\mu q_\nu)\Pi^{(A)}(q^2)$$

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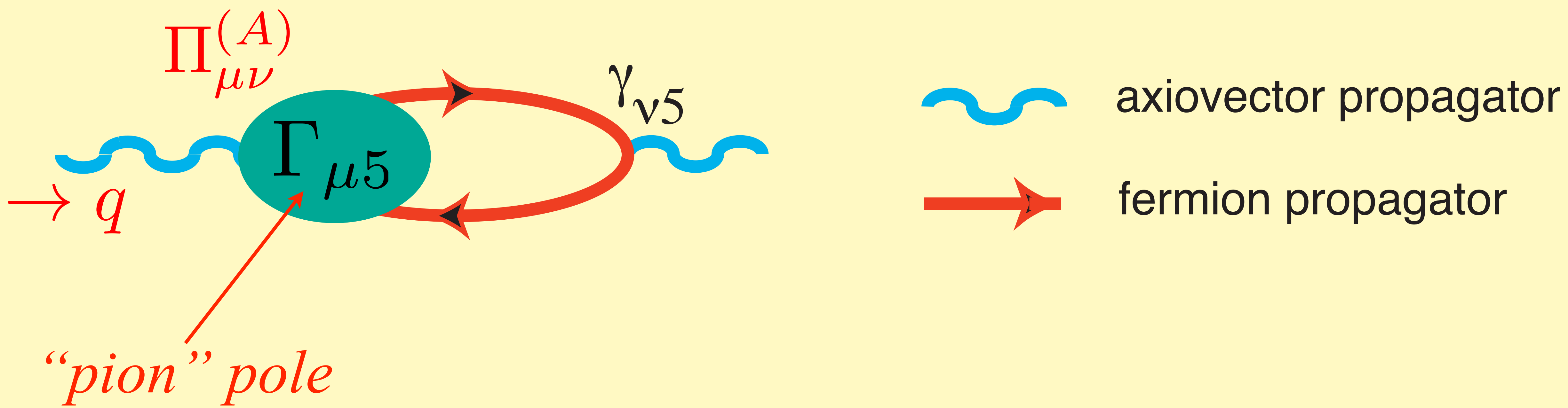

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Mass arises from the absorption of the NG boson

4. The equations of motion approach

P.W. Higgs, Phys. Rev. Lett. **13** (1964) 508.

$$B_\mu = A_\mu - \frac{1}{e\langle\phi_1\rangle}\partial_\mu\phi_2$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}$$

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$$D_{\mu\nu} \equiv \frac{g_{\mu\nu} - q_\mu q_\nu / q^2}{q^2 - \mu^2} = \frac{g_{\mu\nu} - q_\mu q_\nu / \mu^2}{q^2 - \mu^2} + \frac{1}{\mu^2} \frac{q_\mu q_\nu}{q^2}$$

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(Brout - Englert)

R. Brout, F. Englert and M.F. Thiry, Il Nuovo Cimento **43A** (1966) 244.
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Consistent quantum theory

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	Article	Reception date	Publication date
1	F. Englert and R. Brout Phys. Rev. Letters 13 (1964) 321	26/06/1964	31/08/1964
2	P.W. Higgs Phys. Letters 12 (1964) 132	27/07/1964	15/09/1964
3	P.W. Higgs Phys. Rev. Letters 13 (1964) 508	31/08/1964	19/10/1964
4	G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Letters 13 (1964) 585	12/10/1964	16/11/1964

IV. The quest for unified laws of nature

1. The electroweak theory

S.L. Glashow, Nucl. Phys. **22** (1961) 579; S. Weinberg, Phys. Rev. Lett. **19** (1967)1264;
A. Salam, Proceedings of the 8th Nobel Symposium, p 367.

Local internal symmetry with four massless gauge fields $SU(2) \times U(1)/U'(1)$

$$g A_\mu^a T^a \qquad g' B_\mu \frac{Y}{2}$$

Symmetry breaking gives mass to three gauge fields and leaves one massless

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BEH mechanism	$\longrightarrow$	magnetic flux tubes
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Confinement	$\longrightarrow$	electric flux tubes

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3. Grand unification

H. Georgi, H.R. Quinn and S. Weinberg, Phys. Rev. Lett. **33** (1974) 451.

4. The unification paradigm

electromagnetism	**weak interactions**	**strong interactions**	**?**	**gravity**

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Spontaneous symmetry breaking

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electromagnetism + weak interactions → *electroweak theory*

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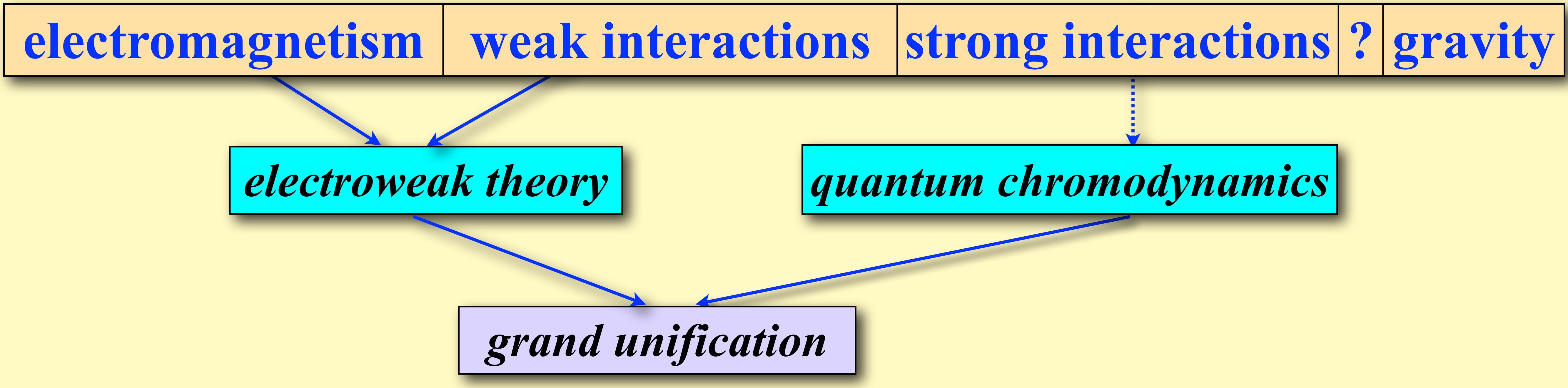

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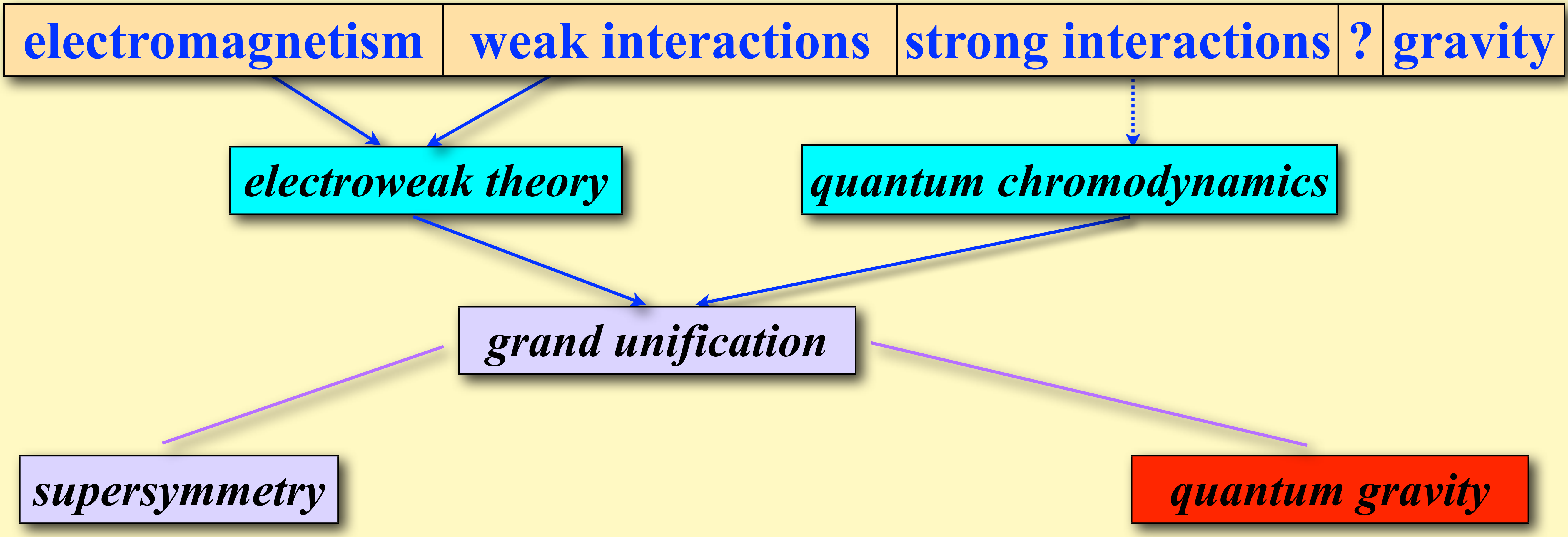

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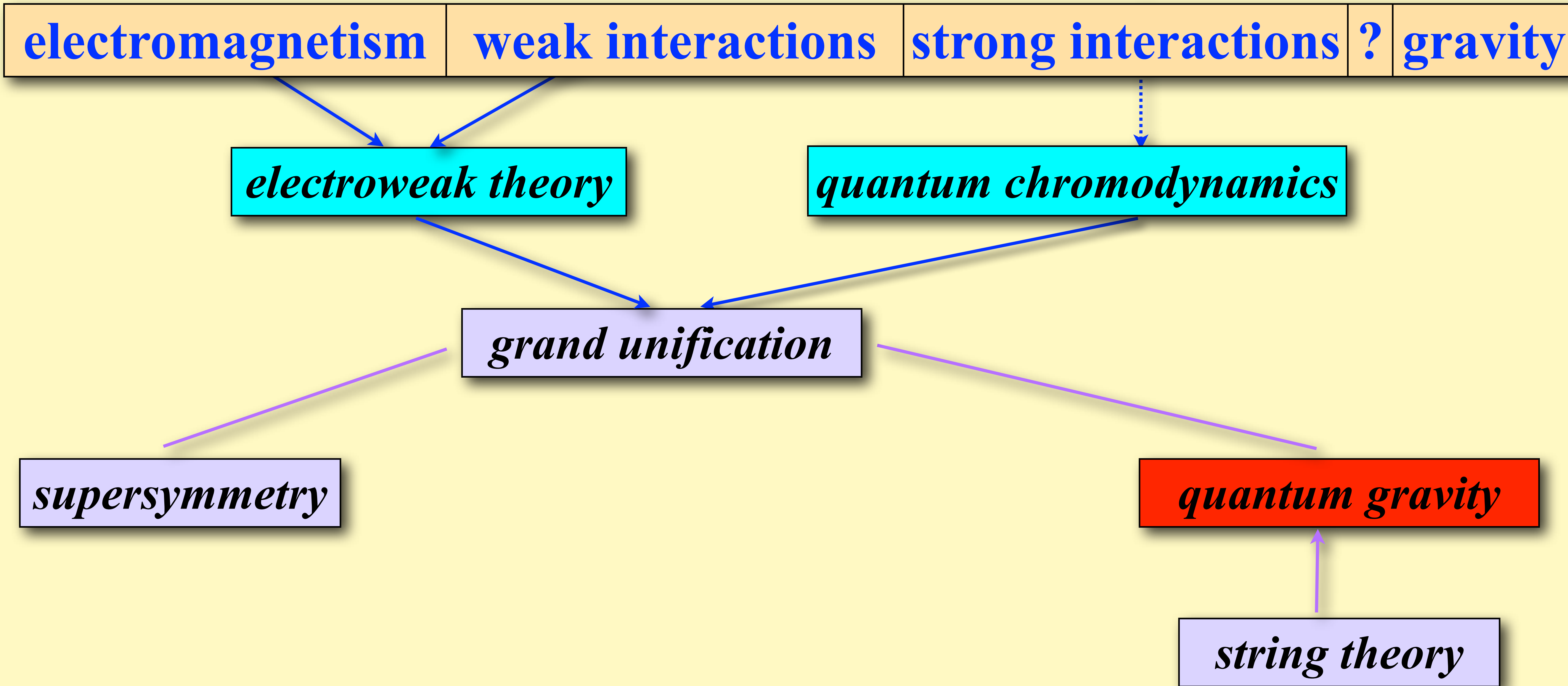

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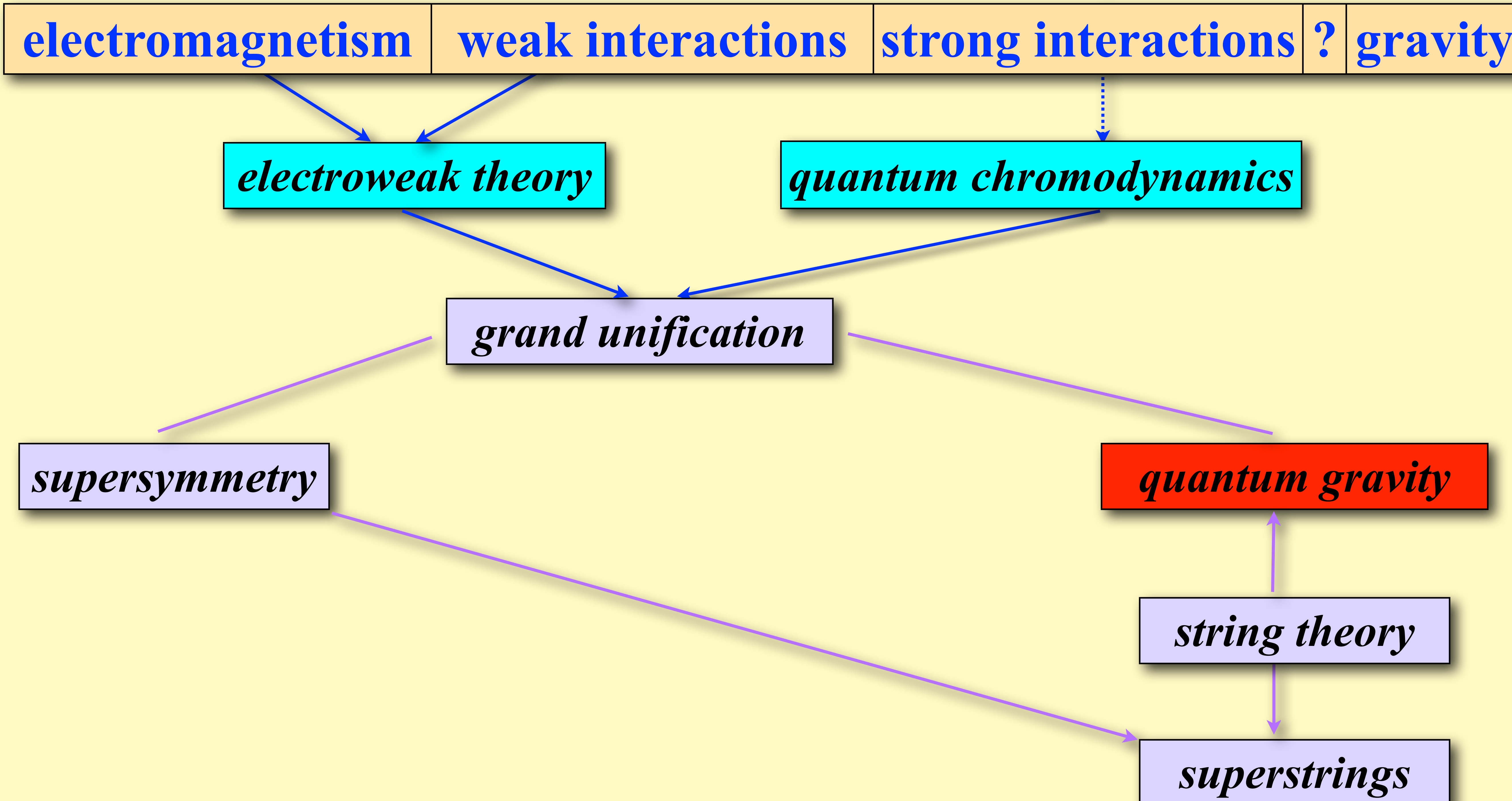

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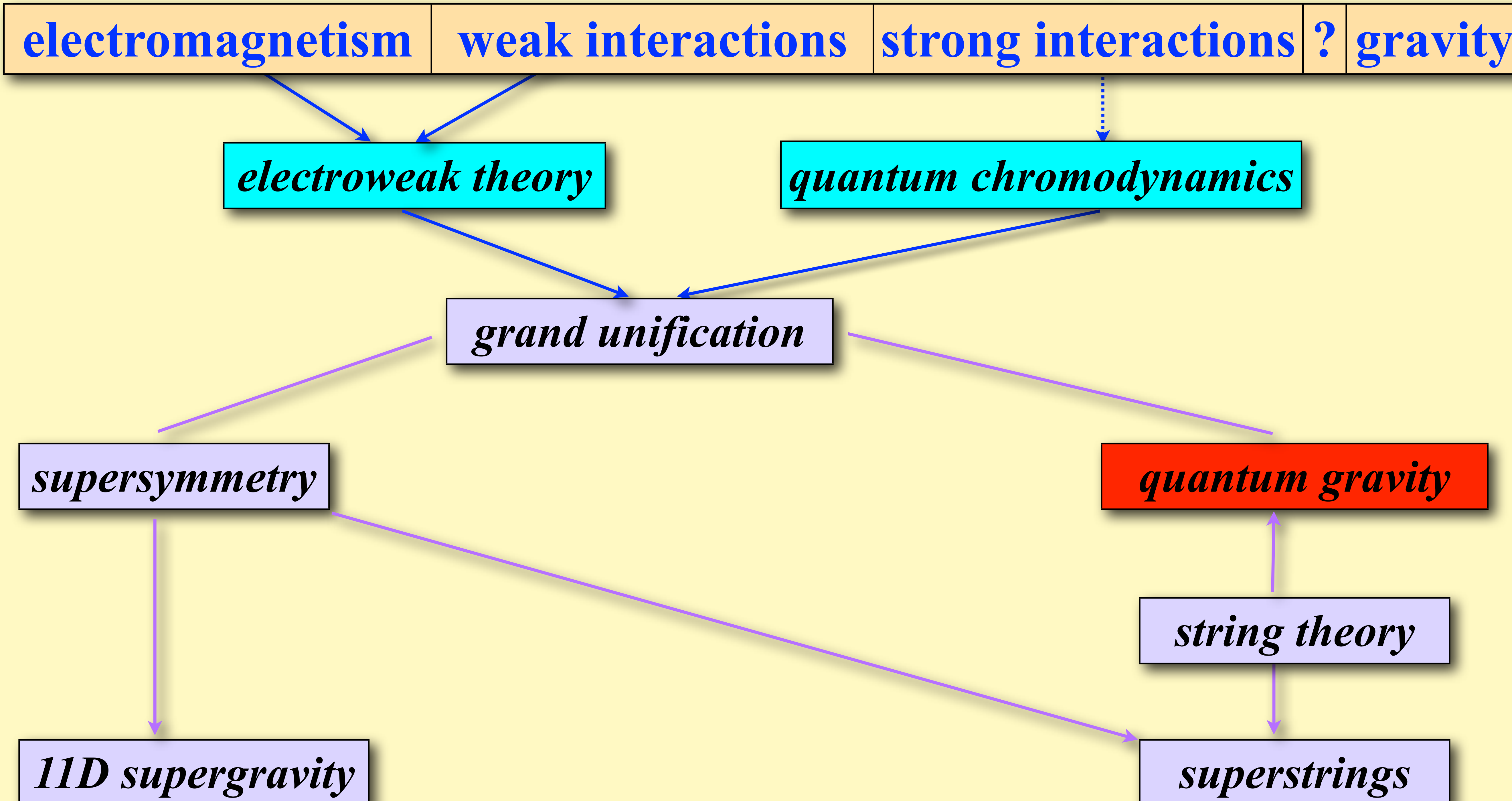

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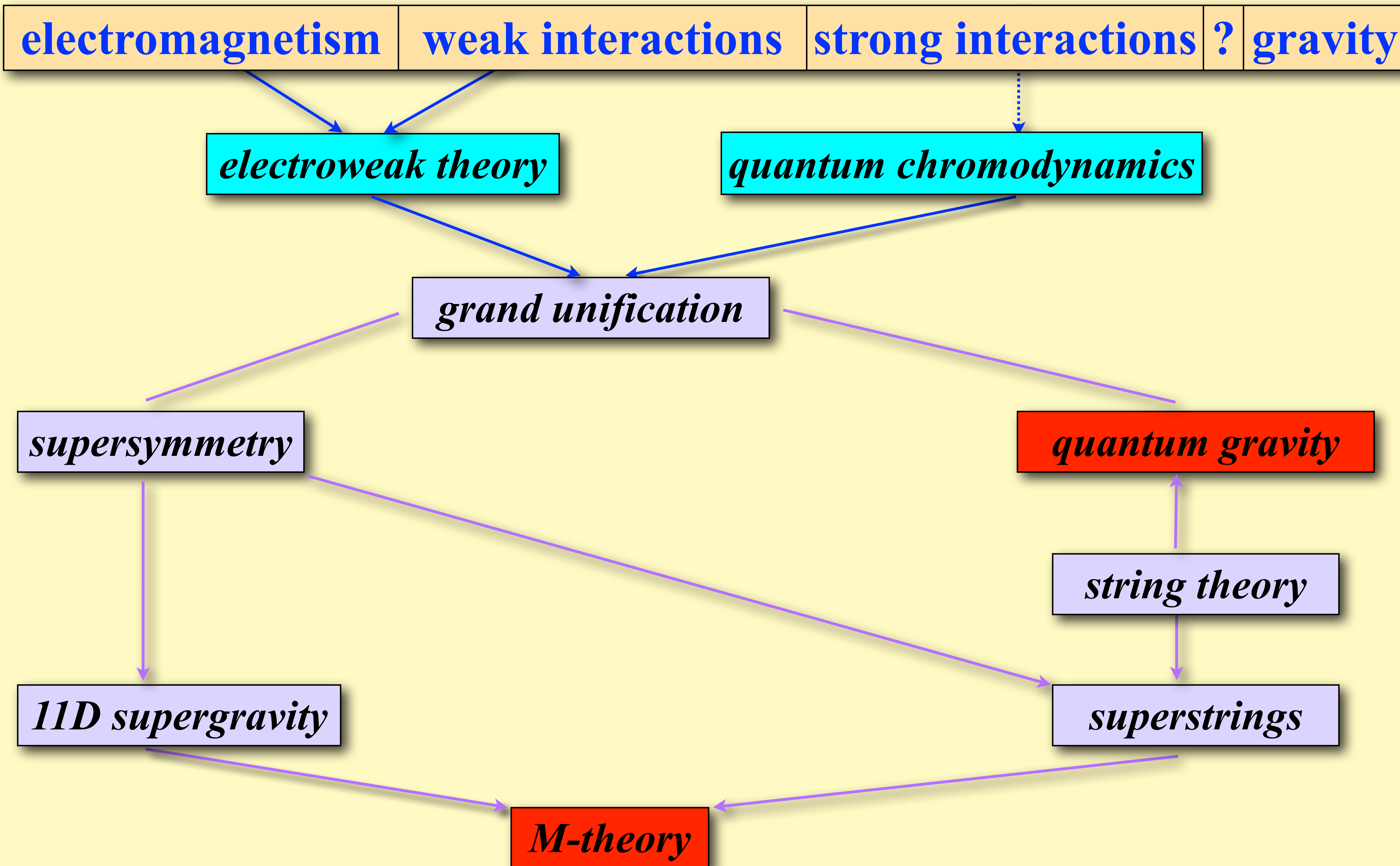

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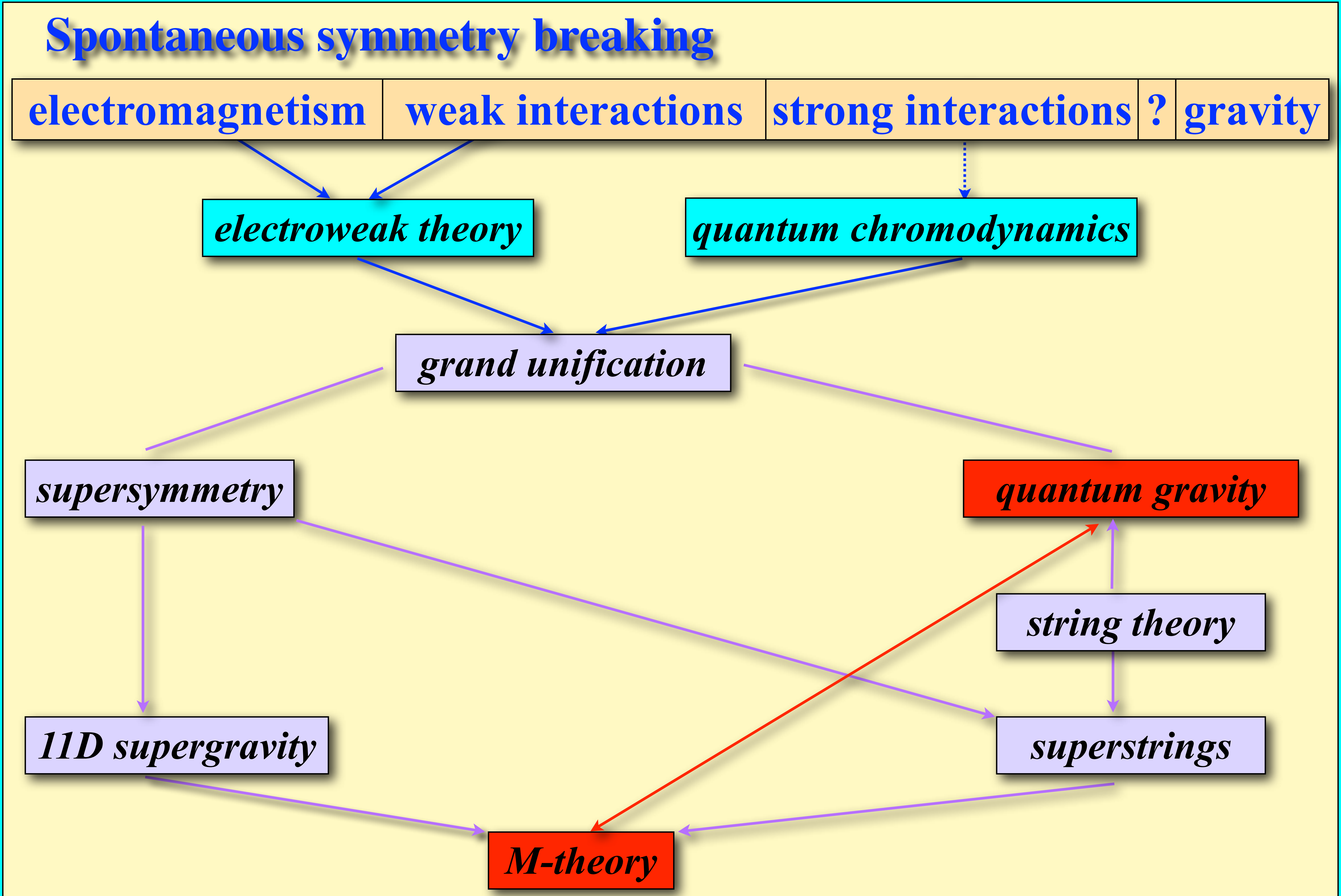

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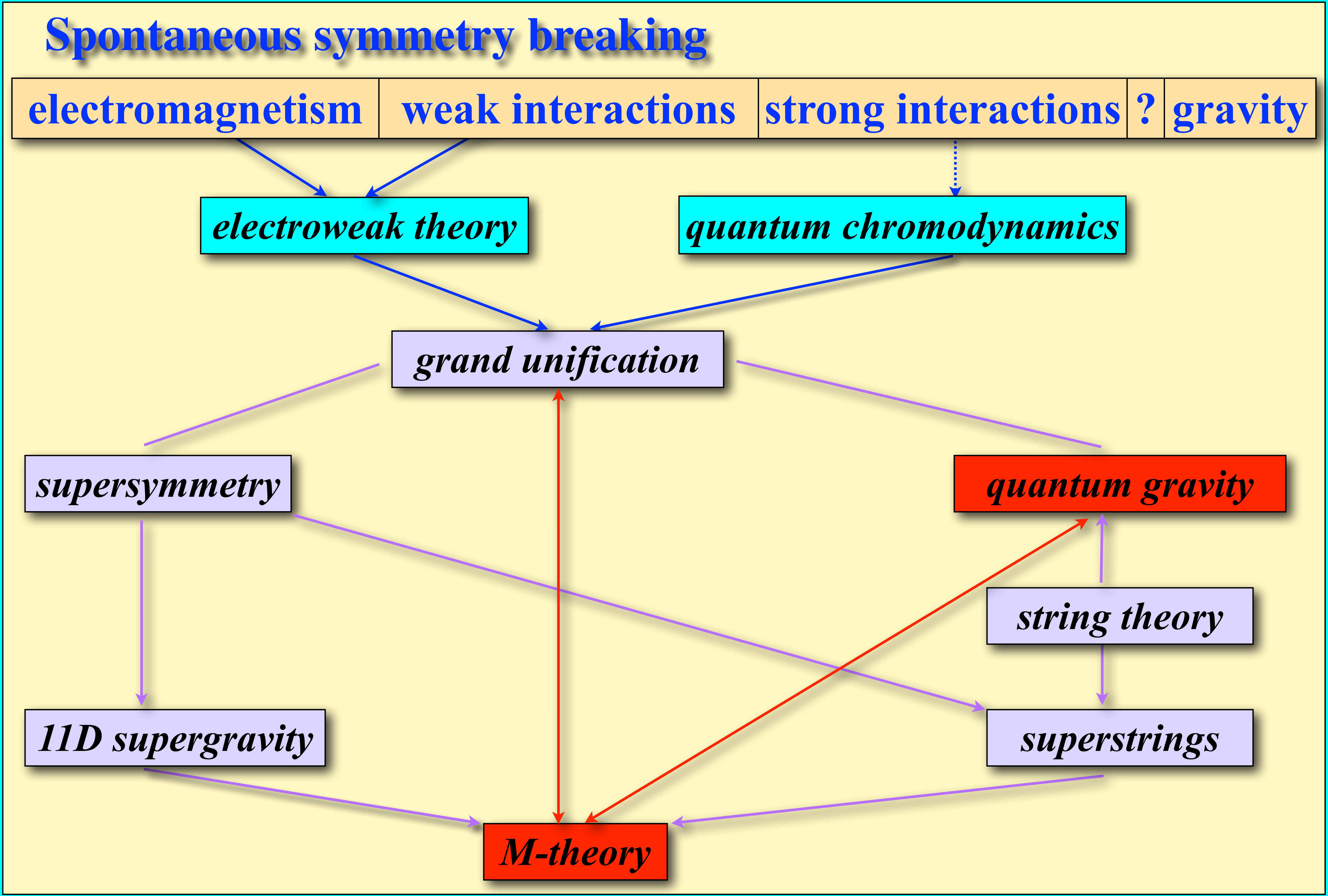

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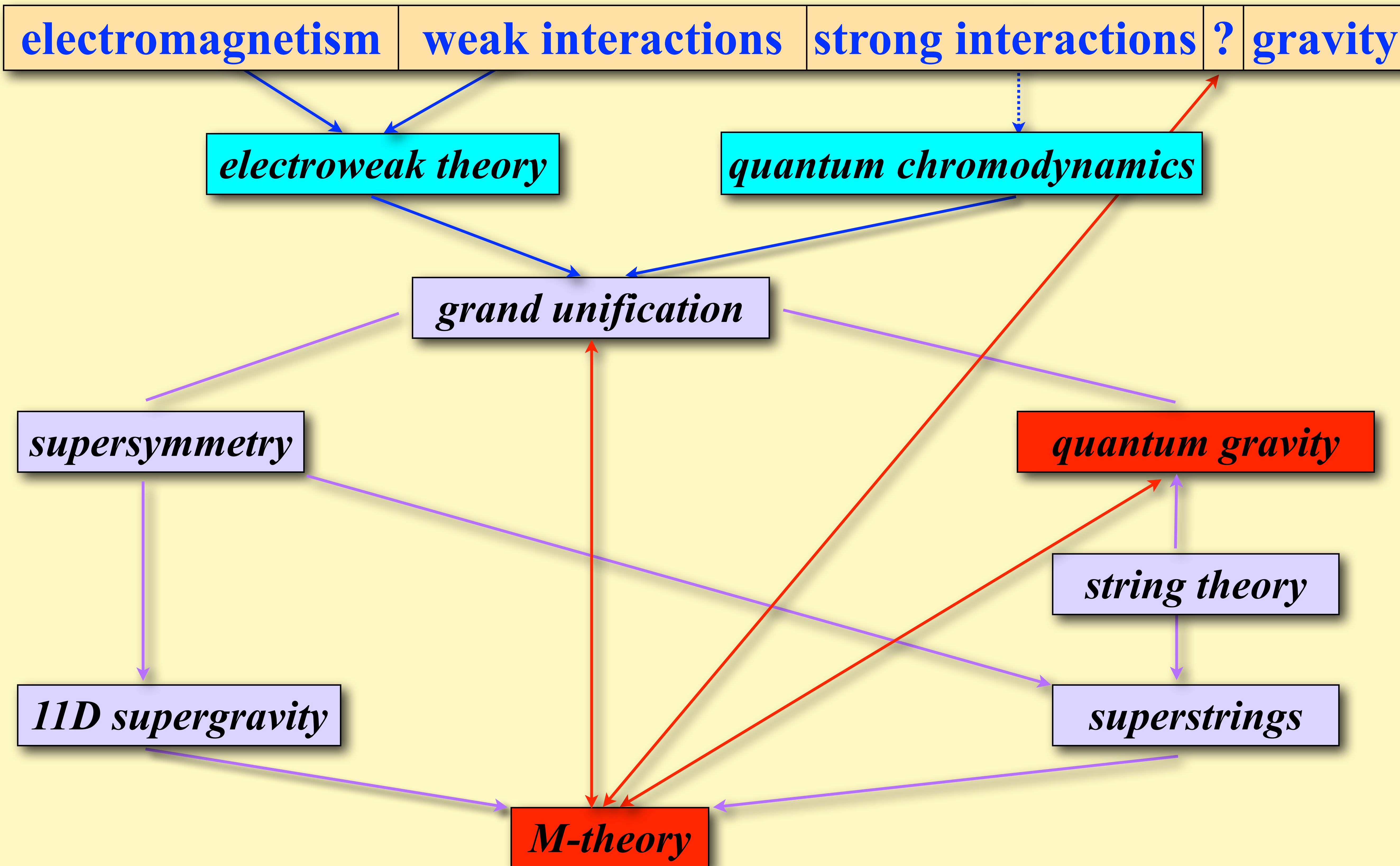

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