Cosmological Phase Transitions in Composite Higgs Models

Higgs as a Probe of New Physics 2023
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“Higgs as a Probe of New Physics (2023)”

In this talk, I assume new physics = composite Higgs
(Please accept this assumption for 15 minutes.)

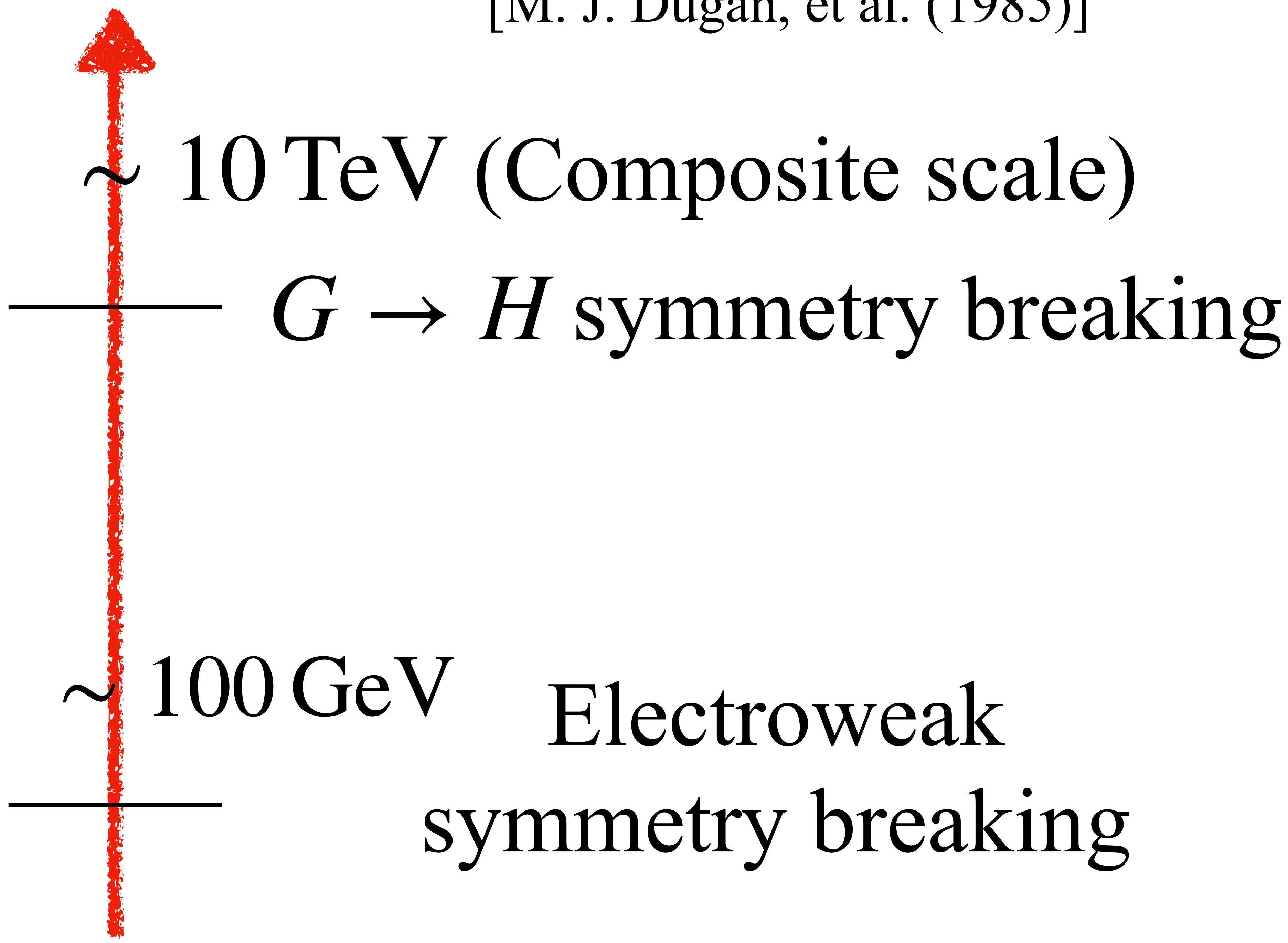
Introduction: Composite Higgs model

SM-like Higgs boson = pseudo-Nambu-Goldstone-Boson (pNGB) of global symmetry breaking, $G \to H$.

[D. B. Kaplan, H. Georgi (1984)]
[D. B. Kaplan, et al. (1984)]
[M. J. Dugan, et al. (1985)]

- $SU(2)_W \times U(1)_Y \subset H$

- $G \to H$ triggered by a strong dynamics



A composite Higgs model provides a solution to the hierarchy problem.
("No elementary scalar field")

Introduction: Cosmological Phase Transitions

Cosmological first order phase transition ⇒ Formation of bubbles

1. Production of Gravitational Wave

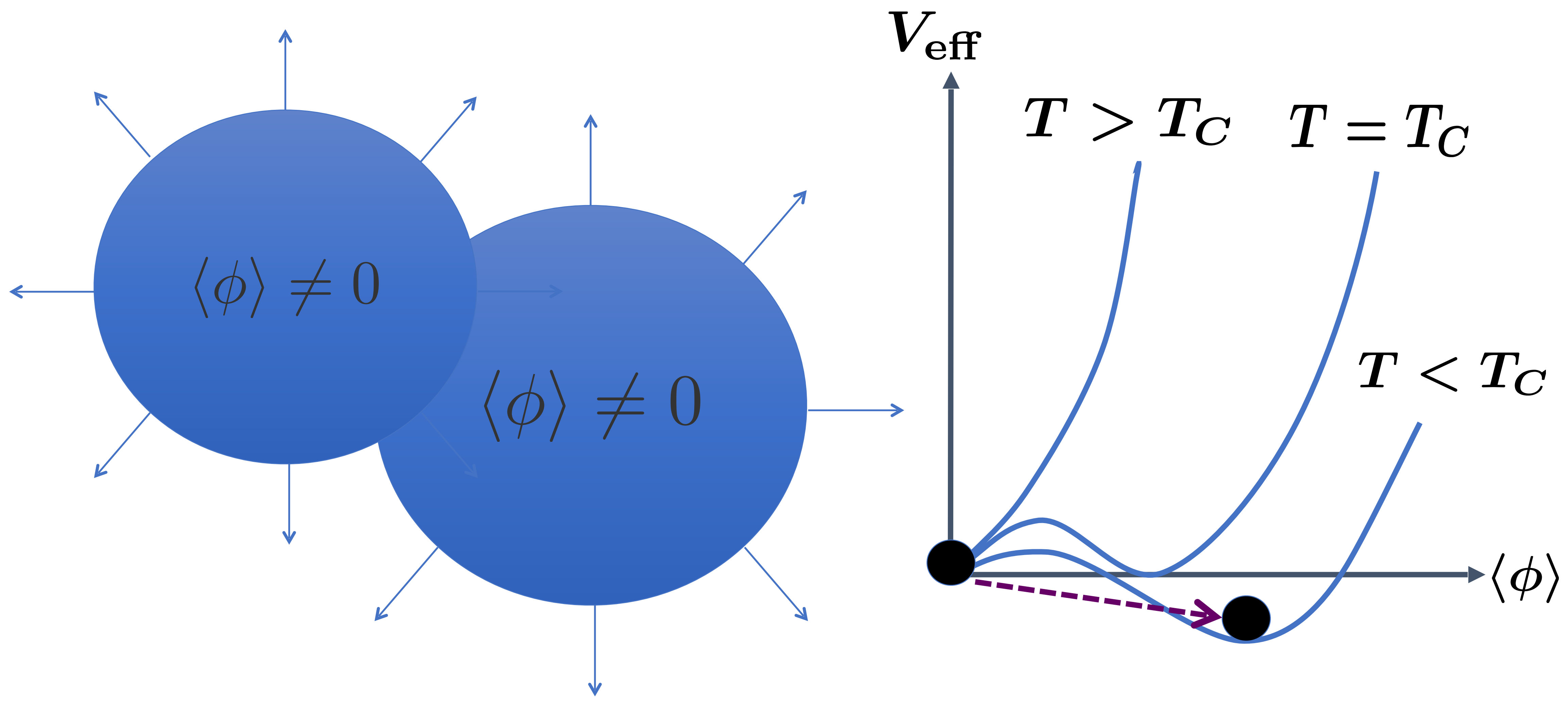
   [Kosowski et al. (1992)]
   [Hindmarsh, et al. (2014)]
   [Kamionkowski, et al. (1993)]

2. Production of Dark Matters

   [Witten (1992), Y. Bai (2018)]

3. Primordial Black hole formation

   (See interesting talks in this session.)



Question: What are order of phase transitions in composite Higgs models?

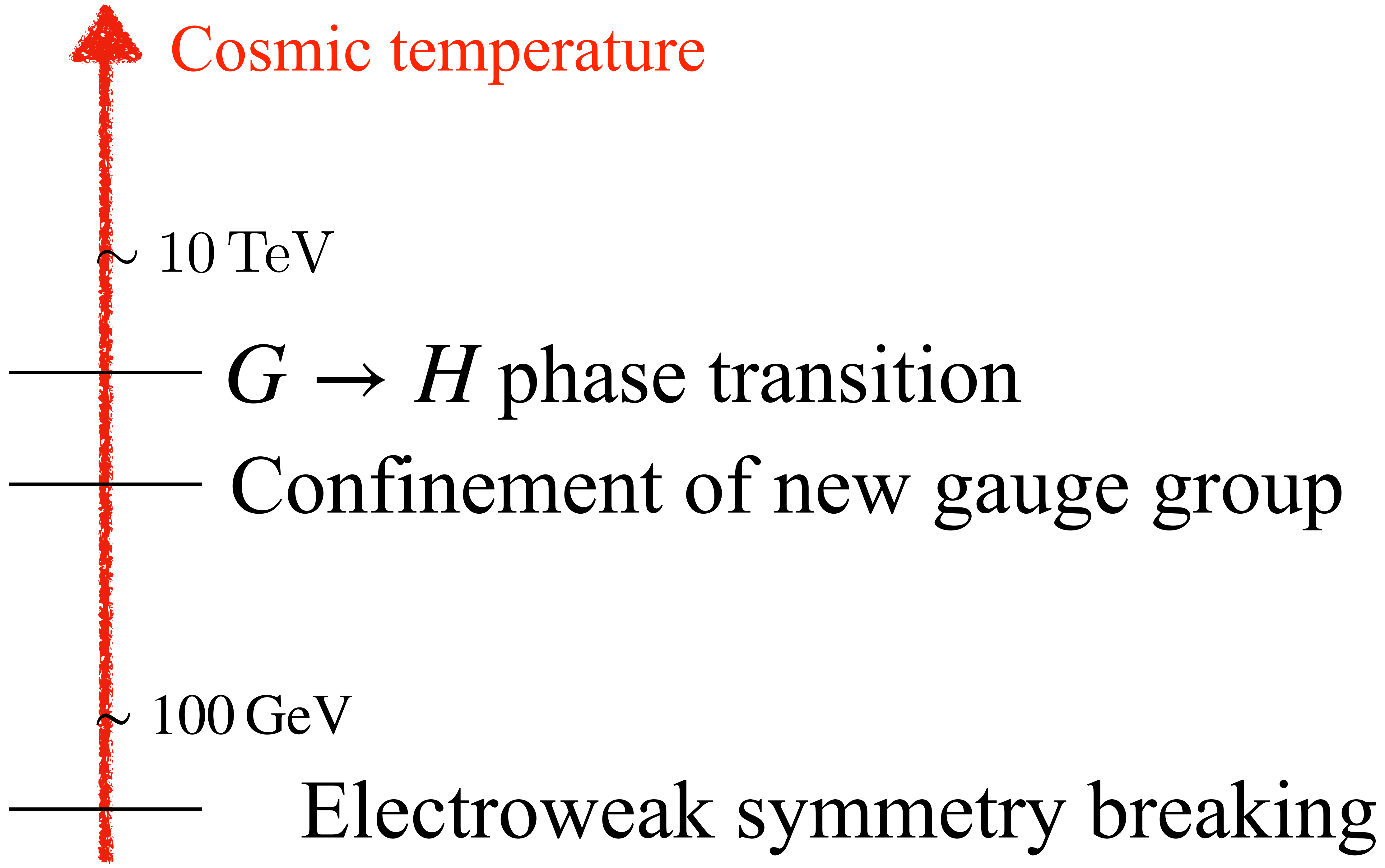
Phase Transitions in Composite Higgs

There can be three phase transitions:

1. Phase transition associated with confinement

2. Phase transition associated with new global symmetry breaking, $G \to H$.

3. The Electroweak Phase Transition



In this talk, I discuss order of the $G \to H$ phase transition.

Summary of this talk

I argue that if

- The argument of universality and ε-expansion are qualitatively good,
- Effects of explicit breaking of global symmetry G are negligible,

first-order $G \to H$ phase transitions are favored in some composite Higgs models.

I am going to explain the argument of universality and ε-expansion.

Details of Phase Transition Dynamics

Effective Field Theory (EFT) of Phase Transitions

Assumption (The argument of universality):

Phase transition dynamics is dominated by the long-wavelength fluctuations by an order parameter, Φ.

(Equilibrium) thermal field theory $\simeq$ Euclidean Field theory on $S^1 \times R^3$

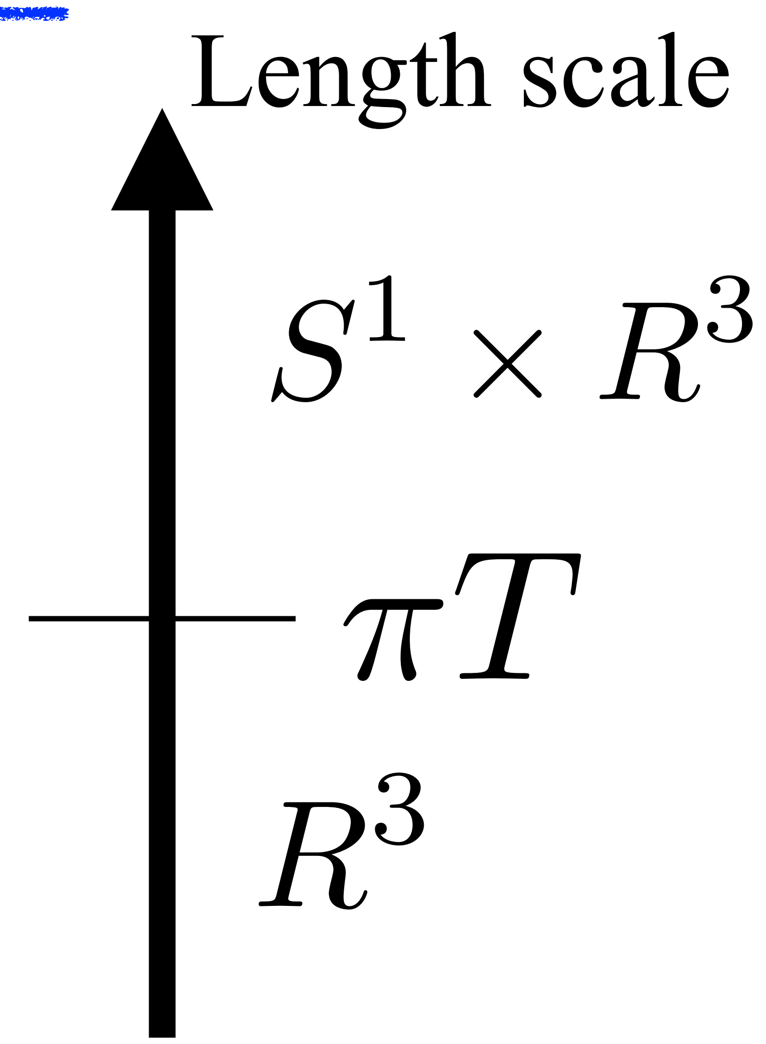
Microscopic 4D Action: $S_4[\sigma(\tau, \boldsymbol{x}), \Psi(\tau, \boldsymbol{x}), \cdots]$

$S^1 : \tau \sim \tau + 1/T$

T : cosmic temperature

S^1 shrinks

3D EFT of phase transition: $S_3[\Phi(\boldsymbol{x}), T]$



We may start from the effective field theory (EFT) of the order parameter in three spatial dimension.

Minimal Composite Higgs Models

- Consider phase transition associated with $O(N) \to O(N-1)$ (Minimal composite Higgs)

[N=5 is proposed by K. Agashe et al. (2005)]

Φ_a ($a = 1,2,\cdots,N$): Order parameter (fundamental representation of $O(N)$).

- Effective theory:

$$S_E = \int d^3\mathbf{x}\left[\frac{1}{2}\partial_i\Phi_a\partial_i\Phi_a + \frac{1}{2}m^2(T)\Phi_a\Phi_a + \frac{\lambda_3}{4}(\Phi_a\Phi_a)^2 + \cdots\right]$$

High T: $m^2(T > T_C) > 0 \Rightarrow \langle\Phi_a\rangle = 0$: Symmetric Phase

Low T: $m^2(T < T_C) < 0 \Rightarrow \langle\Phi_a\rangle \neq 0$: Broken Phase

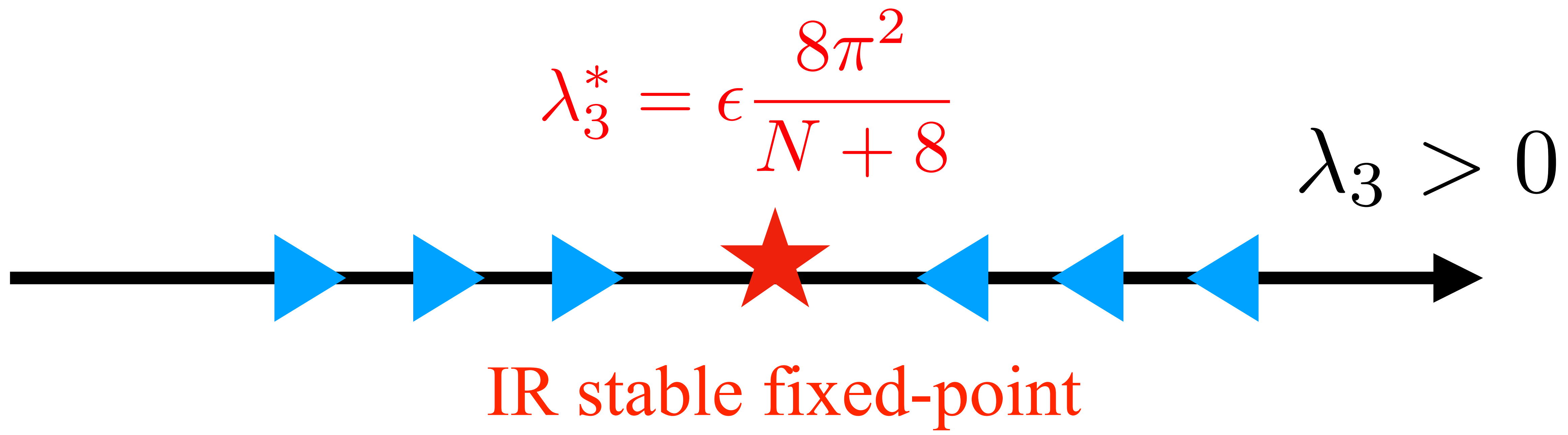
- Without fluctuations, a 2'nd order transition takes place at $m(T_C) = 0$.

Infra-red (IR) fluctuation and ε-expansion

- In three dimension, a fluctuation of Φ at critical point $m^2(T_C) = 0$ is non-perturbatively large.

- ε-expansion: Compute the renormalization group equation in $4 - \varepsilon$ dimension (instead of 3), and finally takes the extrapolation, $\varepsilon \to 1$.

$$\beta_{\lambda_3} \equiv \mu \frac{\partial \lambda_3}{\partial \mu} = -\epsilon \lambda_3 + (N+8) \frac{\lambda_3^2}{8\pi^2}$$



[K.G. Wilson and M.E. Fisher (1972), E. Brezin et al. (1973)]

- Divergence of correlation length at the IR fixed-point $\Rightarrow$ Divergence of susceptibility $\Rightarrow$ 2'nd order phase transition

Phase transition: $O(N) \to O(N-M) \times O(M)$

- Composite Higgs model: $O(N) \to O(N-M) \times O(M)$

[N=9 and M=4 proposed by S. Chang (2013)]

Order parameter: Φ_{ab} in two-index symmetric traceless representation under $O(N)$

$$\Phi_{ab} \to V\Phi V^T, V \in O(N), \qquad \mathrm{Tr}\,\Phi = 0, \Phi = \Phi^T$$

- Effective Action:

$$S_E = \int d^3\boldsymbol{x} \left[\frac{1}{2}\mathrm{Tr}\,(\partial_i\Phi)^2 + \frac{1}{2}m^2(T)\mathrm{Tr}\,(\Phi^2) + \frac{u}{4!}\left(\mathrm{Tr}\Phi^2\right)^2 + \frac{v}{4!}\mathrm{Tr}\,(\Phi^4)\right]$$

- Without fluctuations, a second-order phase transition takes place.

- What happens when we include fluctuation?

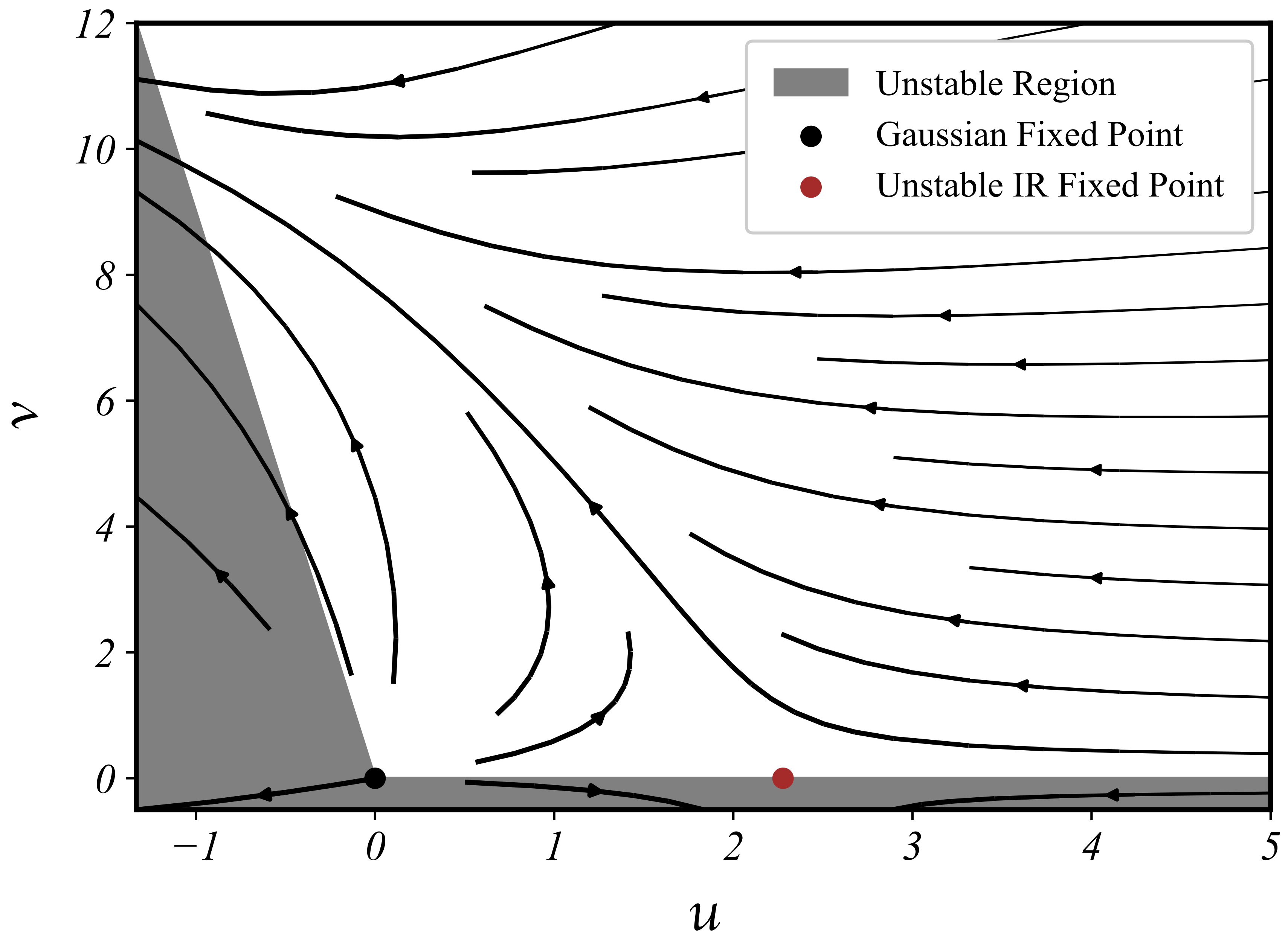
Phase transition: $O(N) \to O(N-M) \times O(M)$

One-loop renormalization group analysis:

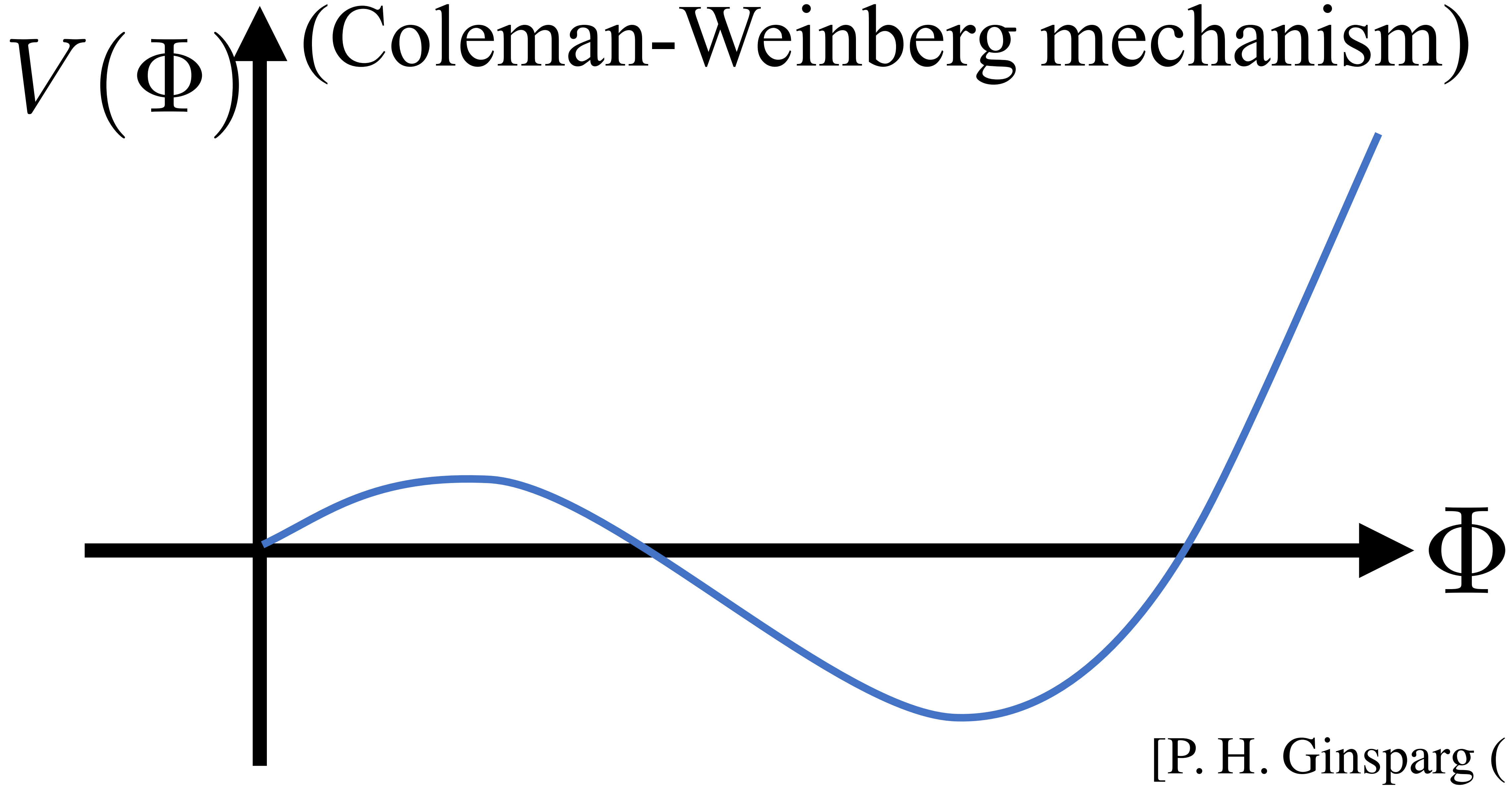
$$\beta_u = -\epsilon u + \frac{1}{16\pi^2}\left[\frac{2}{3}\left(N^2+N+14\right)u^2 + \left(\frac{8}{3}N + 4 - \frac{8}{N}\right)uv + \left(2+\frac{12}{N^2}\right)v^2\right],$$

$$\beta_v = -\epsilon v + \frac{1}{16\pi^2}\left[16uv + \left(\frac{4}{3}N + 6 - \frac{24}{N}\right)v^2\right]$$

$N = 9$



New minimum appears (Coleman-Weinberg mechanism)



[P. H. Ginsparg (1980)]

No stable IR fixed points ⇒ fluctuation-induced first-order phase transition

Results (ε-expansion)

Good News: predictions are largely model-independent

$\mathcal{G} \to \mathcal{H}$	PT dynamics	Model	Order
$SO(N) \to SO(N-1)$	E. Brezin et al. (1973) P. H. Ginsparg (1980)	$N=5$ K. Agashe et al. (2005) $N=9$ E. Beltuzzo et al. (2013)	2'nd 2'nd
$SO(9) \to \mathrm{SO}(5) \times \mathrm{SO}(4)$	This work	S. Chang (2013)	1'st
$SU(2N)\,(U(2N)) \to Sp(2N)$	J. Wirstam (2000)	$N=2$ J. Barnald et al. (2014) $N=3$ E. Katz et al. (2005) … and many works	anomaly 1'st
$SU(N)\,(U(N)) \to SO(N)$	F. Basile et al. (2005)	$N=5$ N. Arkani-Hamed et al. (2005)	1'st

Combining important related works, we can make lists of order of $G \to H$ phase transitions in various composite Higgs models.

Conclusion and Comment

- Composite Higgs models may lead to additional two phase transitions associated with global symmetry breaking $G \to H$ and confinement.
- Assuming the argument of universality, phase transition dynamics near the critical temperature may be captured by the effective theory of order parameter.
- Some composite Higgs models lead to first-order $G \to H$ phase transitions if the argument of universality and ε-expansion are qualitatively good.
- In our paper, we also discuss confinement phase transition and $G \to H$ phase transition in a specific UV-complete Higgs model.

Thank you!