Electroweak Baryogenesis

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Outline

- Motivation
- Electroweak baryogenesis (EWBG)
  - sphaleron decoupling condition
  - strong 1^{st} order EW phase transition (PT)
- Triple Higgs bosons coupling as a probe of EWBG
  2HDM, MSSM
- Summary

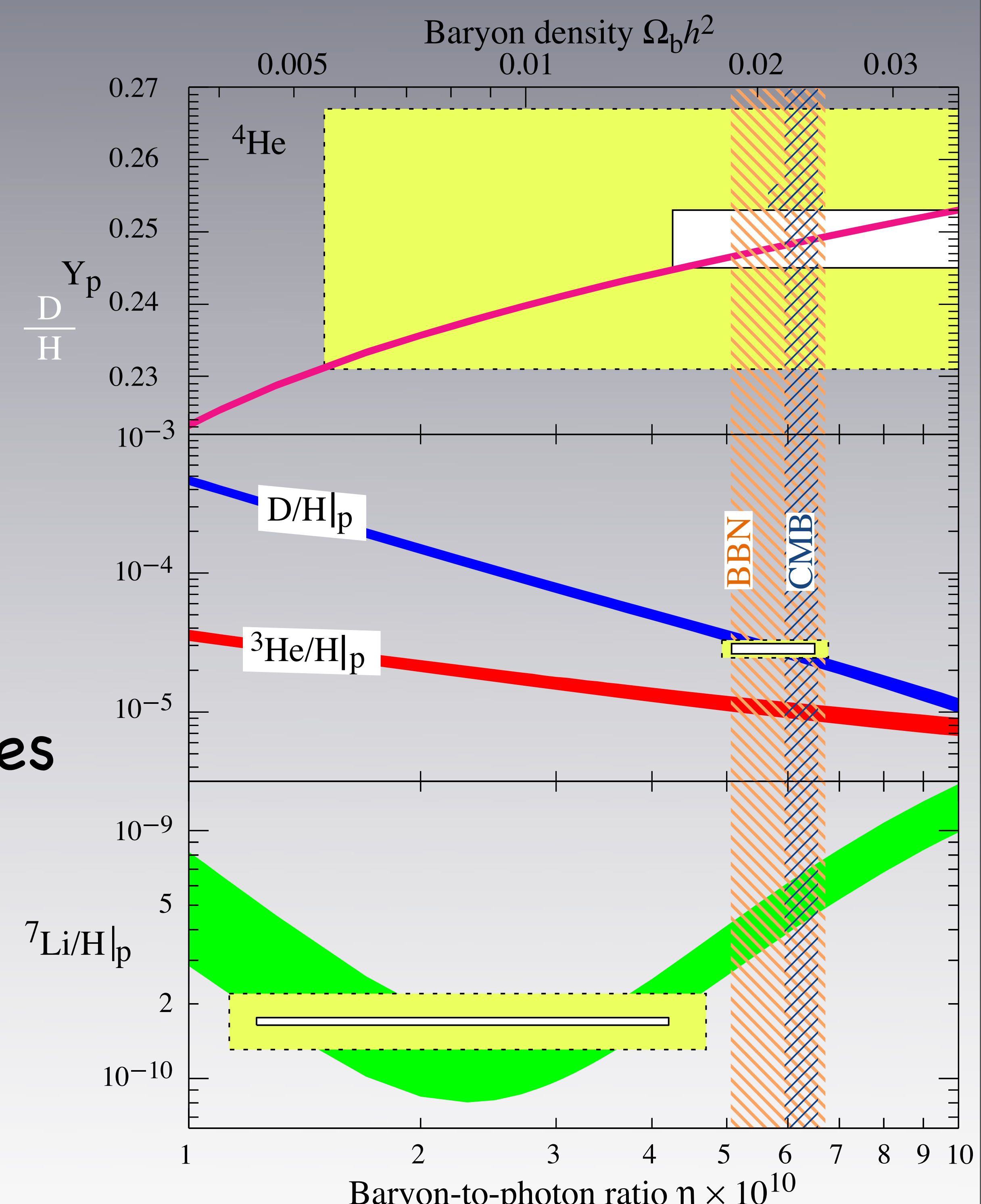
Baryon Asymmetry of the Universe (BAU)

❒ Our Universe is baryon-asymmetric.

$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$
$$= (5.1 - 6.5) \times 10^{-10} \ (95\%\ \mathrm{CL})$$

▪ If the BAU is generated before $T \simeq O(1)$ MeV, the light element abundances ($D, {}^3He, {}^4He, {}^7Li$) can be explained by the standard Big-Bang cosmology.

Baryogenesis = generate right η



[PDG 2012]

Sakharov's criteria

To get the BAU from initially baryon symmetric Universe, the following conditions must be satisfied. [Sakharov, '67]

(1) Baryon number (B) violation
(2) C and CP violation
(3) Out of equilibrium

BAU must arise

- ❒ After inflation (scale is model-dependent)
- ❒ Before Big-Bang Nucleosynthesis ($T \simeq 1$ MeV).

What kind of model can satisfy these conditions?

Many possibilities

[Shaposhnikov, J.Phys.Conf.Ser.171:012005,2009.]

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

❒ Electroweak baryogenesis (EWBG) is testable.

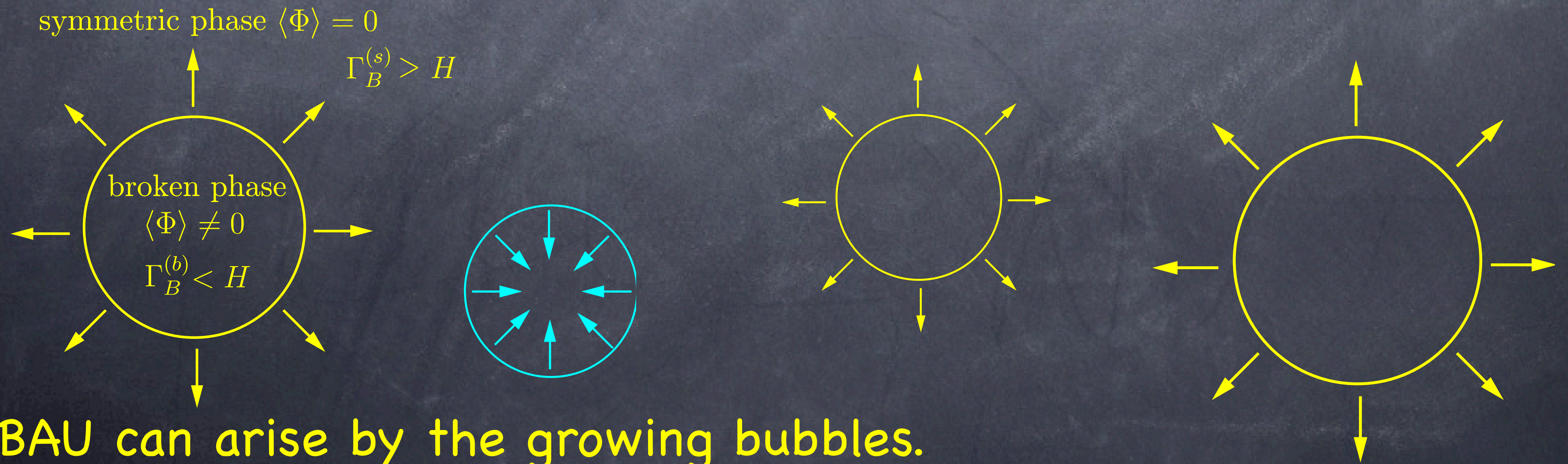
→ directly linked to the low energy observables, e.g. Higgs physics.

Electroweak baryogenesis

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

Sakharov's conditions

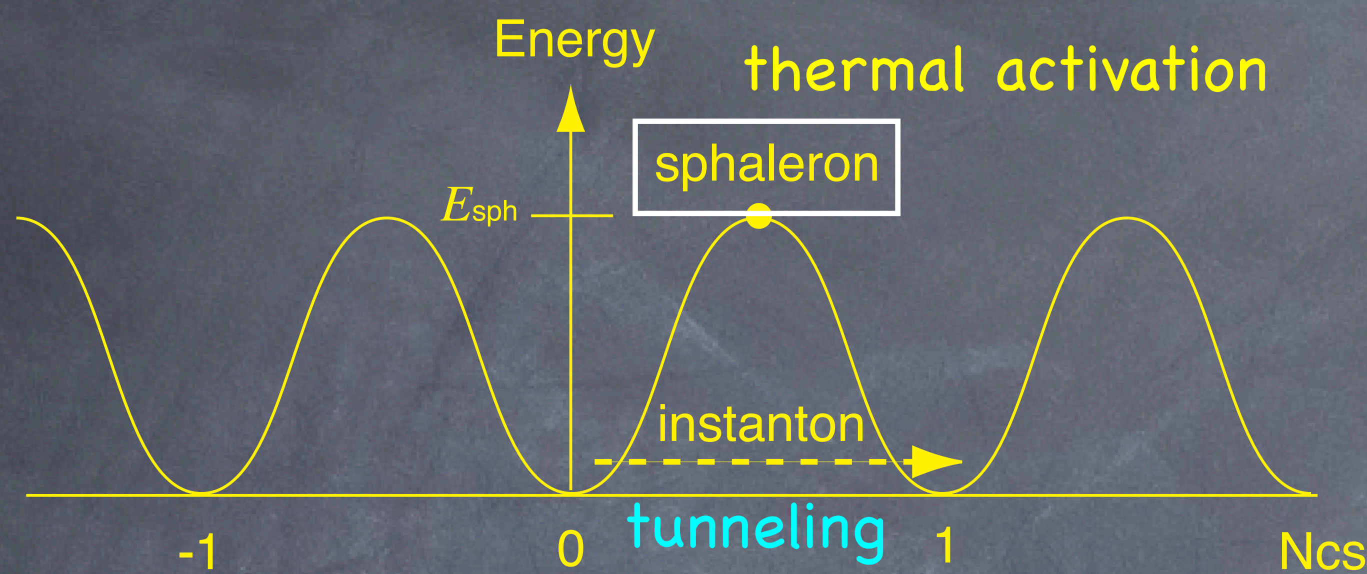
- B violation: anomalous process (sphaleron)
- C violation: chiral gauge interaction
- CP violation: Kobayashi-Maskawa (KM) phase and other complex phases in the beyond the SM
- Out of equilibrium: 1st order EW phase transition (EWPT) with expanding bubble walls



❒ BAU can arise by the growing bubbles.

(B+L) transition

(B+L) current is violated by the quantum anomaly. But (B−L) is conserved.



$$N_{CS}(t) = \frac{1}{32\pi^2}\int d^3x\, \epsilon_{ijk}\left[g_2^2 {\rm Tr}\left(F_{ij}A_k - \frac{2}{3}g_2 A_i A_j A_k\right) - g_1^2 B_{ij}B_k\right]$$

Δ(B+L)≠0

low T: tunneling

high T: thermal activation

e.g. $1 \text{ gen.}, \; 0 \leftrightarrow u_L d_L d_L \nu_{eL}$

$$N_g \text{ gen.}, \; 0 \leftrightarrow \sum_{i=1}^{N_g}(3q_L^i + l_L^i)$$

left-handed fermion only

Tunneling probability:

$$\Gamma_{\rm instanton} \simeq e^{-2S_{\rm instanton}} = e^{-16\pi^2/g_2^2} \simeq 10^{-162}.$$ unobservable!

sphaleron = static saddle point solution with finite energy of the gauge-Higgs system.

[N.S. Manton, PRD28 ('83) 2019]

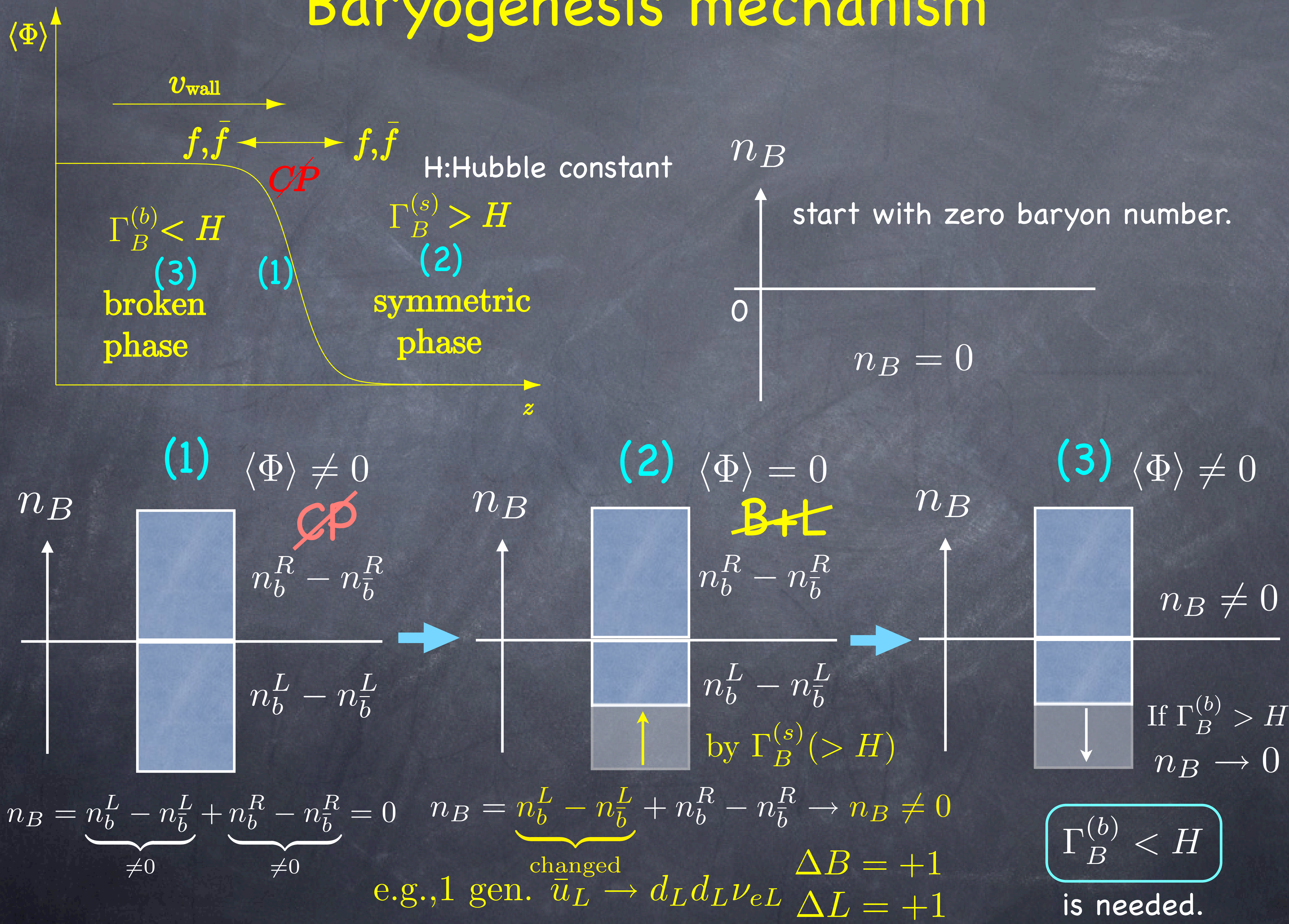
sphaleron rates (/time/volume):

$$\text{broken phase}: \quad \Gamma_{\rm sph}^{(b)} \simeq T^4 e^{-E_{\rm sph}/T},$$

$$\text{symmetric phase}: \quad \Gamma_{\rm sph}^{(s)} \simeq \kappa(\alpha_W T)^4, \quad \alpha_W = g_2^2/(4\pi), \; \kappa = \mathcal{O}(1)$$

$(B+L)$-violating process is active at finite T but is suppressed at T=0.

Baryogenesis mechanism



$$\Gamma_B^{(b)} < H$$

B-changing rate in the broken phase is

$$\Gamma_B^{(b)}(T) \simeq (\text{prefactor})\frac{\Gamma_{\text{sph}}^{(b)}}{T^3} \simeq (\text{prefactor})e^{-E_{\text{sph}}/T},$$

E_{sph} is a sphaleron energy which is proportional to Higgs VEV

$$E_{\text{sph}} \propto v$$

what we need:
large Higgs VEV after the EWPT -> EWPT should be strongly 1st order.

❒ sphaleron decoupling condition gives strong constraints on Higgs sector.

❒ In most cases, collider signals of EWBG is consequence of this condition.

More on $\Gamma_B^{(b)} < H$

After the EWPT, the sphaleron process must be decoupled.

$$\boxed{\Gamma_B^{(b)}(T) \simeq (\text{prefactor})e^{-E_{\text{sph}}/T} < H(T) \simeq 1.66\sqrt{g_*}T^2/m_{\text{P}}}$$

g_* massless dof, 106.75 (SM) m_{P} Planck mass ≃ $1.22\text{x}10^{19}$ GeV

$E_{\text{sph}} = 4\pi v\mathcal{E}/g_2$ (g_2: SU(2) gauge coupling),

$$\boxed{\frac{v}{T} > \frac{g_2}{4\pi\mathcal{E}}\left[42.97 + \log\text{ corrections}\right]}$$

- ❒ sphaleron energy gives the dominant effect.
- ❒ log corrections are subleading.
- ❒ Commonly, the sphaleron decoupling condition is evaluated at a critical temperature (Tc.).

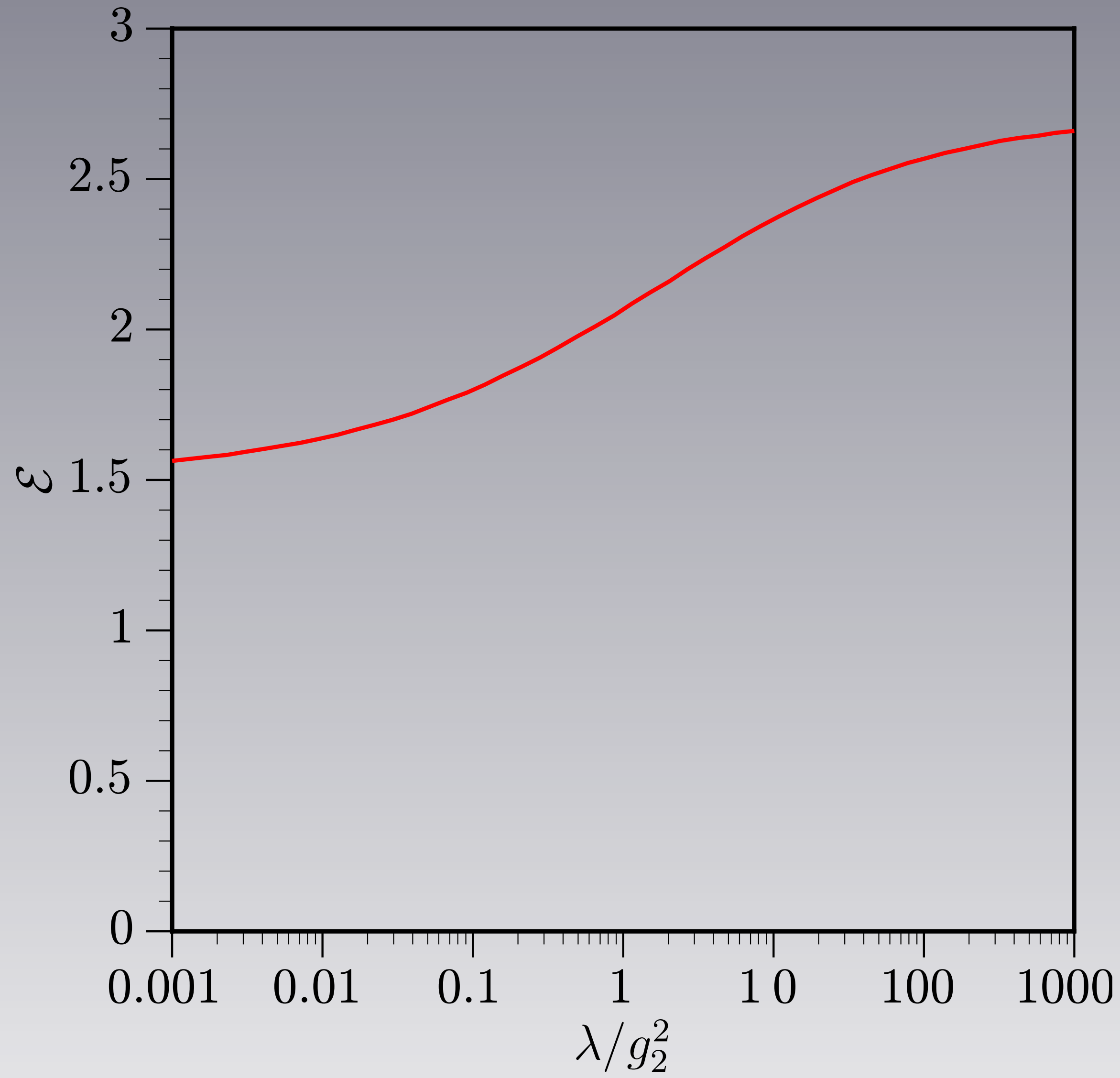
Sphaleron energy

For simplicity, we evaluate sphaleron energy at T=0. [Klinkhammer and Manton, PRD30, ('84) 2212]

We take SM as an example. ($U(1)_Y$ is neglected)

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + (D_\mu \Phi)^\dagger D^\mu \Phi - V_0(\Phi)$$

$$V_0(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$



sphaleron energy:

$$E_{\rm sph} = \frac{4\pi v}{g_2} \mathcal{E}$$

Higgs mass (λ) ↗ -> E_{sph} ↗

$$\text{For } m_h = 126 \text{ GeV } (\lambda = 0.13),\ \mathcal{E} \simeq 1.92 \quad \rightarrow \quad \boxed{\frac{v}{T} \gtrsim 1.16}$$

SM EWBG

It turned out that the SM EWBG was ruled out.

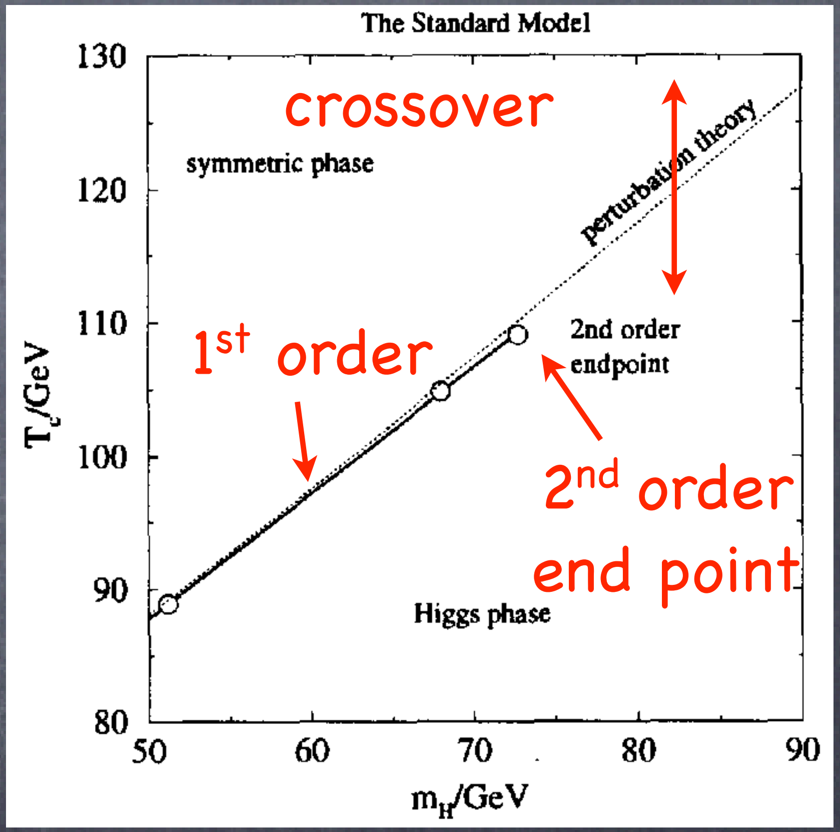
- KM phase is too small to generate the observed BAU.

[Gavela et al, NPB430,382 ('94); Huet and Sather, PRD51,379 ('95).]

- EWPT is a crossover for m_H>73 GeV.

[Kajantie at al, PRL77,2887 ('96); Rummukainen et al, NPB532,283 ('98); Csikor et al, PRL82, 21 ('99); Aoki et al, PRD60,013001 ('99), Laine et al, NPB73,180('99)]

(LHC exp., m_H=126GeV)

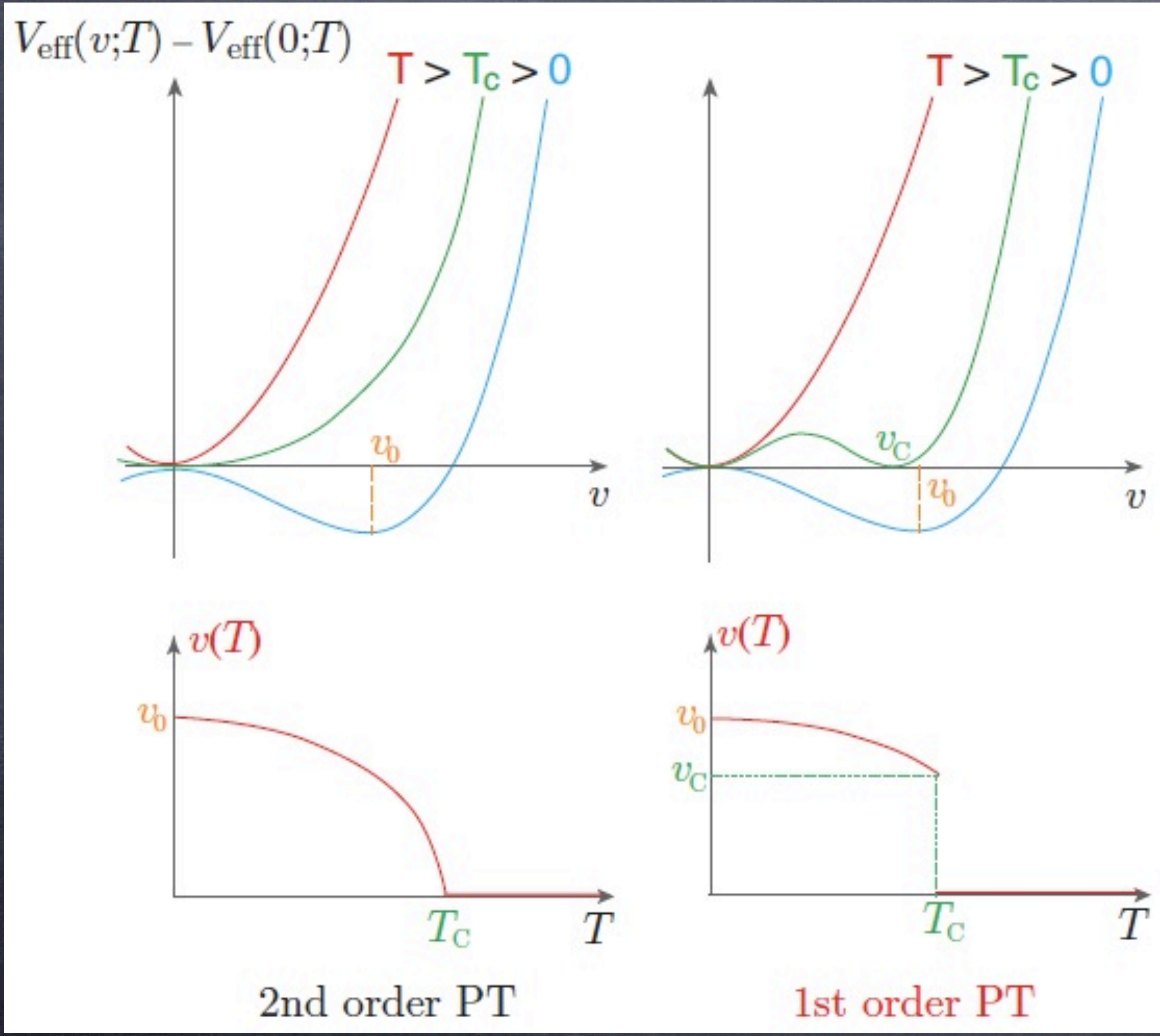


-> New Physics is required.

Many directions to go: SUSY models or non-SUSY models etc.

1^{st} and 2^{nd} order EWPTs

This is what the 1^{st} and 2^{nd} order PTs look like.



[From K. Funakubo's slide]

- order parameter = Higgs VEV
- EWBG requires "1^{st} order" PT

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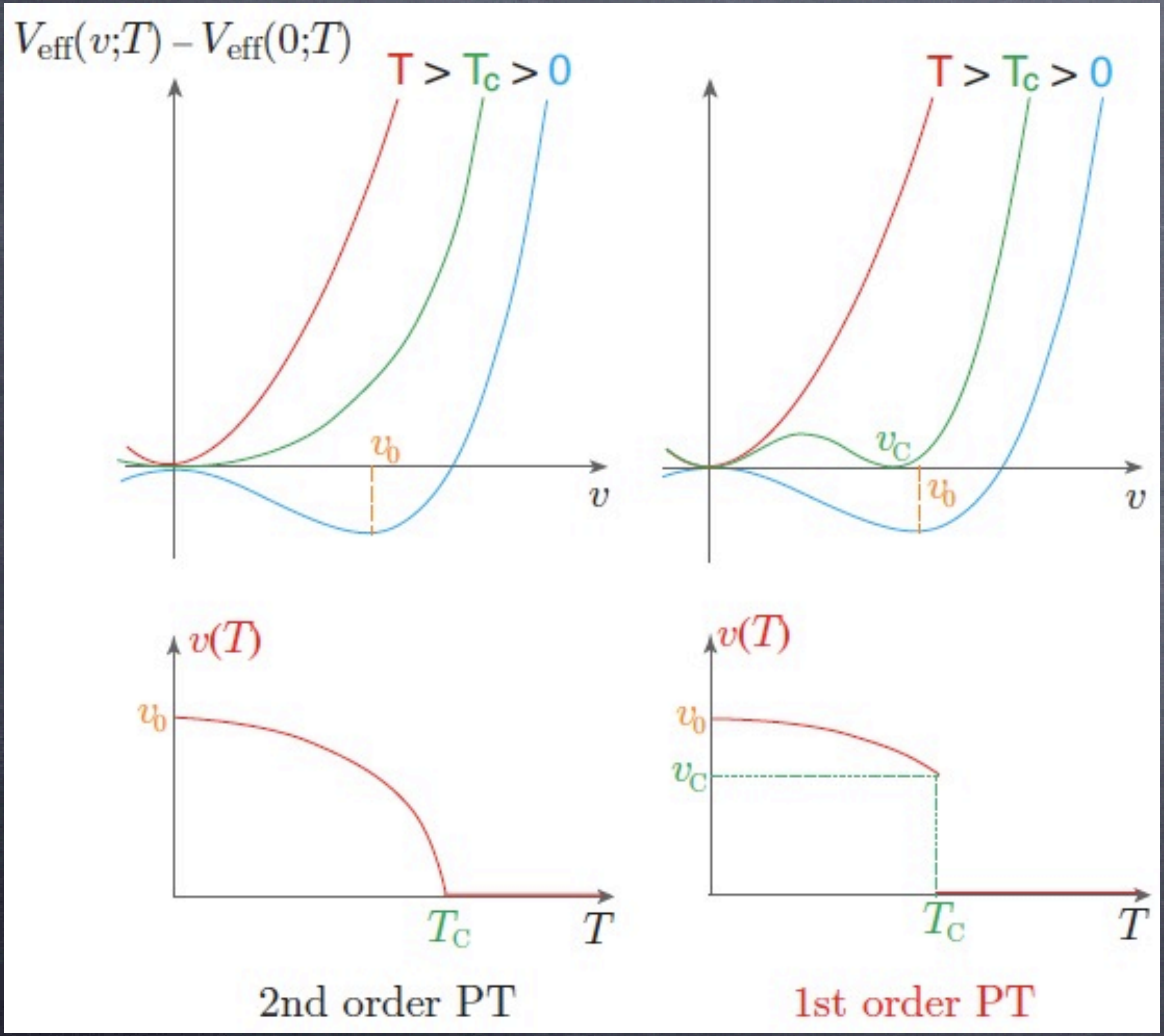

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- order parameter = Higgs VEV
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- A negative contributions is necessary.

1st and 2nd order EWPTs

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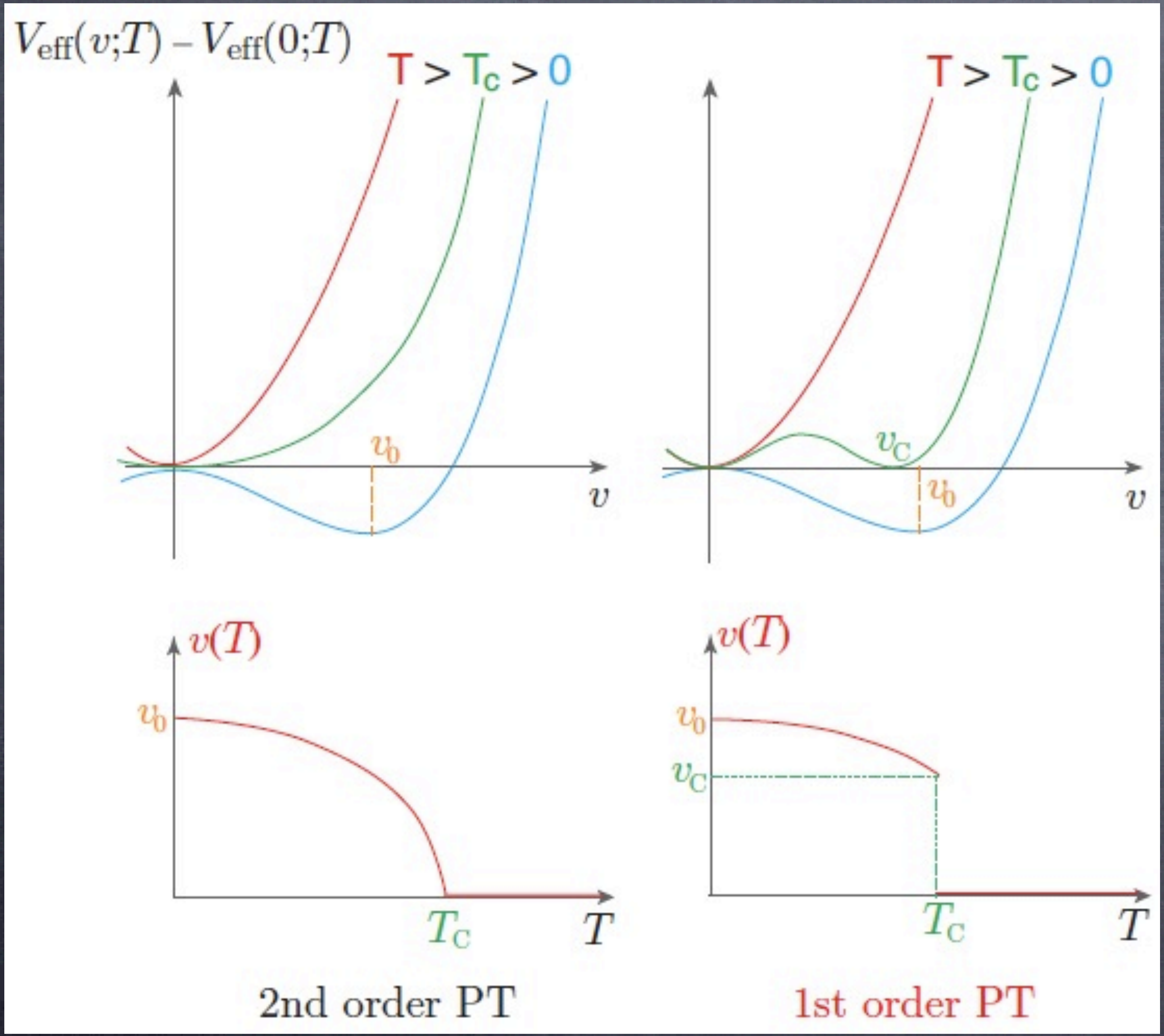

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- A negative contributions is necessary.

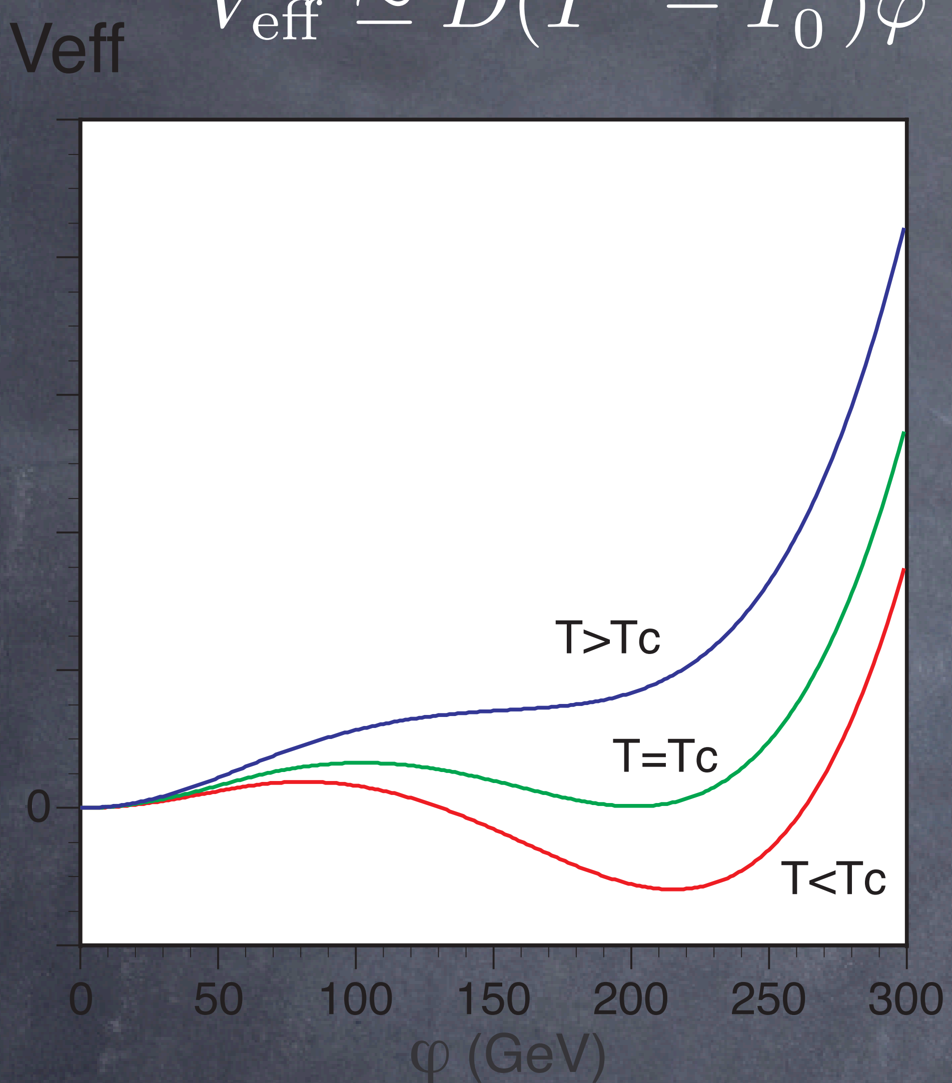
e.g.

Bosonic thermal loop

$$V_1^{\rm (boson)} \ni -|{\rm const}| \cdot m(v)^{3/2} T$$

SM EWPT at 1-loop order

$$V_{\rm eff} \simeq D(T^2 - T_0^2)\varphi^2 - ET|\varphi|^3 + \frac{\lambda_T}{4}\varphi^4 \underset{T=T_C}{\longrightarrow} \frac{\lambda_{T_C}}{4}\varphi^2(\varphi - v_C)^2$$



❒ T_C is defined at which V_{eff} has two degerate minima.

❒ 1st order EWPT is realized by the boson loops

$$E_{\rm SM} \simeq \frac{1}{4\pi v^3}(2m_W^3 + m_Z^3) \simeq 0.01$$

$$v_C = \frac{2ET_C}{\lambda_{T_C}} \quad \Rightarrow \quad \frac{v_C}{T_C} = \frac{2E}{\lambda_{T_C}} = \frac{\text{cubic coeff.}}{\text{quartic coeff.}}$$

$$\lambda_{T_C} \simeq \lambda = m_{h^{\rm SM}}^2/(2v^2)$$

sphaleron decoupling condition

$$\Gamma_B^{(b)} < H \quad \Rightarrow \quad \frac{v_C}{T_C} \gtrsim 1 \quad \Longrightarrow \quad \boxed{m_{h^{\rm SM}} \lesssim 48\ \text{GeV}}$$

excluded by LEP

way out: enhance E by adding new bosons.

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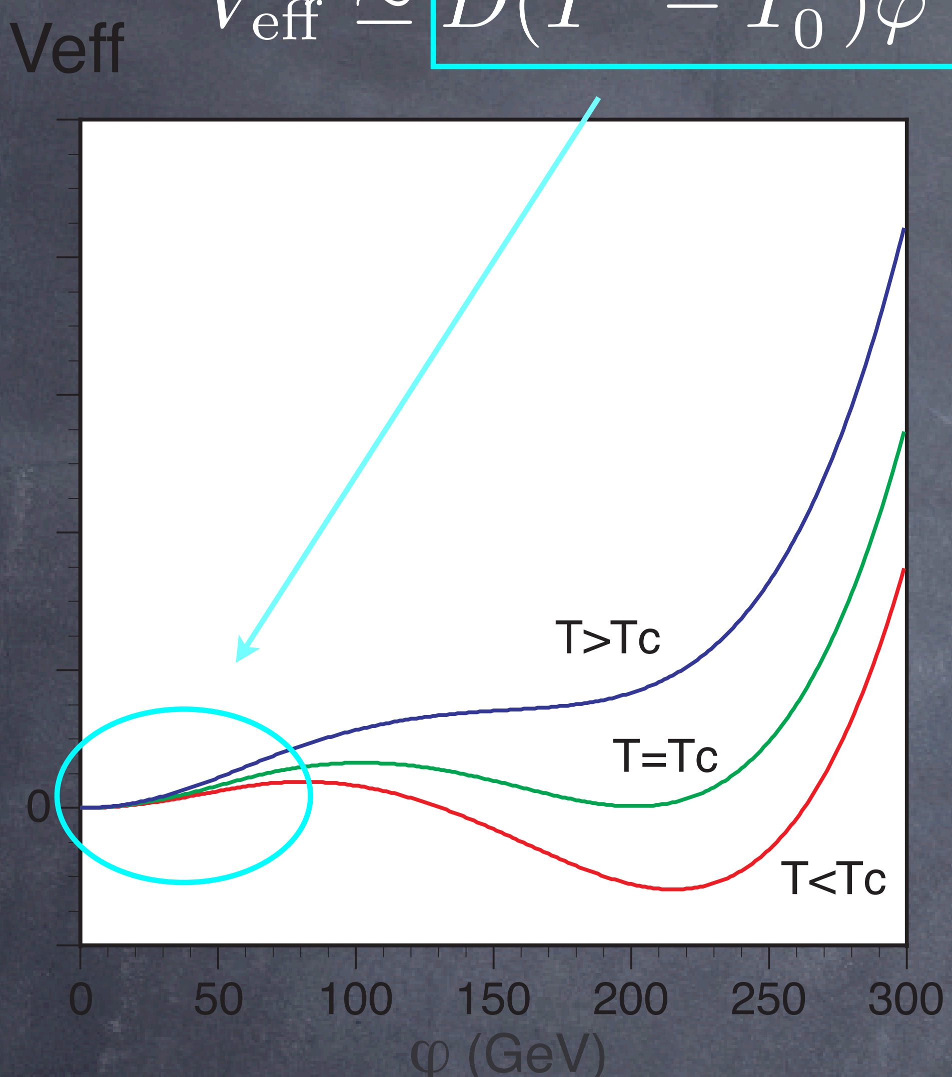

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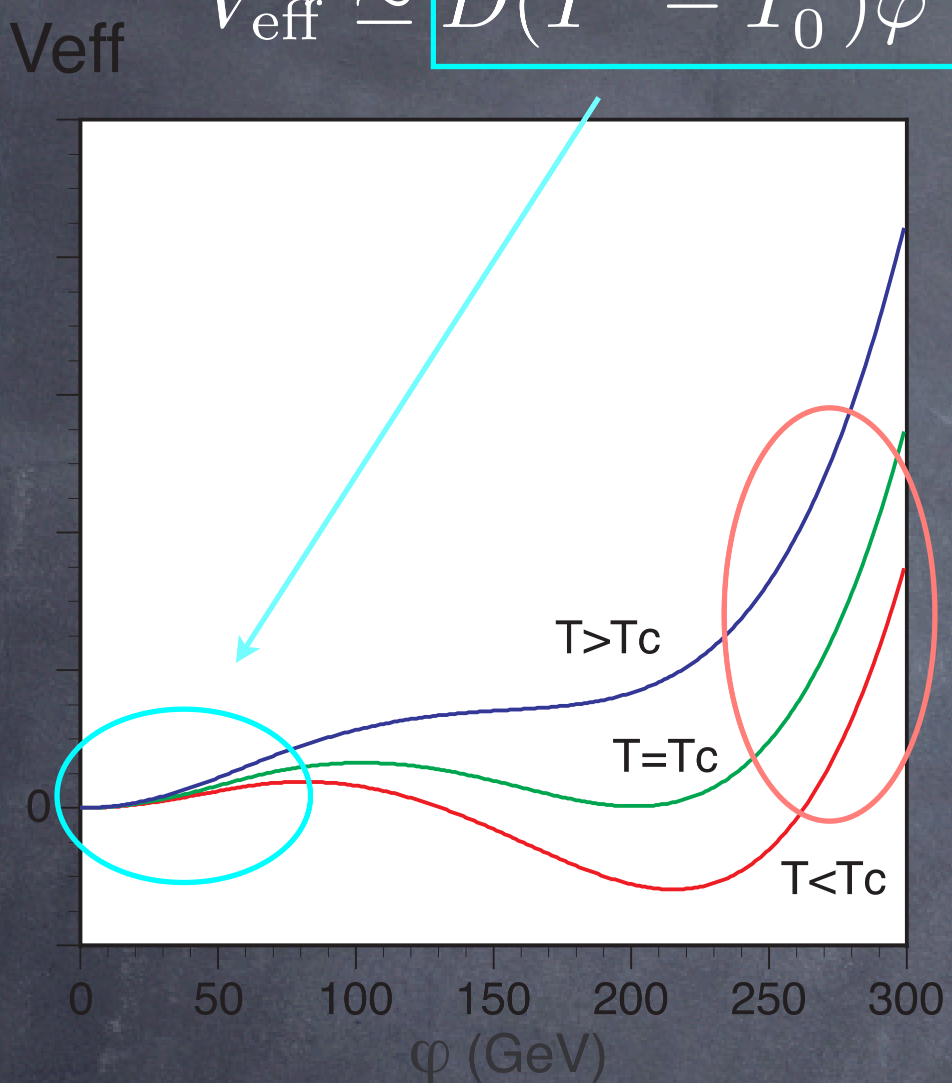

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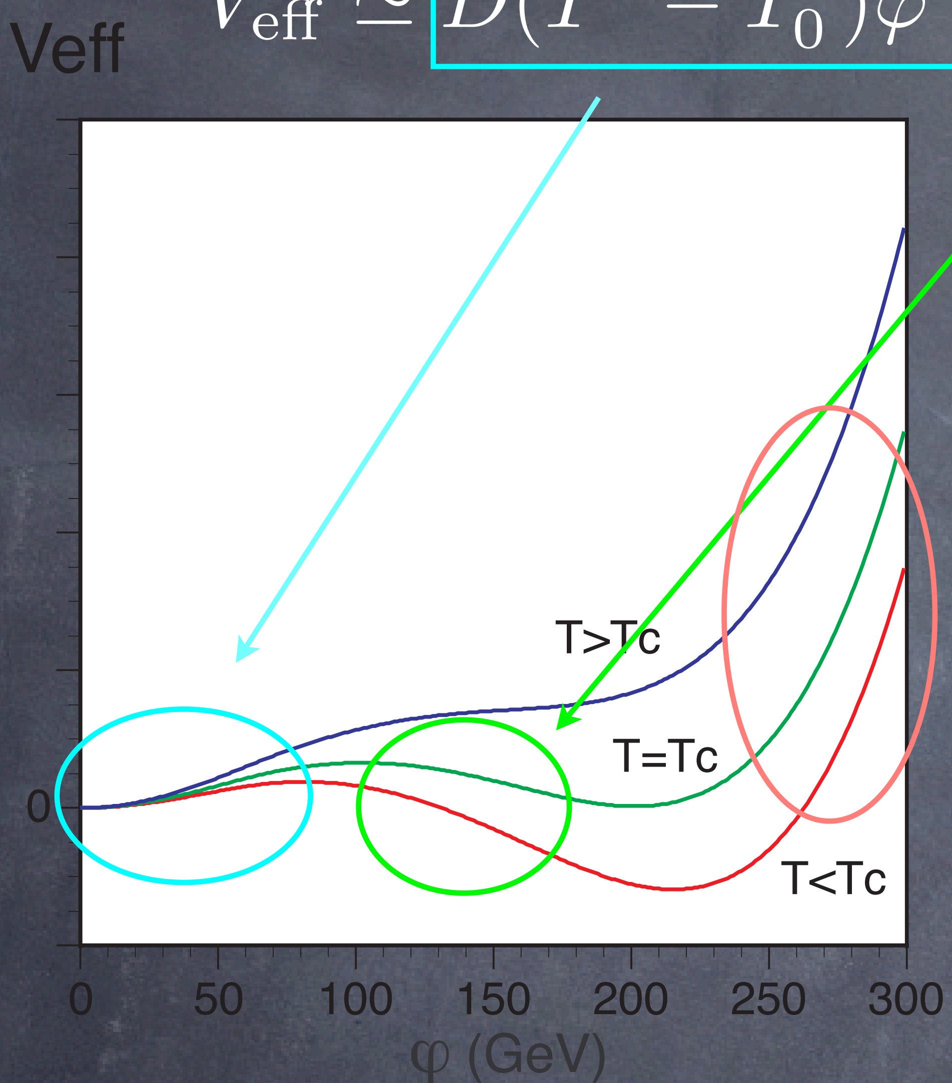

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way out: enhance E by adding new bosons.

Caveat

"Scalar does not always play a roll."

Suppose the scalar mass is given by

$$m^2 = M^2 + \lambda v^2$$

M : mass parameter in the Lagrangian

λ : coupling between Higgs and a scalar

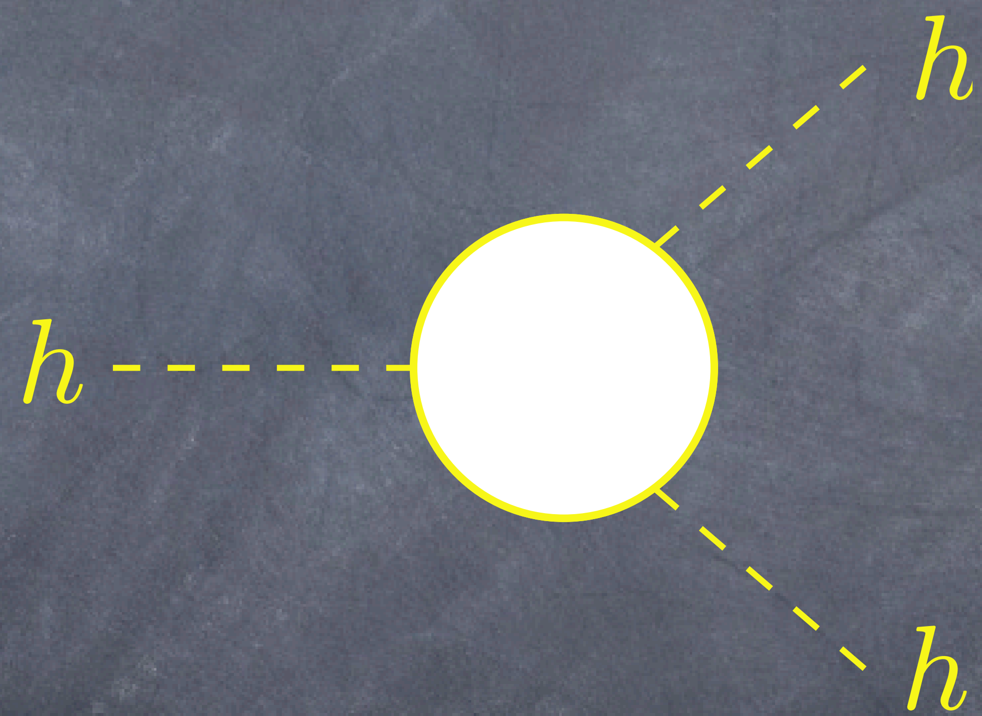
$M^2 \ll \lambda v^2$ nondecoupling $\quad V_{\rm eff} \ni -\lambda^{3/2} T v^3 \left(1 + \frac{M^2}{\lambda v^2}\right)^{3/2}$ contribute

$M^2 \gg \lambda v^2$ decoupling $\quad V_{\rm eff} \ni -|M|^3 T \left(1 + \frac{\lambda v^2}{M^2}\right)^{3/2}$ does not

$\boxed{\text{requirements: 1. large coupling } \lambda\text{, 2. small M}}$

nondecoupling scalar $\Rightarrow \quad E = E_{\rm SM} + \Delta E \quad \Rightarrow \quad \frac{v_C}{T_C} \nearrow$

Triple Higgs boson coupling as a probe of EWBG



EWBG signal can appear in the triple Higgs boson coupling.

2 Higgs doublet model (2HDM)

- ❒ Additional Higgs doublet is added to the SM Higgs sector.
- ❒ To suppress the FCNC processes, Z_2 symmetry is imposed

$$\Phi_1 \to \Phi_1,\ \ \Phi_2 \to -\Phi_2 \ (\text{Type I, II etc})$$

Higgs potential

$$\begin{aligned} V_{\text{2HDM}} &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) \\ &+ \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)^2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_4 (\Phi_1^\dagger \Phi_2)^2 (\Phi_2^\dagger \Phi_1)^2 \\ &+ \left[\frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right], \end{aligned}$$

$$m_3^2,\ \lambda_5 \in \mathbb{C}$$

charged Higgs

$$\Phi_{1,2}(x) = \begin{pmatrix} \phi_i^+(x) \\ \frac{1}{\sqrt{2}}\Big(v_i + h_i(x) + i a_i(x)\Big) \end{pmatrix}.$$

Higgs VEV

CP-even Higgs

CP-odd Higgs

6 free parameters (v and m_h are known.)

$m_h,\ m_H,\ m_A,\ m_{H^\pm}$

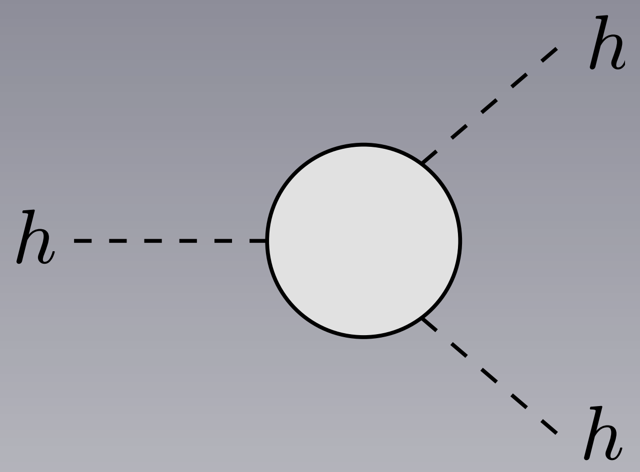
α : mixing angle between h and H

$$\tan\beta = v_2/v_1, \quad (v = \sqrt{v_1^2 + v_2^2} \simeq 246\ \text{GeV}) \qquad M^2 = m_3^2/(\sin\beta\cos\beta)$$

Quantum corrections to hhh coupling

Loop corrections of heavy Higgs bosons

[S. Kanemura, S. Kiyoura, Y. Okada, E.S., C.-P. Yuan, PLB558 (2003) 157]



For $\sin(\beta-\alpha)=1$ (SM-like limit)

$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\sum_{\Phi=H,A,H^\pm}\frac{c}{12\pi^2}\frac{m_\Phi^4}{m_h^2 v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3\right].$$

c=1(2) for neutral (charged Higgs bosons)

2 kinds of large mass limits $m_\Phi^2 \simeq M^2+\lambda_i v^2$

For $M^2 \ll \lambda_i v^2$ $(m_\Phi^2 \simeq \lambda_i v^2)$, the quantum corrections would grow with m_Φ^4.

$\Rightarrow$ nondecoupling limit (coupling constants get large)

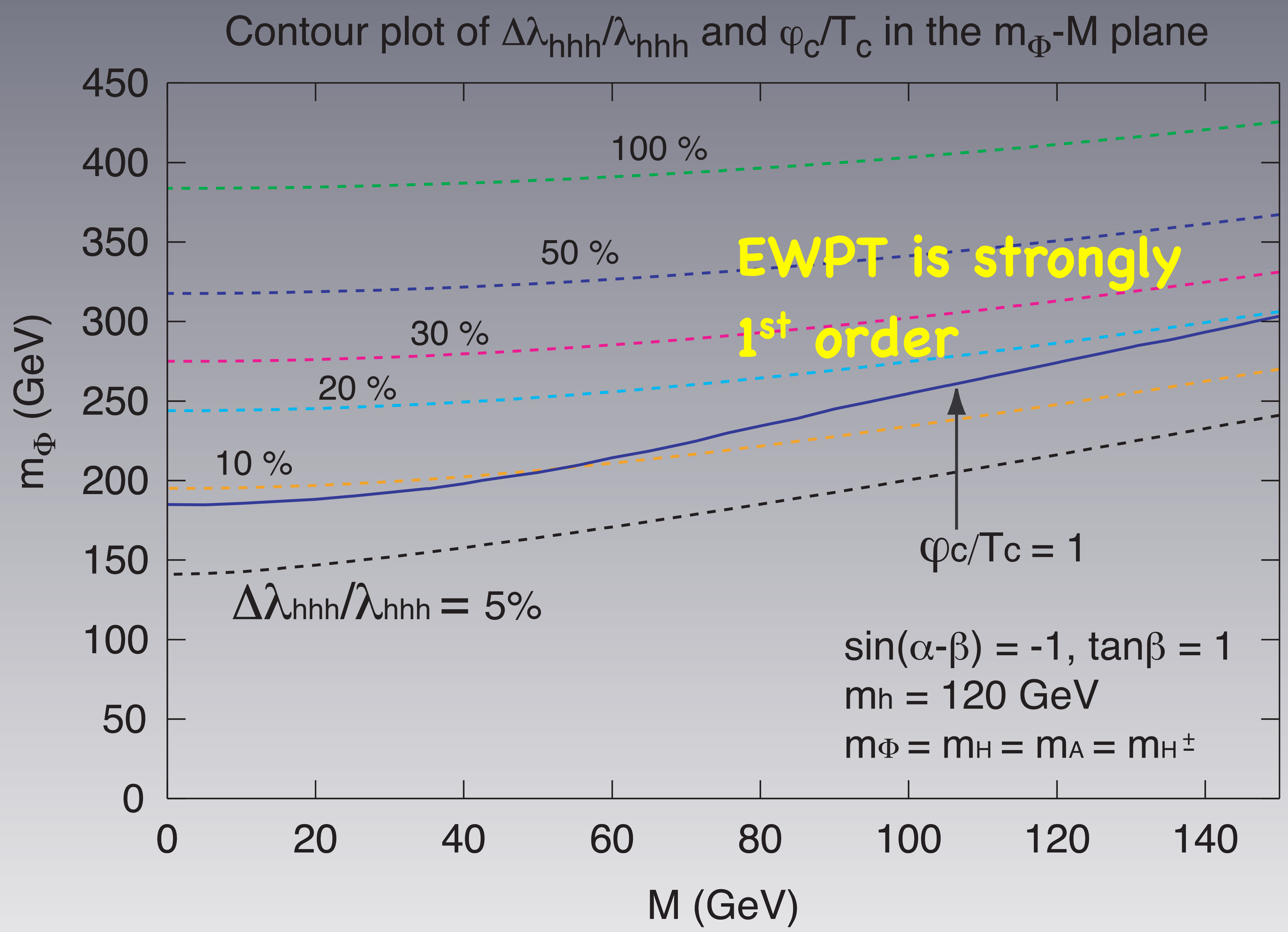
For $M^2 \gg \lambda_i v^2$ $(m_\Phi^2 \simeq M^2)$, the quantum corrections would be suppressed.

$\Rightarrow$ ordinary decoupling limit (1/mass)

Loop corrections are sizable if the heavy Higgs bosons have nondecoupling property. **(Successful EWBG enforces the former limit.)**

Correlation between $\Delta\lambda_{hhh}/\lambda^{SM}_{hhh}$ and v_C/T_C

[S. Kanemura, Y. Okada, E.S.,PLB606 (2005) 361]



- ❒ Heavy Higgs boson loops enhance the 1st order EWPT → $\Delta E_{\rm 2HDM} \nearrow$
- ❒ For $v_C/T_C > 1$, $\Delta\lambda_{hhh}/\lambda^{SM}_{hhh}$ is greater than (10-20)%.

How about the MSSM?

Light stop scenario

[Carena, Quiros, Wagner, PLB380 ('96) 81]

requirements: 1. large coupling λ, 2. small M

top Yukawa — small soft SUSY mass

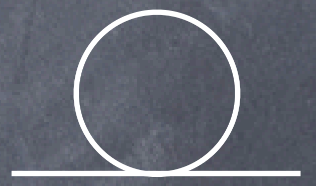
LEP bound on m_H
ρ parameter

$$m_{\tilde{q}}^2 \gg m_{\tilde{t}_R}^2, X_t^2, \quad X_t = A_t - \mu/\tan\beta.$$

stop mass

$$\bar{m}_{\tilde{t}_2}^2 = m_{\tilde{q}}^2 + \frac{y_t^2 \sin^2\beta}{2}\left(1 + \frac{|X_t|^2}{m_{\tilde{q}}^2}\right) v^2 + \mathcal{O}(g^2) \simeq m_{\tilde{q}}^2,$$

$$\bar{m}_{\tilde{t}_1}^2 = m_{\tilde{t}_R}^2 + \frac{y_t^2 \sin^2\beta}{2}\left(1 - \frac{|X_t|^2}{m_{\tilde{q}}^2}\right) v^2 + \mathcal{O}(g^2).$$



At finite T, there is a thermal correction, $\boxed{\Delta_T m_{\tilde{t}_R}^2} \sim \mathcal{O}(T^2) > 0.$

To have a large loop effect, $m_{\tilde{t}_R}^2 + \Delta_T m_{\tilde{t}_R}^2$ must be small.

$m_{\tilde{t}_R}^2(T) \equiv m_{\tilde{t}_R}^2 + \Delta_T m_{\tilde{t}_R}^2 = 0 \;\Rightarrow\; m_{\tilde{t}_R}^2 < 0$ Charge-Color-Breaking vacuum

$\boxed{m_{\tilde{t}_1} < m_t}$ **light stop is needed!!**

$X_t = 0$ (no-mixing) maximizes the loop effect

$\Delta\lambda_{hhh}/\lambda^{SM}_{hhh}$

- Coefficient of cubic term in $V_{eff}(T)$

$$V_{\rm eff} \ni -(E_{\rm SM} + E_{\tilde{t}_1})Tv^3$$

$$E_{\tilde{t}_1} \simeq +\frac{y_t^3 \sin^3\beta}{4\sqrt{2}\pi}\left(1 - \frac{|X_t|^2}{m_{\tilde{q}}^2}\right)^{3/2}.$$

- Deviation of hhh coupling

$$\frac{\Delta\lambda_{hhh}^{\rm MSSM}}{\lambda_{hhh}^{\rm SM}} \simeq \frac{m_t^4}{2\pi^2 v^2 m_h^2}\left(1 - \frac{|X_t|^2}{m_{\tilde{q}}^2}\right)^3 = \frac{2v^4}{m_t^2 m_h^2}(E_{\tilde{t}_1})^2$$

For $m_h = 126$ GeV, $\tan\beta = 10,\ X_t = 0$

$$\boxed{\frac{\Delta\lambda_{hhh}^{\rm MSSM}}{\lambda_{hhh}^{\rm SM}} \simeq 0.05}$$

Size of the loop effect is fixed by the top Yukawa coupling.

SUSY models based on the strong dynamics can have a larger coupling constant, so the deviation can be larger. (Toshifumi Yamada's talk)

Current status of MSSM EWBG

$\tilde{t}_1 =$ mostly right-handed.

- EWPT can be strong 1st order if $m_H \lesssim 127$ GeV, $m_{\tilde{t}_1} \lesssim 120$ GeV

[M. Carena, G. Nardini, M. Quiros, CEM. Wagner, NPB812, (2009) 243]

- This light stop scenario is now in tension with the current LHC data.

In this scenario, σ(gg -> H) ⤴, Γ(H->γγ) ⤵, Γ(H->VV) has no drastic change. ➔ Enhanced σ(gg -> H -> VV) is not favored by the LHC data.

[D. Curtin, P. Jaiswall, P. Meade., arXiv:1203.2932]

For $m_H \simeq 125$ GeV, MSSM EWBG is ruled out
at greater than 98% CL ($m_A > 1$ TeV),
at least 90% CL for light value of m_A (~300 GeV)

loophole

[M. Carena, G. Nardini, M. Quiros, CEM. Wagner, arXiv:1207.6330]

If $m_{\tilde{\chi}_1^0} \lesssim 60$ GeV, Higgs invisible decay mode is open.
➔ reduce σ(gg -> H -> VV) ➔ tension may be loosen.

MSSM EWBG is not fully excluded but is more and more unlikely.

Beyond the MSSM

- ❒ Next-to-MSSM (NMSSM) $W_{\rm NMSSM} \ni \lambda S H_u H_d + \frac{\kappa}{3} S^3$
- ❒ nearly-MSSM (nMSSM) $W_{\rm nMSSM} \ni \lambda S H_u H_d + \frac{m_{12}^2}{\lambda} S$
- ❒ U(1)'-extended-MSSM (UMSSM) $W_{\rm UMSSM} \ni \lambda S H_u H_d$

$\because$ 1st order EWPT is driven by singlet Higgs

- ❒ 4 Higgs doublets+singlets-extended MSSM (Toshifumi Yamada's talk)

$$W = \lambda \Big[H_d \Phi_u \zeta + H_u \Phi_d \eta - H_u \Phi_u \Omega^- - H_d \Phi_d \Omega^+ + n_\Phi \Phi_u \Phi_d + n_\Omega (\Omega^+ \Omega^- - \zeta\eta) \Big]$$
$$- \mu (H_u H_d - n_\Phi n_\Omega) - \mu_\Phi \Phi_u \Phi_d - \mu_\Omega (\Omega^+ \Omega^- - \zeta\eta).$$

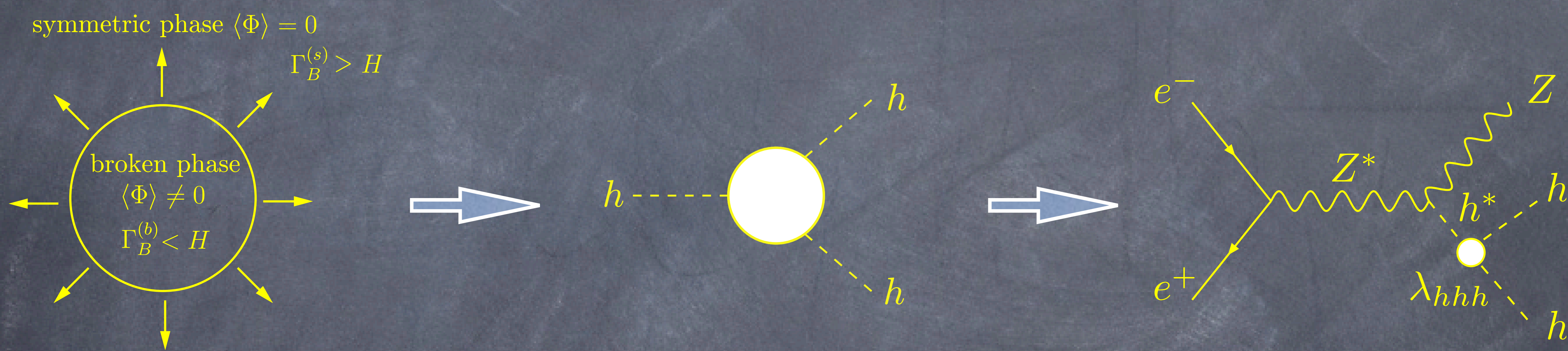
$\because$ 1st order EWPT is driven by extra charged Higgs

"In the beyond the MSSM, the light stop is not necessarily required to have the strong 1st order EWPT."

Summary

- SM EWBG was ruled out.
- Nondecoupling scalar is one of the possibilities to overcome the issue.
- Triple Higgs boson coupling is useful for probing the signal of EWBG.

2HDM: $\Delta\lambda_{hhh}/\lambda^{SM}_{hhh}$ is greater than (10-20)% if the EWTP is strong 1st order.



EW baryogenesis | Large corrections to λ_{hhh} | test @LC

- MSSM EWBG is not fully excluded but is more and more unlikely due to the recent LHC data. (light stop scenario is not favored.)
- In the beyond the MSSM (e.g. NMSSM etc.), the light stop is not necessarily required to have the strong 1st order EWPT.

Outlook

❒ To have the strong 1st order EWPT, the Higgs sector must be modified.

❒ Most of the EWBG scenarios would be tested by the LHC data., especially by

$$\frac{\sigma \cdot \mathrm{Br}}{(\sigma \cdot \mathrm{Br})_{\mathrm{SM}}}$$

❒ Tree-level mixing driven 1st order PT scenarios driven by $\lambda_{HS}|S|^2H^2$ (S ≠ inert) -> universal reduction of signal strengths.

❒ Thermal cubic term driven scenarios

-colored scalar loop -> enhancement of σ(gg -> H)

-charged scalar loop -> reduction of Γ(H->γγ)