F-term loop driven electroweak baryogenesis

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Collaboration with

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Ref. *Phys.Lett. B706 (2011) 40. [arXiv: 1109.5226]*

Outline

- Higgs physics/cosmology connections
  - Electroweak baryogenesis and Higgs self coupling
- SUSY 4 Higgs Doublet Model + charged singlets (4HDMΩ)
- Strong 1^{st} order EWPT and hhh coupling
- Summary

Higgs physics/Cosmology connection

❒ Higgs physics at colliders

- Discovery of the Higgs boson and mass measurement (@LHC) ~125 GeV?
- Measurements of the Higgs couplings with $\left\{ \begin{array}{l} \text{gauge bosons} \\ \text{fermions} \end{array} \right.$ mass generation
- Measurements of the Higgs self couplings (access to Higgs potential)

  Existence of the hhh coupling $\Longleftrightarrow$ test of EW symmetry breaking.
- etc

❒ cosmology

- Baryon Asymmetry of the Universe (BAU) $\frac{n_B}{s} \simeq 10^{-11}$

  Lots of attempts: GUT, Lepotogenesis, Electroweak baryogenesis etc.

<u>connection with collider physics</u>

$\boxed{\text{Electroweak baryogenesis}}$

Higgs potential at T≠0.

⇓ remnant appears!

$\boxed{\text{Higgs self couplings}}$

Higgs potential at T=0.

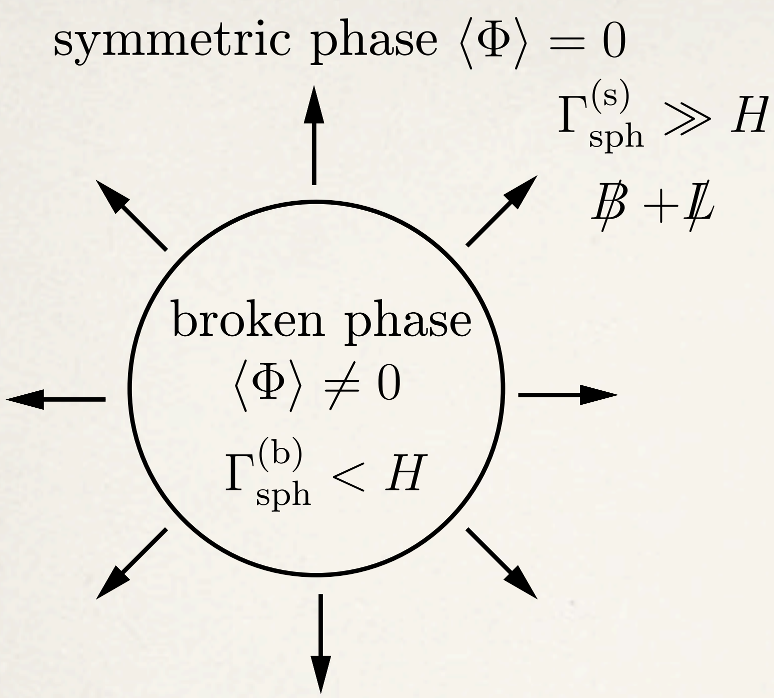
e.g., 2HDM case
[PLB606 (2005) 361, S. Kanemura, Y. Okada, E.S.]

If EW phase transition is a strong 1st order, λ_{hhh} would receive large quantum corrections!

"Nondecoupling loop effect plays a central role."

We consider such a possibility in a SUSY model.

Electroweak baryogenesis



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

Baryogenesis could occur if EWPT is of 1st order.

Sakharov's conditions

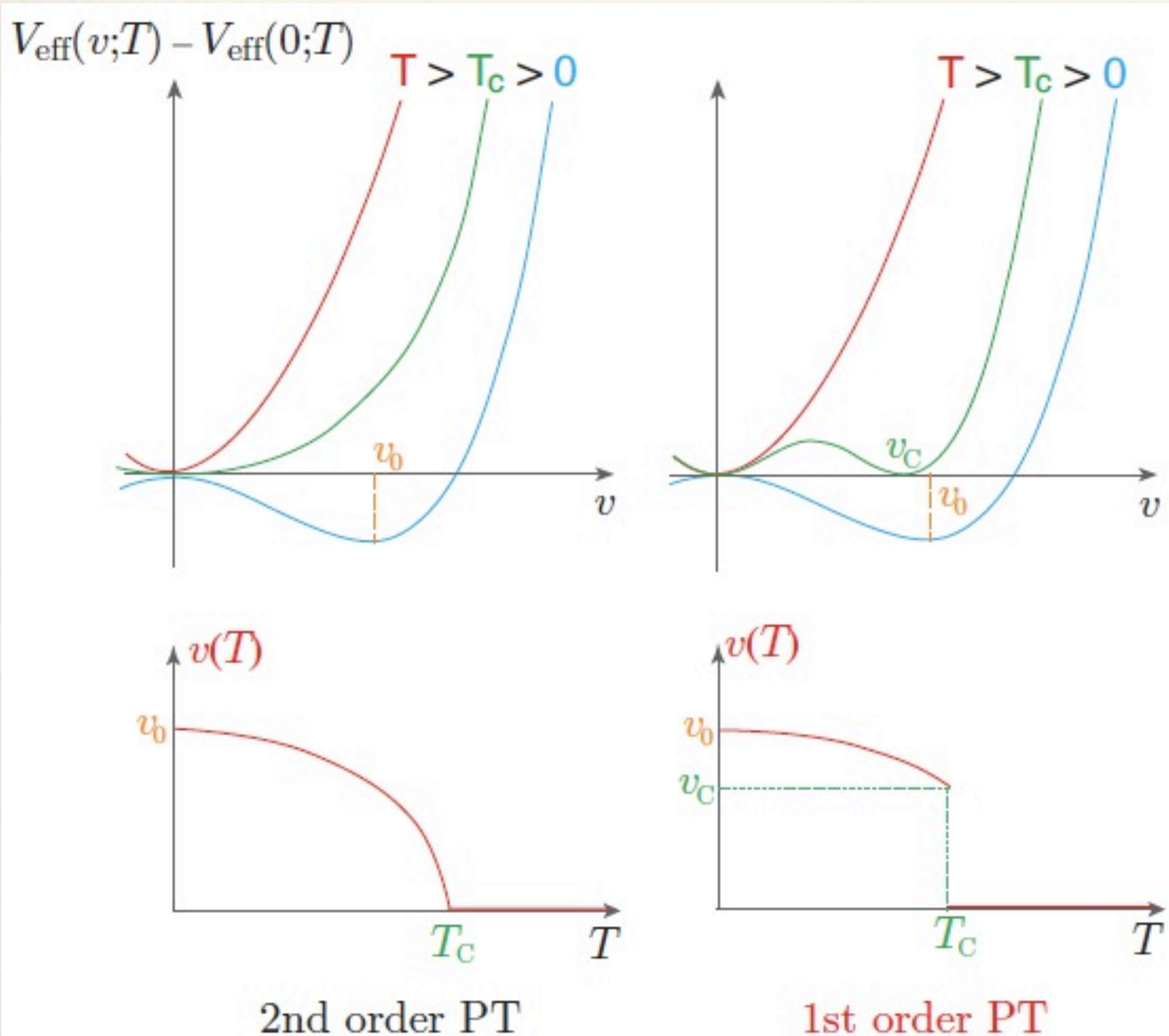
- B violation: anomalous process at finite temperature (sphaleron)
- C violation: chiral gauge interaction
- CP violation: KM phase and/or other sources in beyond the SM
- Out of equilibrium: 1st order EW phase transition (EWPT) with expanding bubble walls -> linked to Higgs physics (today's topic)

well-known fact: Standard Model EWBG was ruled out.

$\because$ KM phase is too small and EWPT is not 1st order for m_h>114.4.

Order of PT

❒ Effective potential (free energy density) is used to study the EWPT.



[From K. Funakubo's slide]

- order parameter = Higgs VEV

- EWBG requires 1st order PT

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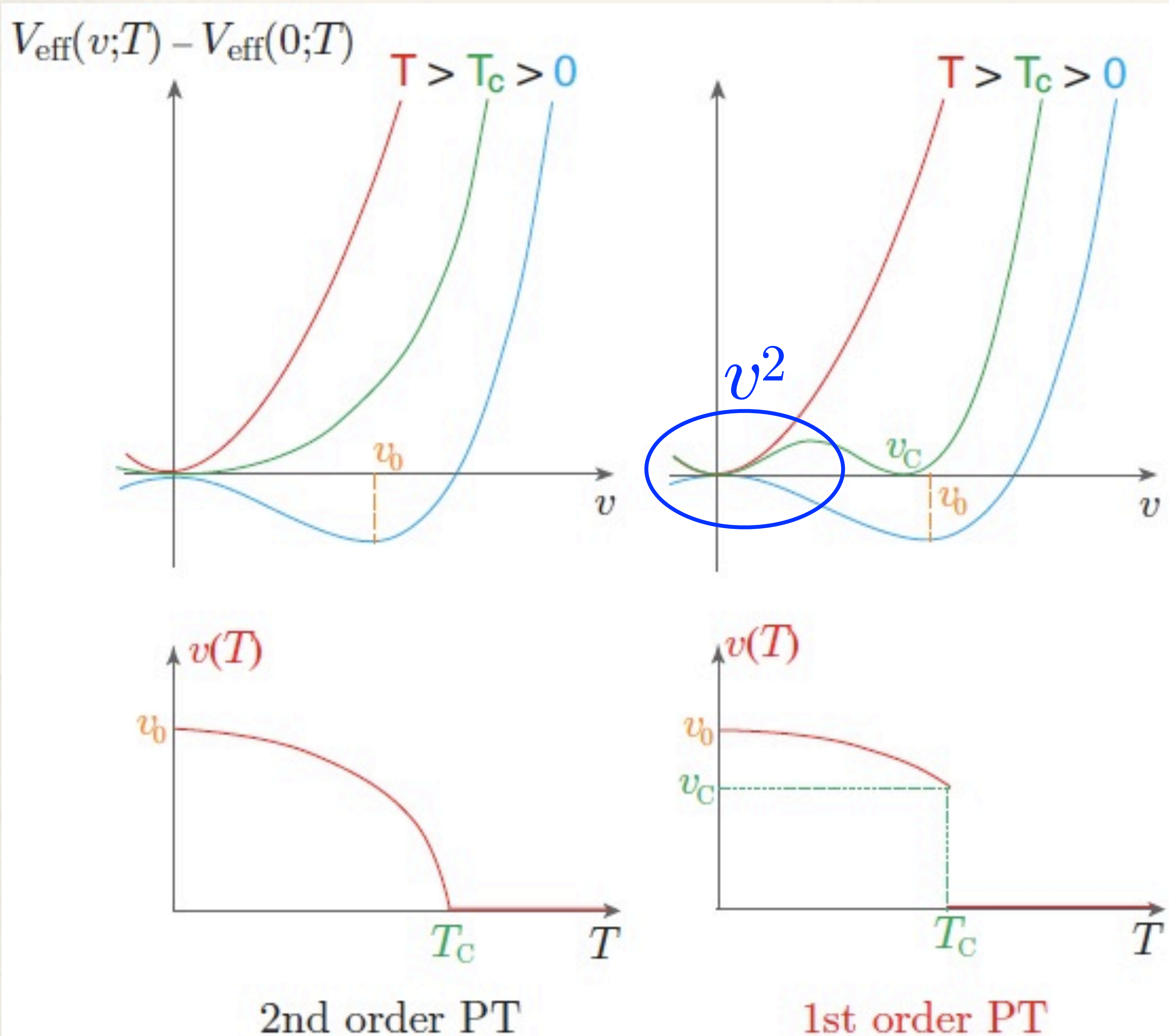

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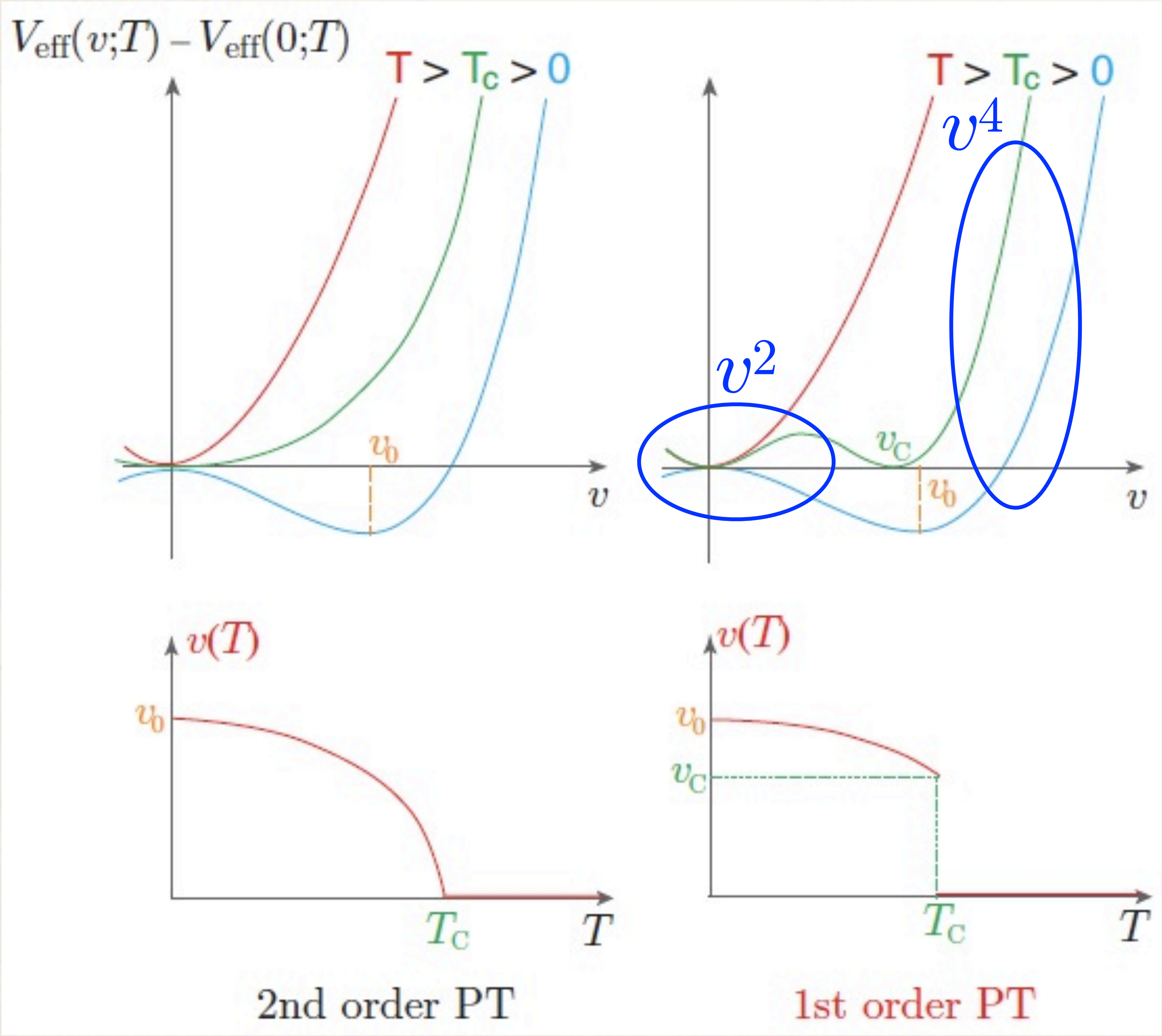

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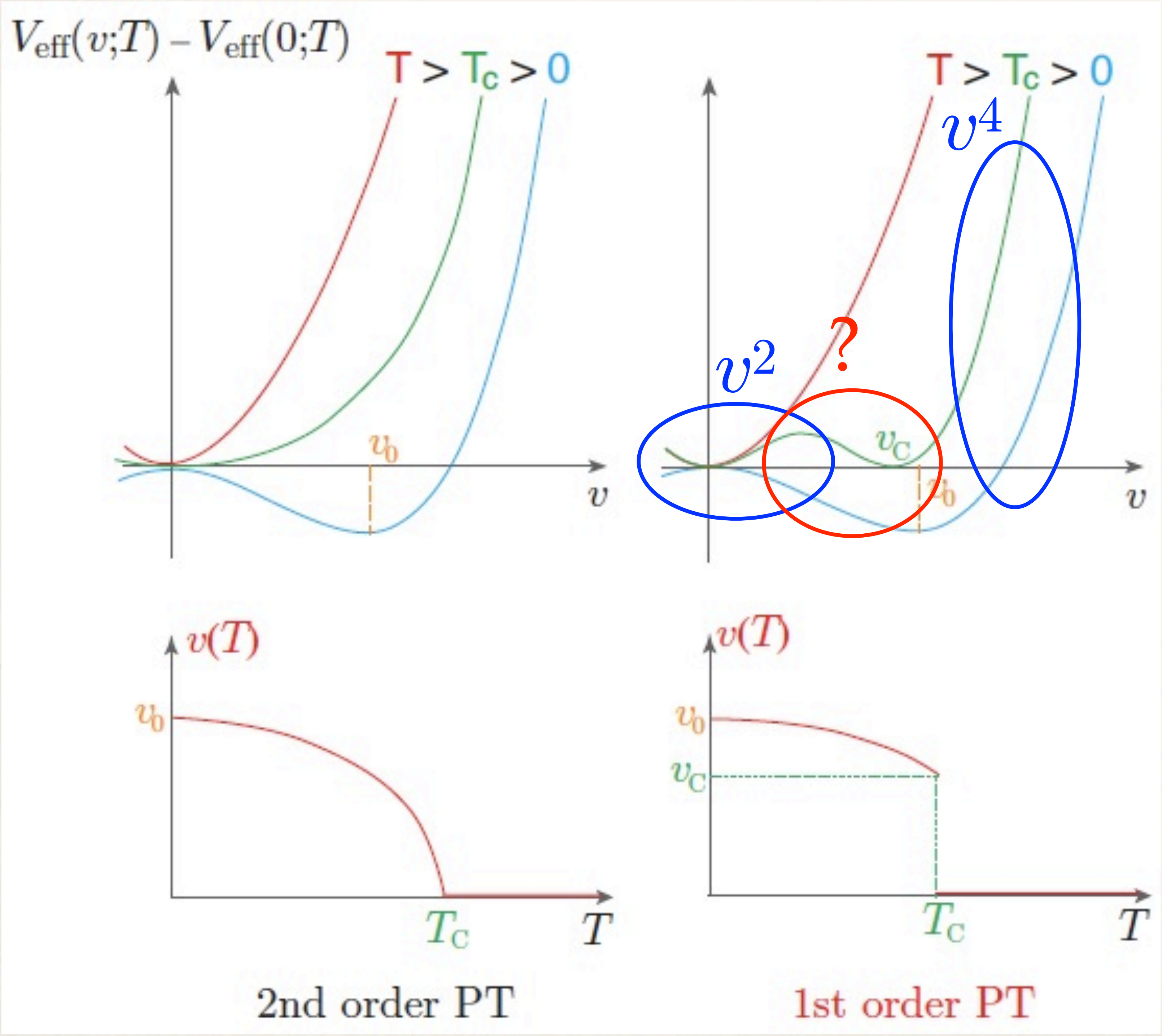

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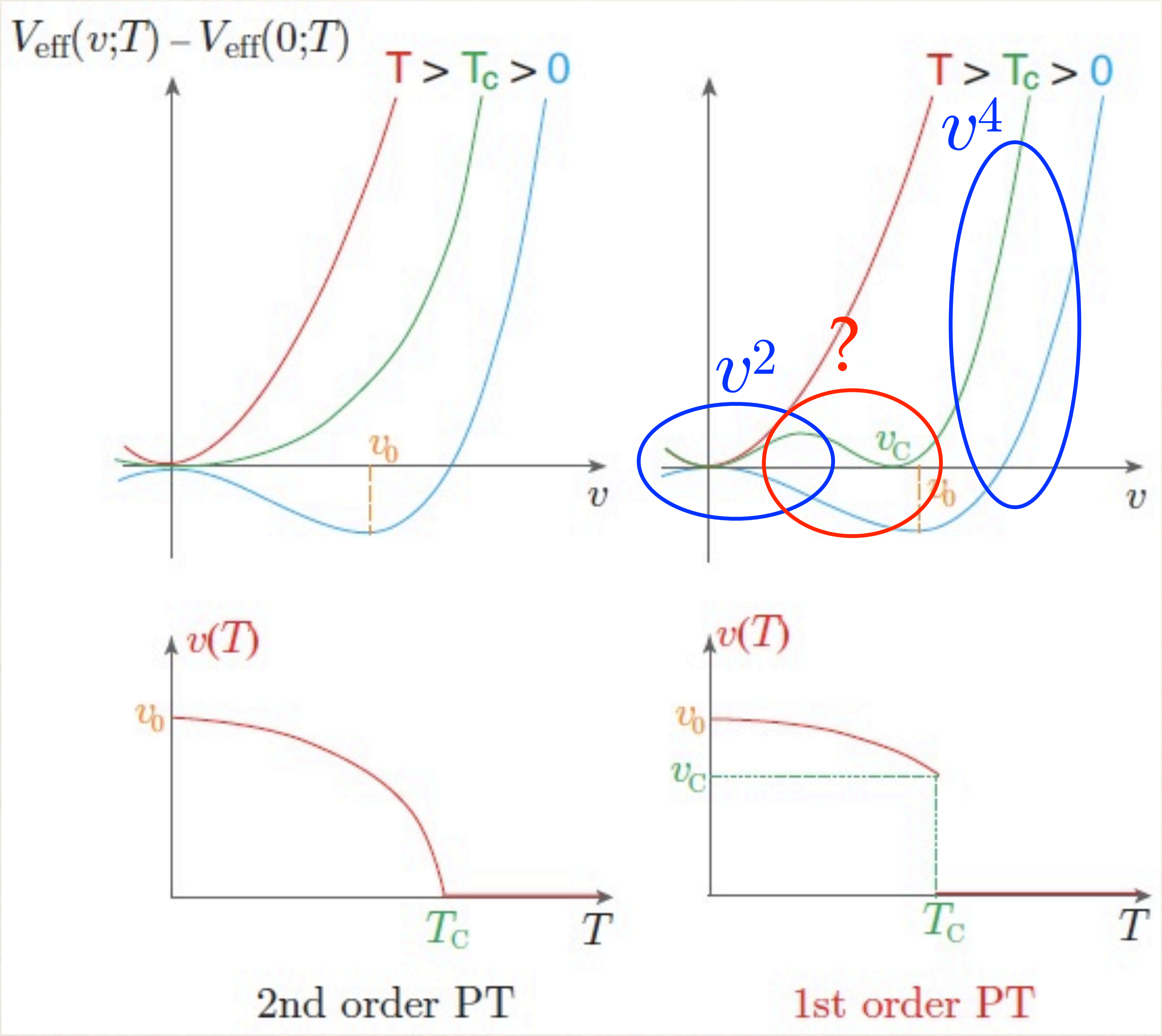

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- order parameter = Higgs VEV

- EWBG requires 1st order PT

- To get a 1st order PT, there must be a negative contribution in the potential.

Order of PT

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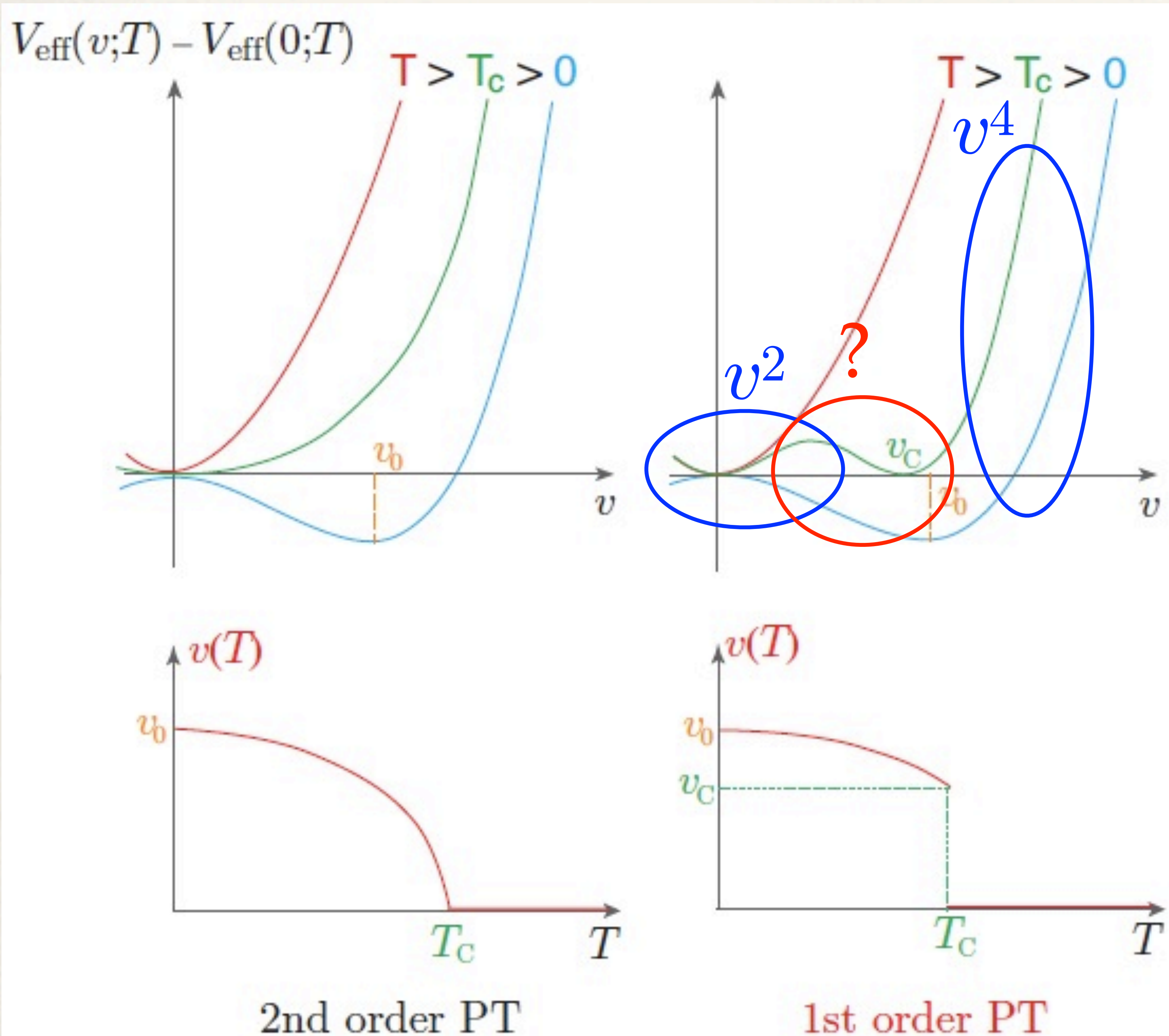

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⇑

thermal boson loop

1-loop thermal potential

$$V_1(\varphi, T) = \sum_i \frac{T^4}{2\pi^2}\Big[n_B I_B(a_i^2) + n_F I_F(a_i^2)\Big], \quad I_{B,F}(a^2) = \int_0^\infty dx\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2+a^2}}\right).$$

boson fermion

$$a = \frac{m(\varphi)}{T}, \quad m(\varphi) = \frac{\partial^2 V_0}{\partial \varphi^2}$$

High-T expansion

❐ For a small $a = m/T$, $I_{BF}(a^2)$ can be expanded in powers of a^2.

$$I_B^{\mathrm{HTE}}(a^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{32}\left(\log\frac{a^2}{\alpha_B} - \frac{3}{2}\right) + \mathcal{O}(a^6),$$

$$I_F^{\mathrm{HTE}}(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{32}\left(\log\frac{a^2}{\alpha_F} - \frac{3}{2}\right) + \mathcal{O}(a^6).$$

❐ Boson loop gives a cubic term with a negative coefficient, which comes from the zero frequency mode.

$$\omega_n = 2n\pi T \text{ for boson} \qquad \textit{cf.}\ \omega_n = (2n+1)\pi T \text{ for fermion}$$

As a simplest example, we consider the EWPT in the SM.

1-loop thermal potential

$$V_1(\varphi,T)=\sum_i \frac{T^4}{2\pi^2}\Big[\underbrace{n_B I_B(a_i^2)}_{\text{boson}}+\underbrace{n_F I_F(a_i^2)}_{\text{fermion}}\Big],\quad I_{B,F}(a^2)=\int_0^\infty dx\, x^2 \ln\left(1\mp e^{-\sqrt{x^2+a^2}}\right).$$

$$a=\frac{m(\varphi)}{T},\quad m(\varphi)=\frac{\partial^2 V_0}{\partial\varphi^2}$$

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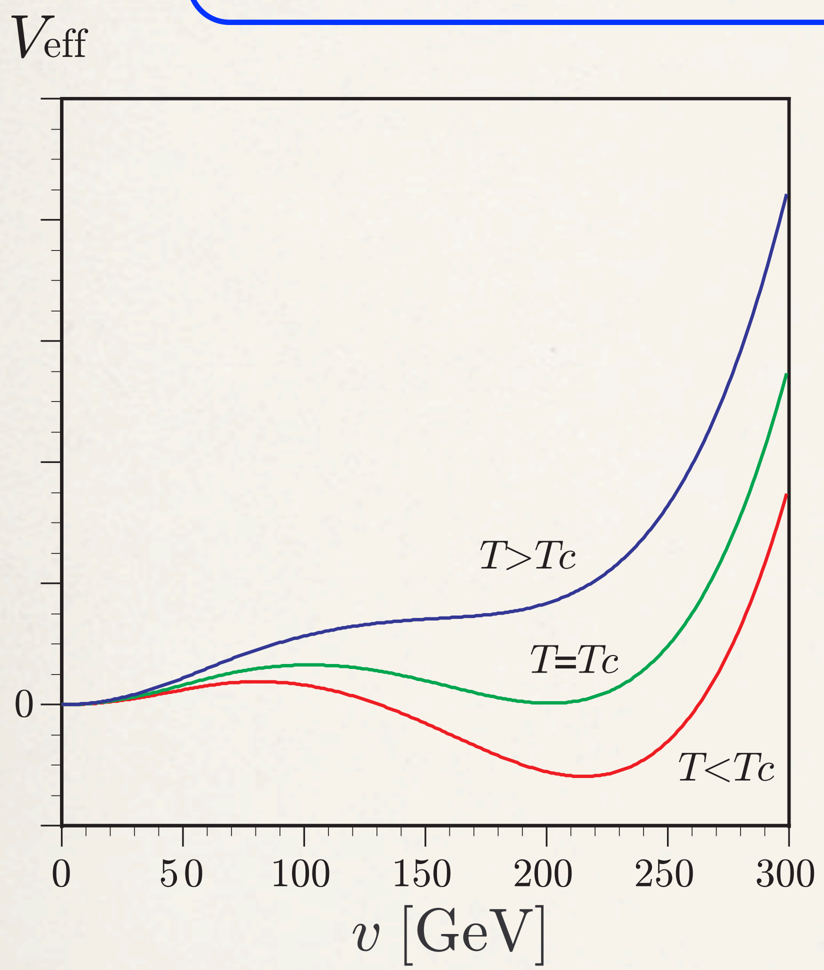
SM EWPT

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



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

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

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

To keep the generated baryon asymmetry, we need

$$\Gamma^{(b)}_{\rm sph} < H \;\Rightarrow\; v_C/T_C > \zeta \;\xrightarrow{\zeta=1}\; m_{h_{\rm SM}} \lesssim 48\ \text{GeV}$$

SM EWBG was ruled out.

- ❐ Light Higgs boson (small λ) is required.
- ❐ Additional bosons (ΔE) can rescue this situation.

Caveat

"scalar does not always play a role."

Suppose that the mass of the scalar is given by

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

M : mass parameter in the Lagrangian,

λ : coupling constant

If $M^2 \ll \lambda v^2$ $\quad V_{\text{eff}} \ni -\lambda^{3/2} T v^3 \left(1 + \frac{M^2}{\lambda v^2}\right)^{3/2}$ It helps.

If $M^2 \gg \lambda v^2$ $\quad V_{\text{eff}} \ni -|M|^3 T \left(1 + \frac{\lambda v^2}{M^2}\right)^{3/2}$ It doesn't

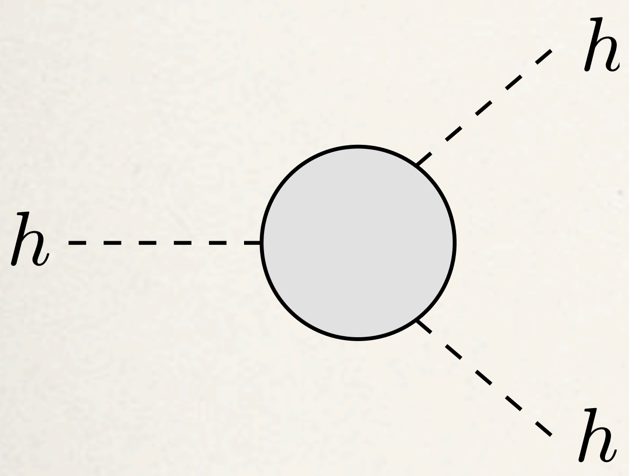
$$\boxed{\text{Requirements: 1. large coupling } \lambda, \text{ 2. small } M.}$$

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

Correlation between $\Delta\lambda_{hhh}$ and v_C/T_C in the 2HDM

Let us consider the quantum corrections to the hhh coupling.

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



For $\sin(\beta-\alpha)=1$

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

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

$$m_\Phi^2 \simeq M^2+\lambda_i v^2, \quad M^2 = m_3^2/(\sin\beta\cos\beta).$$

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.

⇒ nondecoupling loop effect. (note: smaller m_h is preferable.)

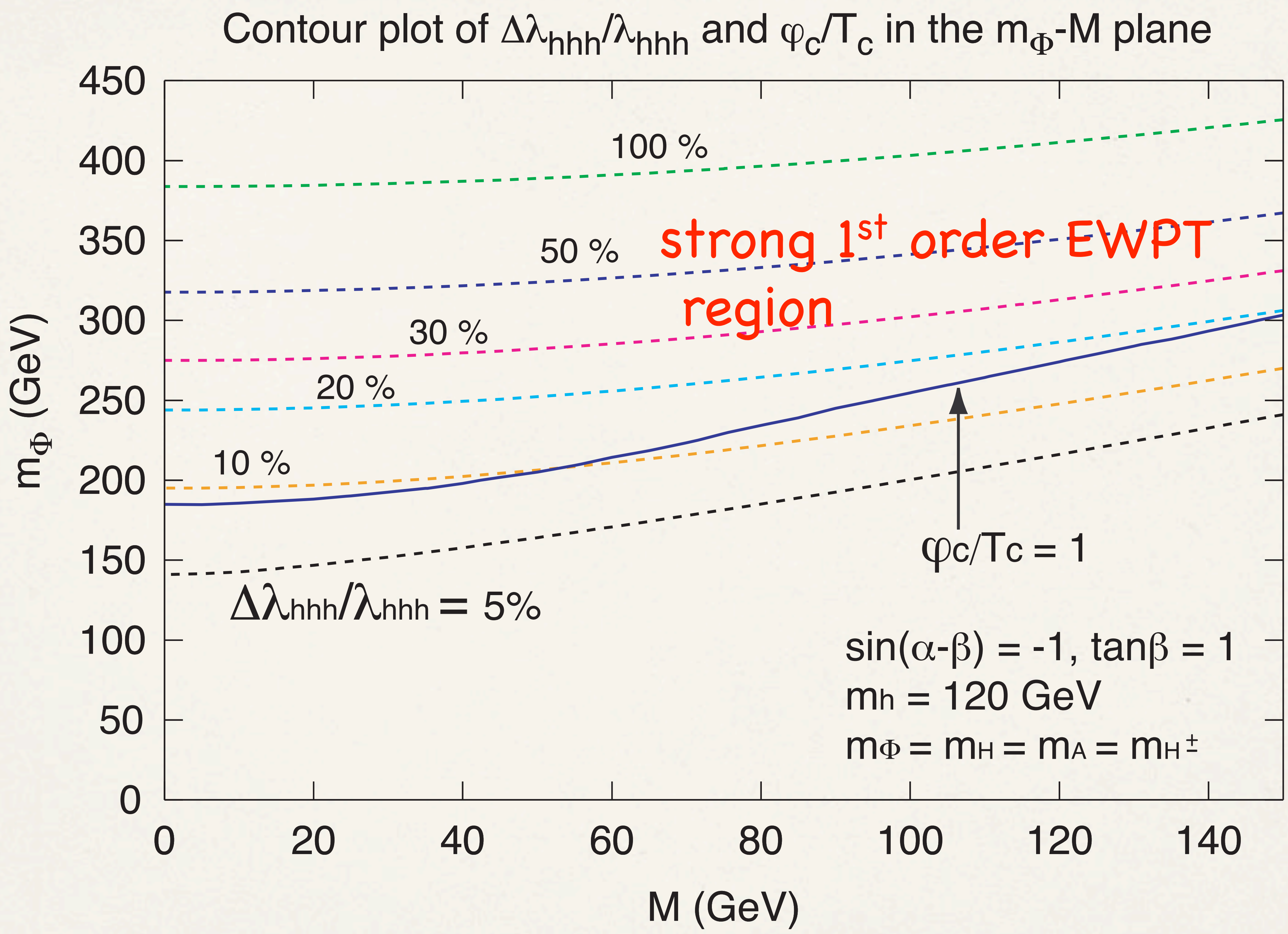
For $M^2 \gg \lambda_i v^2$ ($m_\Phi^2 \simeq M^2$), the quantum corrections would be suppressed.

⇒ ordinary decoupling limit

Obvious strong correlation between enhancement of v_C/T_C and the large quantum corrections to λ_{hhh}!!

Correlation between $\Delta\lambda_{hhh}$ and v_C/T_C in the 2HDM

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



- ❒ If EWPT is the strong 1st first order, $\Delta\lambda_{hhh}/\lambda^{SM}_{hhh}$ is more than 10%.
- ❒ This correlation is due to the nondecoupling effects of the heavy Higgs bosons.

4HDMΩ

particle content = MSSM+2 doublets+2 charged singlets

	Spin 0	Spin 1/2	SU(3)	SU(2)	$\mathrm{U}(1)_Y$	Z_2
H_1	$\Phi_1 = \begin{pmatrix} \varphi_1^0 \\ \varphi_1^- \end{pmatrix}$	$\tilde{\Phi}_{1L} = \begin{pmatrix} \tilde{\varphi}_{1L}^0 \\ \tilde{\varphi}_{1L}^- \end{pmatrix}$	**1**	**2**	$-\frac{1}{2}$	$+$
H_2	$\Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \varphi_2^0 \end{pmatrix}$	$\tilde{\Phi}_{2L} = \begin{pmatrix} \tilde{\varphi}_{2L}^+ \\ \tilde{\varphi}_{2L}^0 \end{pmatrix}$	**1**	**2**	$+\frac{1}{2}$	$+$
H_3	$\Phi_3 = \begin{pmatrix} \varphi_3^0 \\ \varphi_3^- \end{pmatrix}$	$\tilde{\Phi}_{3L} = \begin{pmatrix} \tilde{\varphi}_{3L}^0 \\ \tilde{\varphi}_{3L}^- \end{pmatrix}$	**1**	**2**	$-\frac{1}{2}$	$-$
H_4	$\Phi_4 = \begin{pmatrix} \varphi_4^+ \\ \varphi_4^0 \end{pmatrix}$	$\tilde{\Phi}_{4L} = \begin{pmatrix} \tilde{\varphi}_{4L}^+ \\ \tilde{\varphi}_{4L}^0 \end{pmatrix}$	**1**	**2**	$+\frac{1}{2}$	$-$
Ω_1	ω_1^+	$\overline{\tilde{\omega}}_1^-$	**1**	**1**	$+1$	$-$
Ω_2	ω_2^-	$\tilde{\omega}_2^-$	**1**	**1**	-1	$-$

Superpotential

$$W = (y_u)^{ij} U_i^c H_2 \cdot Q_j + (y_d)^{ij} D_i^c H_1 \cdot Q_j + (y_e)^{ij} E_i^c H_1 \cdot L_j$$
$$+ \lambda_1 \Omega_1 H_1 \cdot H_3 + \lambda_2 \Omega_2 H_2 \cdot H_4$$
$$- \mu H_1 \cdot H_2 - \mu' H_3 \cdot H_4 - \mu_\Omega \Omega_1 \Omega_2.$$

Higgs potential

$$
\begin{aligned}
V_0 = {} & V_F|_{\text{Higgs}} + V_D|_{\text{Higgs}} - \mathcal{L}_{\text{soft}}|_{\text{Higgs}} \\
& + \bar{m}_1^2 \Phi_1^\dagger \Phi_1 + \bar{m}_2 \Phi_2^\dagger \Phi_2 + \bar{m}_3^2 \Phi_3^\dagger \Phi_3 + \bar{m}_4^2 \Phi_4^\dagger \Phi_4 + \bar{m}_+^2 \omega_1^+ \omega_1^- + \bar{m}_-^2 \omega_2^+ \omega_2^- \\
& + \epsilon_{ij} \Big[B\mu \Phi_1^i \Phi_2^j + B'\mu' \Phi_3^i \Phi_4^j + B_\Omega \mu_\Omega \omega_1^+ \omega_2^- + A_1 \omega_1^+ \Phi_1^i \Phi_3^j + A_2 \omega_2^- \Phi_2^i \Phi_4^j + \text{h.c.} \Big]
\end{aligned}
$$

$V_F|_{\text{Higgs}}$

$$
\begin{aligned}
& + |\lambda_1|^2 |\epsilon_{ij} \Phi_1^i \Phi_3^j|^2 + |\lambda_2|^2 |\epsilon_{ij} \Phi_2^i \Phi_4^j|^2 + |\lambda_1|^2 \omega_1^+ \omega_1^- (\Phi_1^\dagger \Phi_1 + \Phi_3^\dagger \Phi_3) \\
& + |\lambda_2|^2 \omega_2^+ \omega_2^- (\Phi_2^\dagger \Phi_2 + \Phi_4^\dagger \Phi_4) + \Big[- \lambda_1 \mu^* \omega_1^+ \Phi_2^\dagger \Phi_3 + \lambda_2 \mu^* \omega_2^- \Phi_1^\dagger \Phi_4 + \lambda_1 \mu'^* \omega_1^+ \Phi_4^\dagger \Phi_1 \\
& - \lambda_2 \mu'^* \omega_2^- \Phi_3^\dagger \Phi_2 - \epsilon_{ij} \lambda_1 \mu_\Omega^* \omega_2^+ \Phi_1^i \Phi_3^j - \epsilon_{ij} \lambda_2 \mu_\Omega^* \omega_1^- \Phi_2^i \Phi_4^j + \text{h.c.} \Big]
\end{aligned}
$$

$V_D|_{\text{Higgs}}$

$$
\begin{aligned}
& + \frac{g^2 + g'^2}{8} (-\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 - \Phi_3^\dagger \Phi_3 + \Phi_4^\dagger \Phi_4)^2 \\
& + \frac{g^2}{2} \Big[(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + (\Phi_1^\dagger \Phi_3)(\Phi_3^\dagger \Phi_1) + (\Phi_1^\dagger \Phi_4)(\Phi_4^\dagger \Phi_1) + (\Phi_2^\dagger \Phi_3)(\Phi_3^\dagger \Phi_2) \\
& \qquad + (\Phi_2^\dagger \Phi_4)(\Phi_4^\dagger \Phi_2) + (\Phi_3^\dagger \Phi_4)(\Phi_4^\dagger \Phi_3) - (\Phi_1^\dagger \Phi_1)(\Phi_3^\dagger \Phi_3) - (\Phi_2^\dagger \Phi_2)(\Phi_4^\dagger \Phi_4) \Big] \\
& + \frac{g'^2}{2} (-\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 - \Phi_3^\dagger \Phi_3 + \Phi_4^\dagger \Phi_4)(\omega_1^+ \omega_1^- - \omega_2^+ \omega_2^-) + \frac{g'^2}{2} (\omega_1^+ \omega_1^- - \omega_2^+ \omega_2^-)^2 .
\end{aligned}
$$

❒ Sizes of the F-term contributions depend on the λ couplings.
c.f. D-term contributions are limited by the gauge couplings.

Mass formulae of the Z_2-odd charged particles

Z_2-odd charged Higgs

$$m^2_{\Phi'^\pm_1} = \bar{m}^2_4 - \frac{m_Z^2 - 2m_W^2}{2} c_{2\beta} + \boxed{\frac{\lambda_2^2 s_\beta^2}{2}} v^2, \qquad m^2_{\Omega^\pm_1} = \bar{m}^2_- + (m_Z^2 - m_W^2) c_{2\beta} + \boxed{\frac{\lambda_2^2 s_\beta^2}{2}} v^2,$$

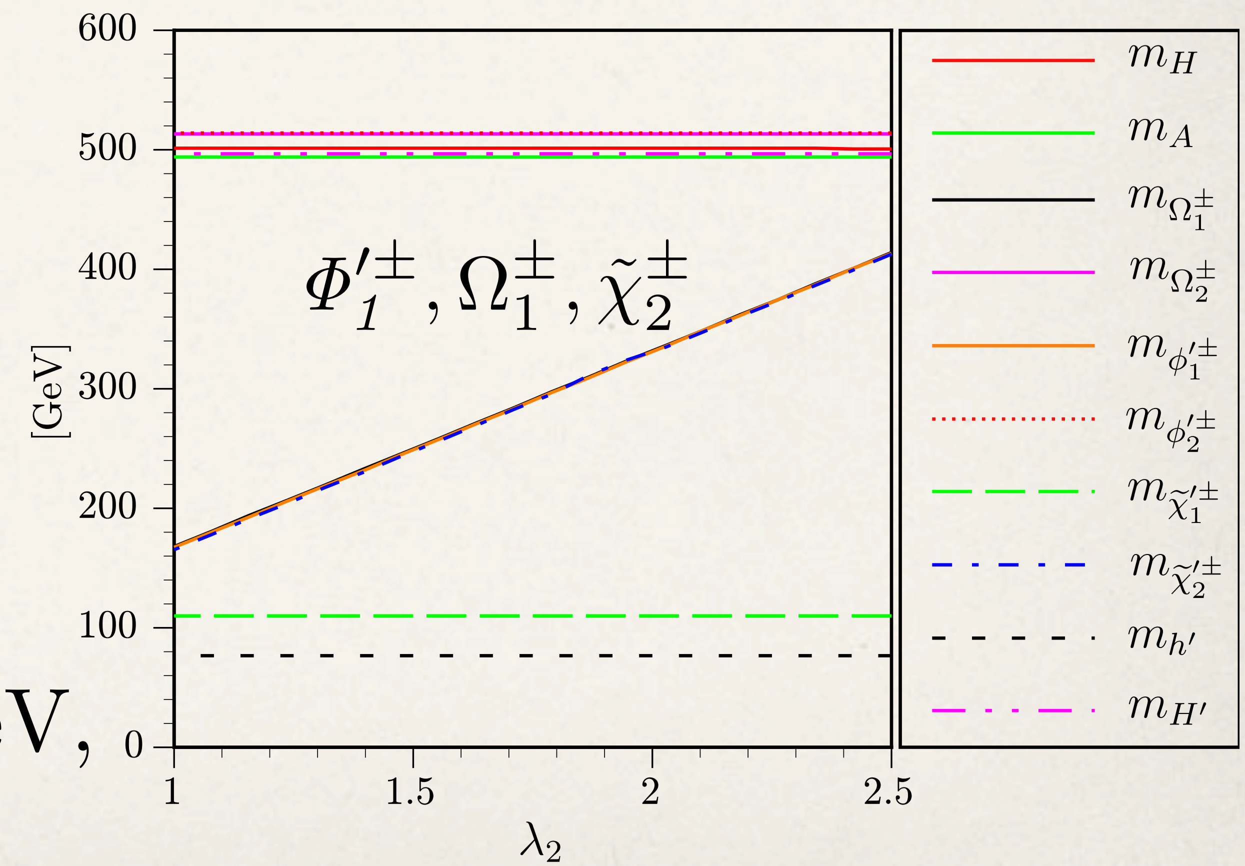
$$m^2_{\Phi'^\pm_2} = \bar{m}^2_3 + \frac{m_Z^2 - 2m_W^2}{2} c_{2\beta} + \frac{\lambda_1^2 c_\beta^2}{2} v^2, \qquad m^2_{\Omega^\pm_2} = \bar{m}^2_+ - (m_Z^2 - m_W^2) c_{2\beta} + \frac{\lambda_1^2 c_\beta^2}{2} v^2,$$

Z_2-odd charginos

$$m^2_{\tilde{\chi}'^\pm_1} = \frac{\lambda_1^2 v^2 c_\beta^2}{2}, \qquad m^2_{\tilde{\chi}'^\pm_2} = \boxed{\frac{\lambda_2^2 v^2 s_\beta^2}{2}}.$$

For $\tan\beta > 1$, $\lambda_1^2 \cos^2\beta \ll \lambda_2^2 \sin^2\beta$, (if $\lambda_1 \sim \lambda_2$).

$$\tan\beta = 3,$$
$$\lambda_1 = 2, \qquad \mu' = \mu_\Omega = B_\Omega = B' = 0,$$
$$\bar{m}^2_+ = \bar{m}^2_3 = (500\ \text{GeV})^2,$$
$$\bar{m}^2_- = \bar{m}^2_4 = (50\ \text{GeV})^2.$$



$m_{\Phi'^\pm_1} \simeq m_{\Omega^\pm_1} \simeq m_{\tilde{\chi}^\pm_2} = 160\text{–}400$ GeV, for $\lambda_2 = 1 - 2.5$.

Λ_{cutoff} = 2 TeV (for λ_2 = 2.5) [S. Kanemura, T. Shindou, K. Yagyu, 2010]

Lightest Higgs boson mass

1-loop corrected lightest Higgs boson mass-squared

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + (\text{MSSM-loop}) + \frac{\lambda_1^4 v^2 c_\beta^4}{16\pi^2} \ln \frac{m^2_{\Omega_2^\pm} m^2_{\Phi_2'^\pm}}{m^4_{\bar{\chi}_1'^\pm}} + \frac{\lambda_2^4 v^2 s_\beta^4}{16\pi^2} \ln \frac{m^2_{\Omega_1^\pm} m^2_{\Phi_1'^\pm}}{m^4_{\bar{\chi}_2'^\pm}},$$

$\tilde{M}_{\tilde{q}} = \tilde{M}_{\tilde{b}} = \tilde{M}_{\tilde{t}} = 1000$ GeV, $m_{H^\pm} = 500$ GeV;

$\mu = M_2 = 2M_1 = 200$ GeV,

$A_t = A_b = X_t + \mu/\tan\beta$;

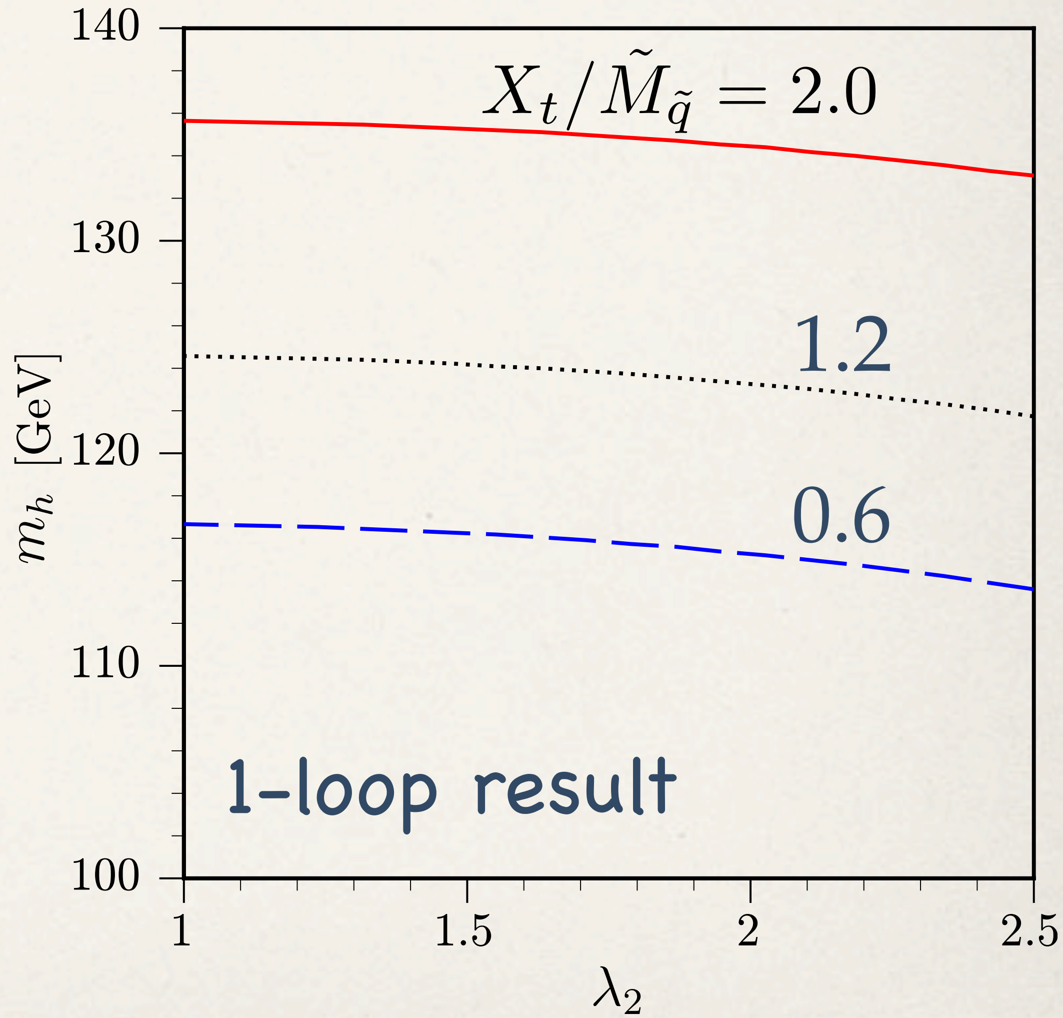
❐ Dependence of the Z_2-odd particle loops on m_h is mild even in the large λ_1 and λ_2.

$\Downarrow$

nice feature for strong 1st order PT

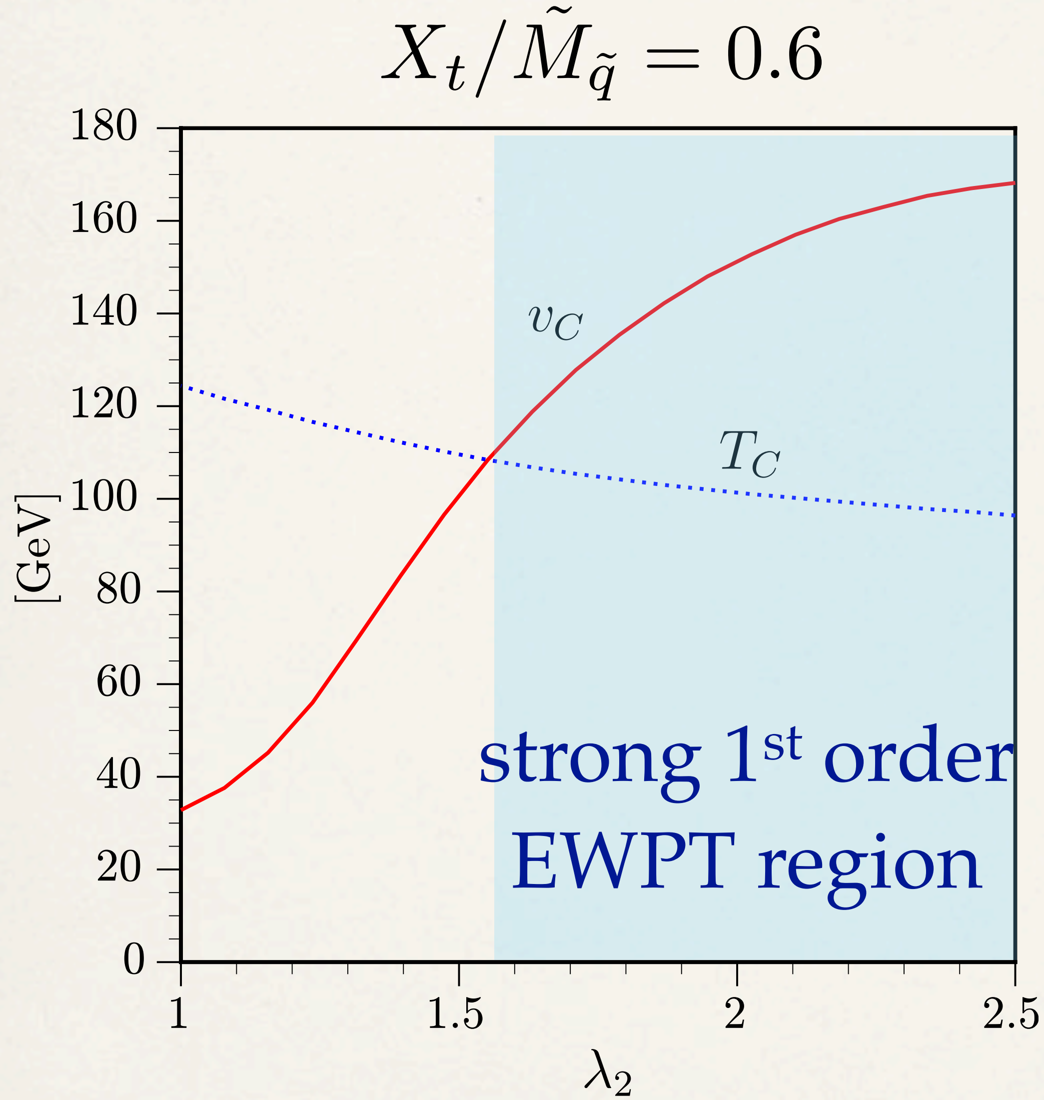
$\left\{\begin{array}{l}\text{Lighter Higgs boson} \\ \text{nondecoupling heavy Higgs boson}\end{array}\right.$

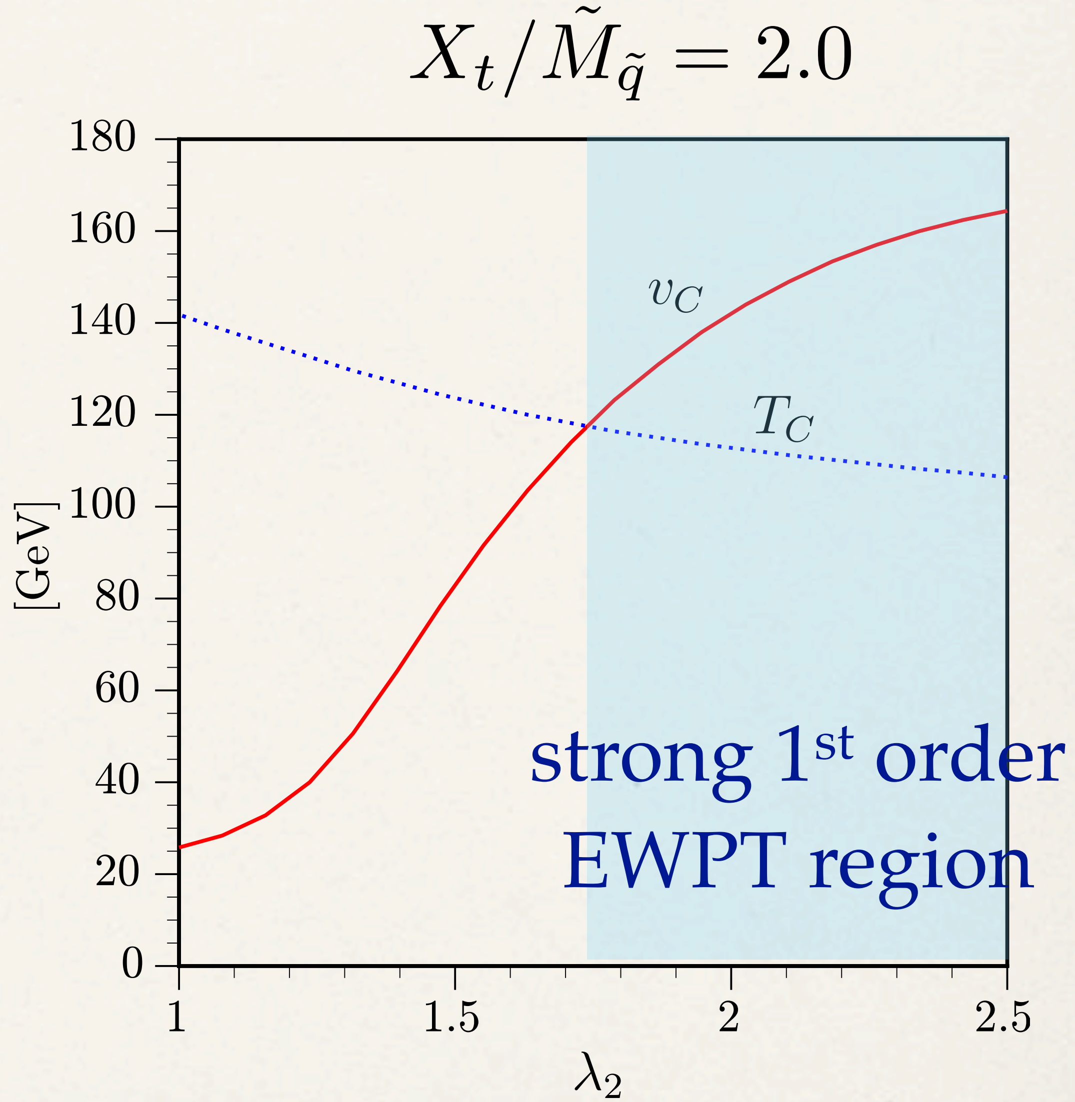
⇨ enhance v_C/T_C



v_C/T_C vs. λ_2

❒ v_C/T_C is calculated using the resummed 1-loop effective potential. (high-T expansion is not used here.)





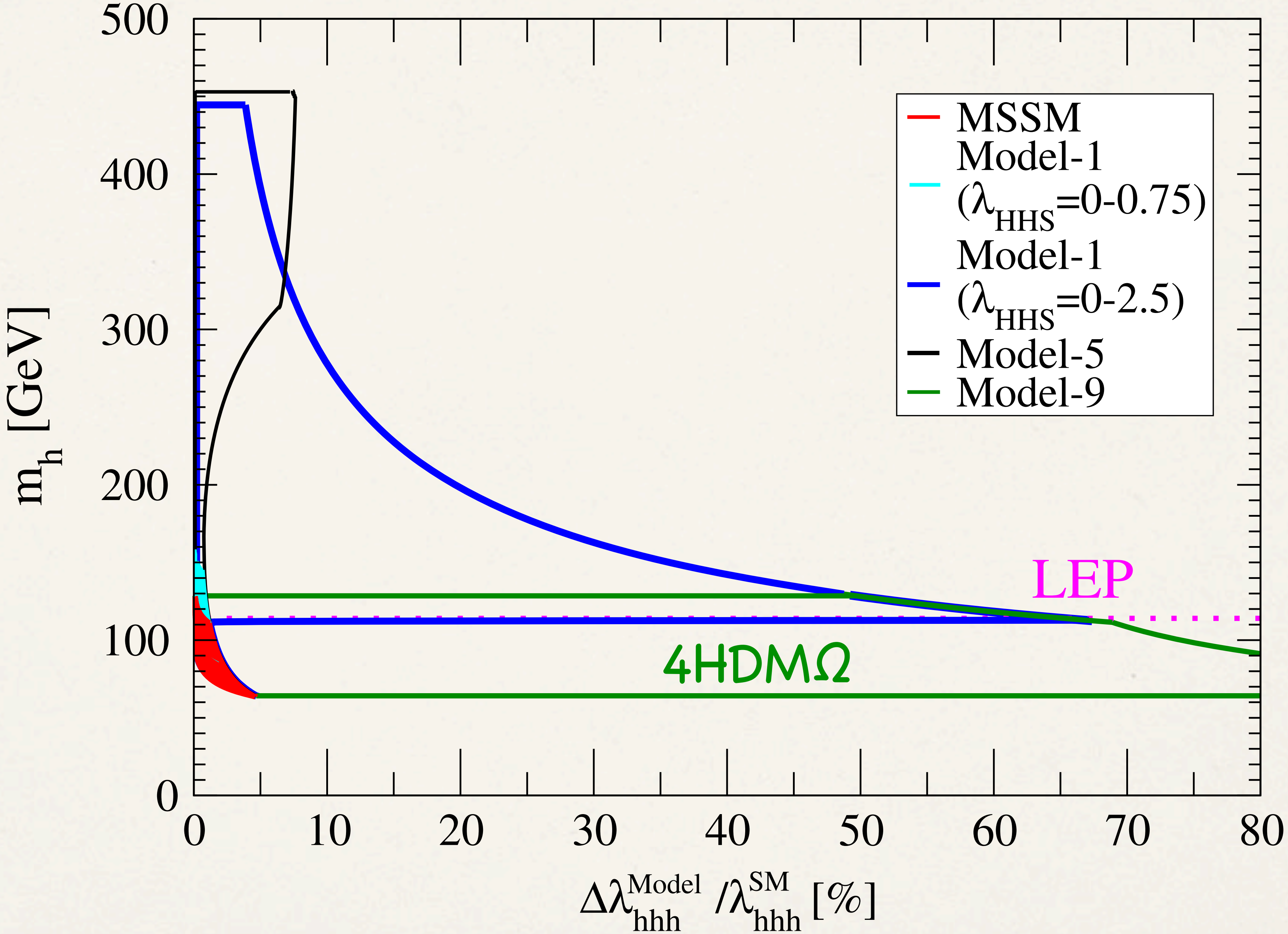
❒ 1st order EWPT gets stronger as λ_2 increases.

❒ Enhancement of v_C/T_C is due to the Z_2-odd charged Higgs loops.

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

❒ Extensive studies of $\Delta\lambda_{hhh}/\lambda^{SM}_{hhh}$ in various SUSY models.

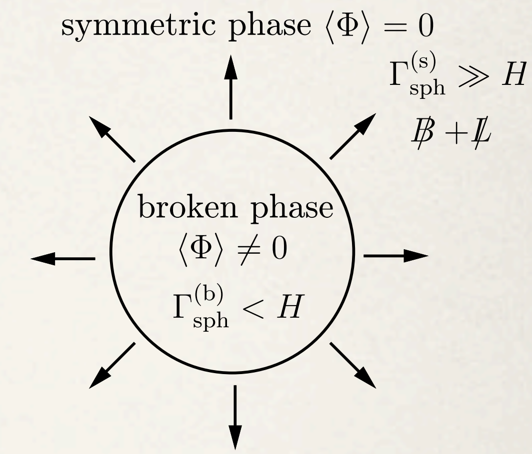
[S. Kanemura, T. Shindou, K, Yagyu, PLB699 (2011) 258]



❒ 4HDMΩ (Model-9) predicts the large $\Delta\lambda_{hhh}/\lambda^{SM}_{hhh}$ which can reach around 50% for m_h=125 GeV.

❒ Nondecoupling loop effect of the Z_2-odd particles is essential.

Summary



- We consider 4HDMΩ.
- EWPT can be strong 1st order.
- $\Delta\lambda_{hhh} / \lambda^{SM}_{hhh}$ can reach 50% for m_h=125 GeV
- Both are due to the nondecoupling loop effects of Z_2-odd charged Higgs bosons.
- Such large deviation of the λ_{hhh} coupling can be measurable at the ILC.

EW baryogenesis

$\Downarrow$

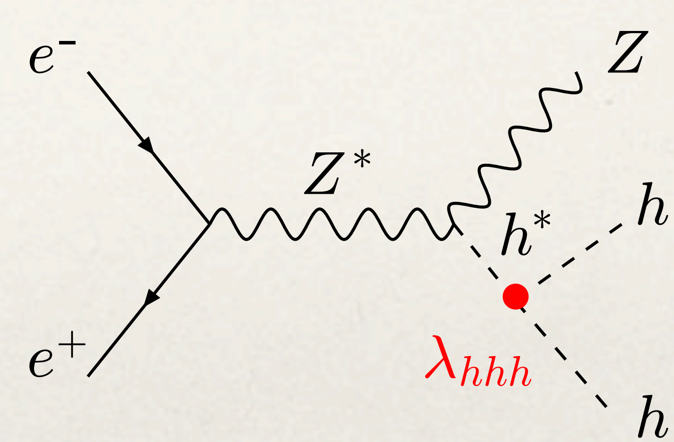
Strong 1st order PT $\quad V_{\rm eff}(\varphi, T)$

$\Downarrow$

Large loop corrections to the λ_{hhh} coupling $\quad V_{\rm eff}(\varphi, T=0)$

$\Downarrow$

Measurement of λ_{hhh} at the ILC



status of MSSM EWBG

❒ Electroweak phase transition is strong 1st order if

$$m_H \lesssim 127 \text{ GeV}, \; m_{\tilde{t}_1} \lesssim 120 \text{ GeV}$$

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

BUT,

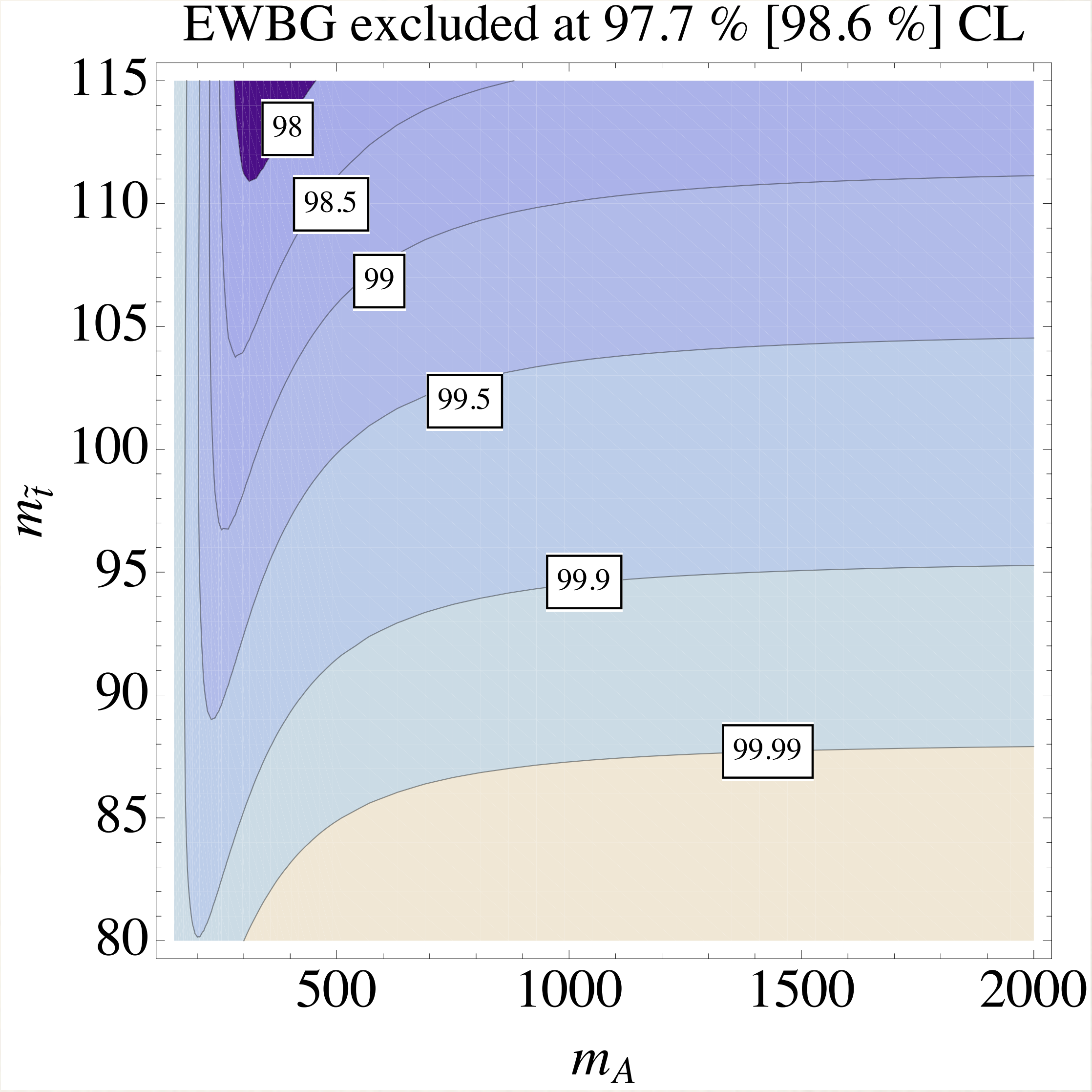
[D. Curtin, P. Jaiswall, P. Meade., arXiv:1203.2932]

* For $m_h \approx 125$ GeV,

  MSSM EWBG is ruled out
  at greater than 97.7% CL.

* Region excluded at "less than 90% CL" is $m_h \approx 117$ - 119 GeV.

  (80-85% CL)



Incidentally, in the NMSSM, so-called type-B phase transition is still viable since light stop ($<m_t$) is not necessarily required.
[K.Funakubo, S. Tao, F. Toyoda., PTP114,369 (2005)]

For a recent study, Singlino-driven EWBG in the NMSSM, K.Cheung et al, PLB710 (2012) 188