Phase Transitions in Twin Higgs Models

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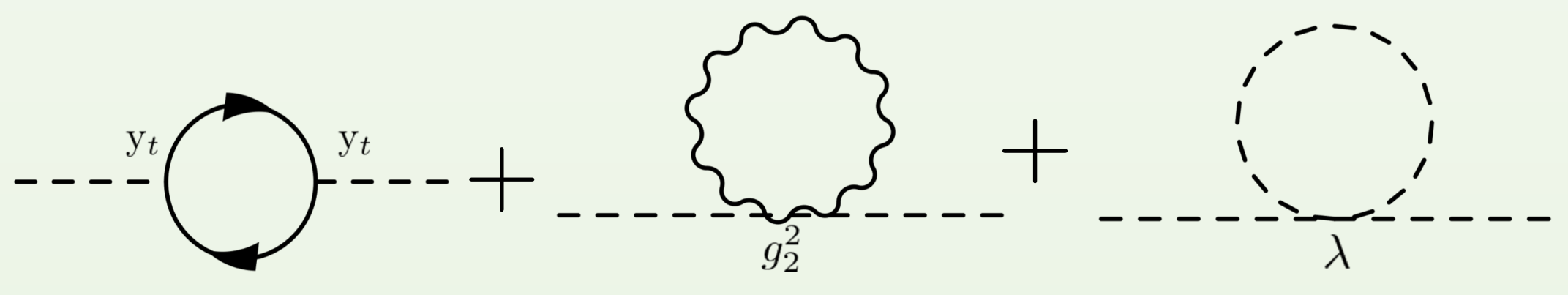
Motivation

Electroweak (Little) Hierarchy problem

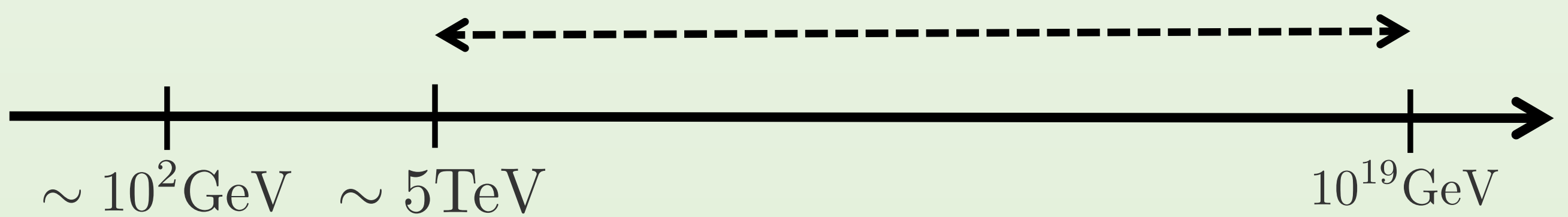


$$\delta m_h^2 = -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \frac{9g_2^2}{32\pi^2}\Lambda^2 + \frac{\lambda}{4\pi^2}\Lambda^2$$

$$m_{h_R}^2 = m_{h_{\rm bare}}^2 + \delta m_h^2$$

Λ : cut-off scale

$m_{h_R}^2 \ll \delta m_h^2$ Why?

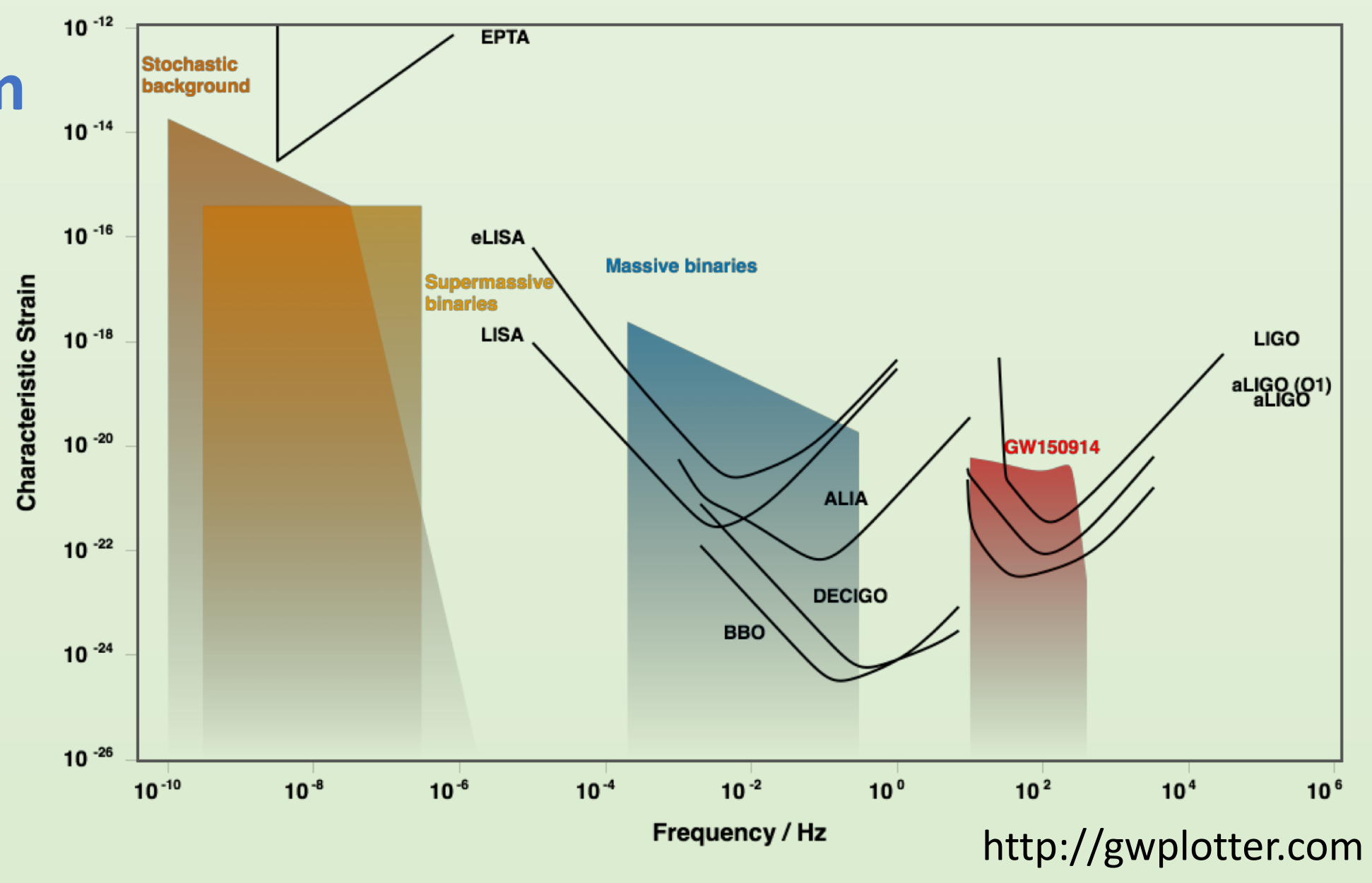


SUSY and Composite Higgs provide solution

Little Hierarchy Problem

Twin Higgs provides solution

We analyze phase transitions and calculate gravitational wave amplitudes generated by a first-order phase transition!



http://gwplotter.com

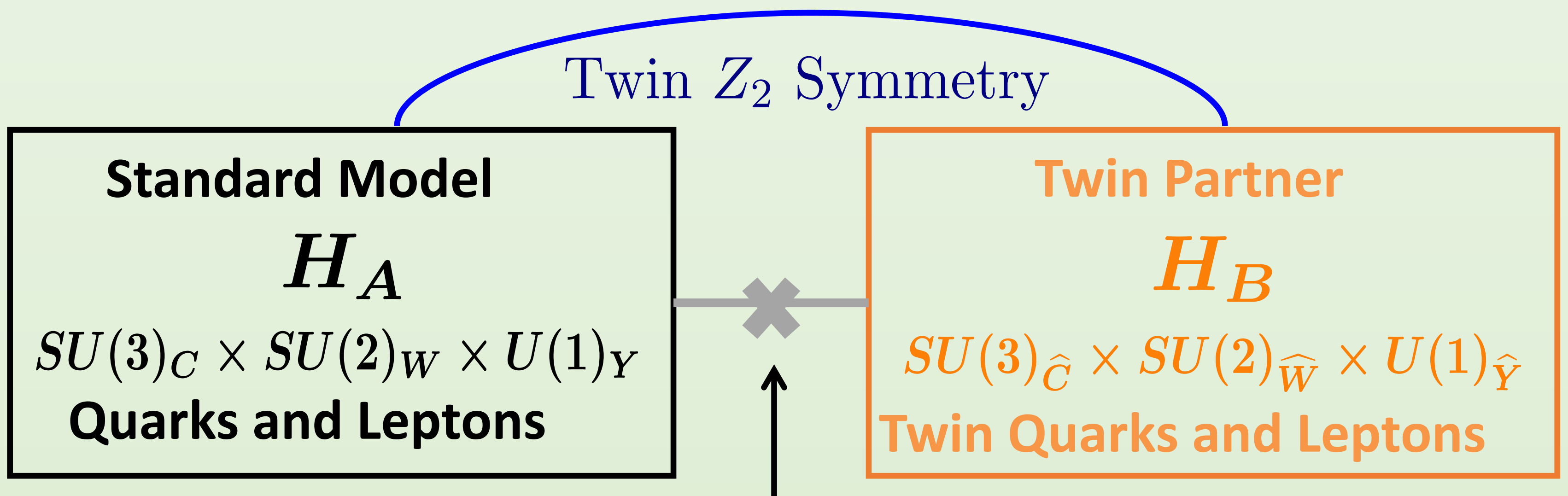
Twin Higgs Model

SM Higgs is considered as pseudo-Nambu-Goldstone Boson.

$$\mathcal{H} = \begin{pmatrix}\Phi_1\\ \Phi_2\\ \Phi_3\\ \Phi_4\end{pmatrix} \quad V(\Phi) = \lambda\left(|\mathcal{H}|^2 - \frac{f^2}{2}\right)^2$$

U(4) symmetry is spontaneously broken to U(3).

7 NG-bosons appear (4 of them are identified with SM-like Higgs)



Standard Model
H_A
$SU(3)_C \times SU(2)_W \times U(1)_Y$
Quarks and Leptons

Twin Partner
H_B
$SU(3)_{\widehat{C}} \times SU(2)_{\widehat{W}} \times U(1)_{\widehat{Y}}$
Twin Quarks and Leptons

Higgs Mixing $V(\Phi) = \lambda\left(|\mathcal{H}|^2 - \frac{f^2}{2}\right)^2$

$V_{\rm eff} \supset \left(-\frac{3y_t^2}{8\pi^2} + \frac{9g_2^2}{64\pi^2}\right)\left(|H_A|^2 + |H_B|^2\right)\Lambda^2$ respects the global U(4) symmetry.

pNGB (SM-like Higgs) is insensitive to the mass correction.

Higgs potential

$$V = \lambda\left(|H_A|^2 + |H_B|^2 - \frac{f^2}{2}\right)^2 + \sigma_1 f^2 |H_A|^2 + \kappa_1\left(|H_A|^4 + |H_B|^4\right) + \rho_1 |H_A|^4$$

This term must be dominant compared to (explicit) U(4) breaking term.

$$\lambda \gg \sigma_1,\ \kappa_1,\ \rho_1$$

Soft twin Z_2 breaking

$$2v_A < f$$

Twin Z_2 preserving but U(4) breaking term.

Generated by Coleman-Weinberg (CW) potential.

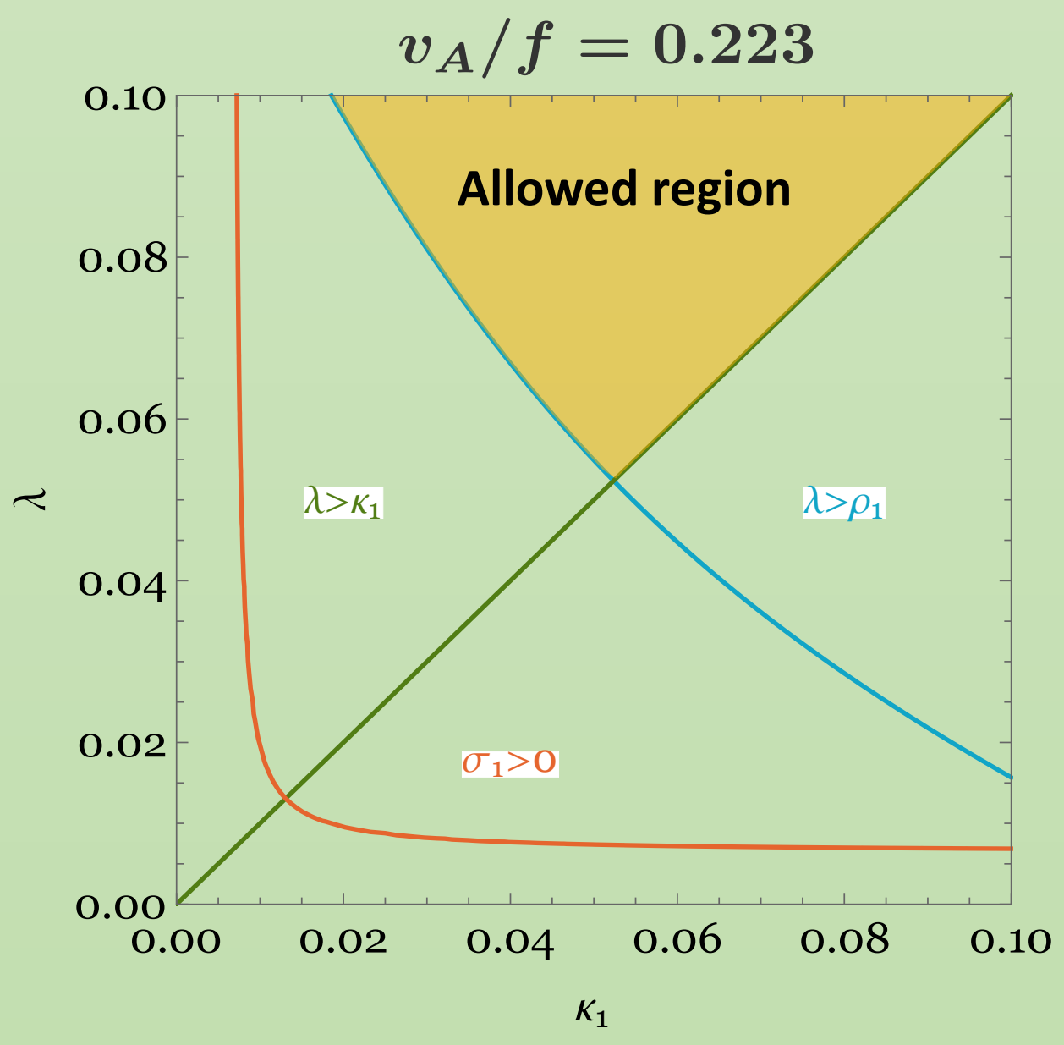
Twin Z_2 and U(4) is broken

These quartic terms generate the SM-like Higgs mass

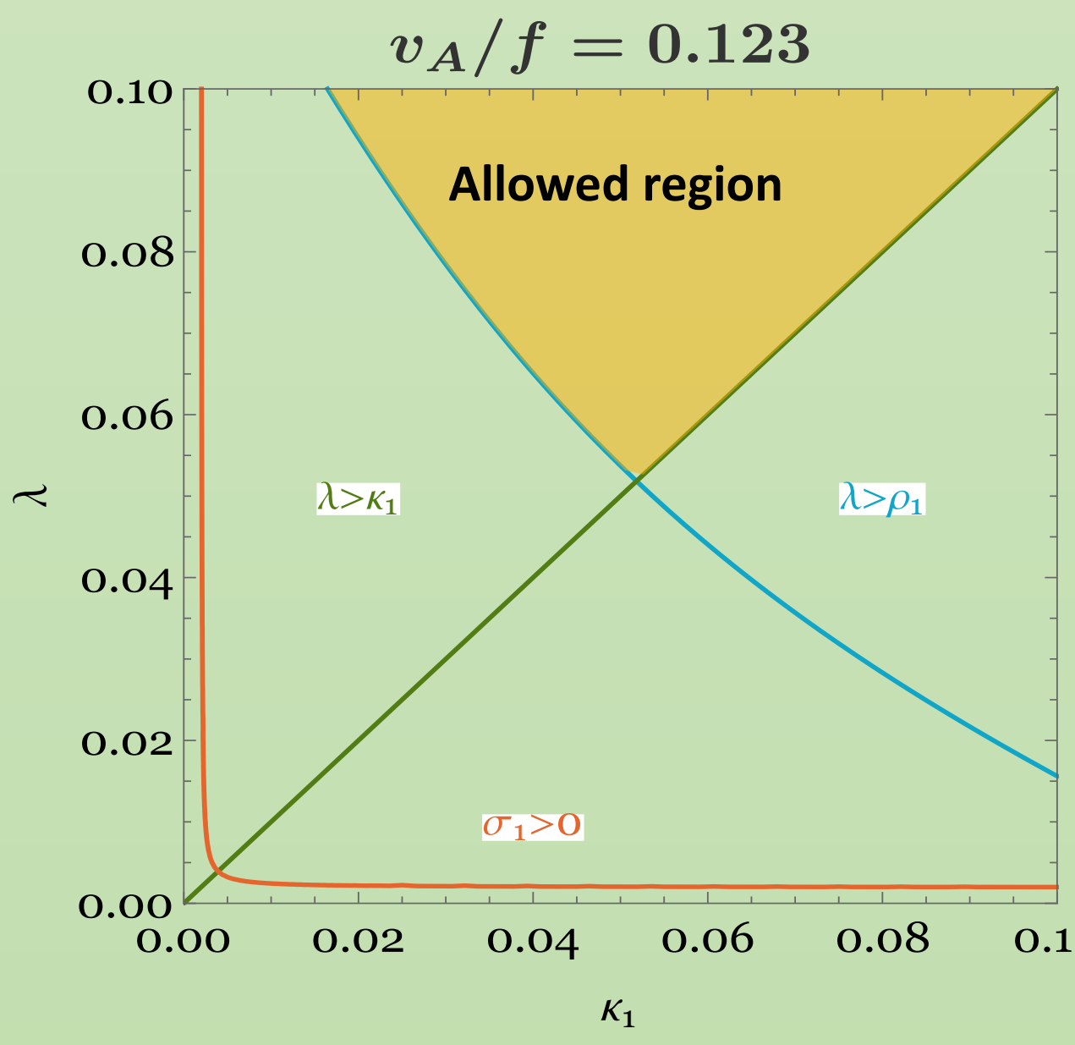
To realize adequate EWSB, following conditions must be satisfied.

$$\langle H_A \rangle = v_A \simeq 246{\rm GeV},\ m_h \simeq 125{\rm GeV}$$

$v_A/f = 0.223$



$v_A/f = 0.123$



Set up and effective potential

There are two spontaneous symmetry breakings (twin EW symmetry and EW symmetry)

$(1)(0,\ 0) \Rightarrow (0,\ v_B) \Rightarrow (v_A,\ v_B)$

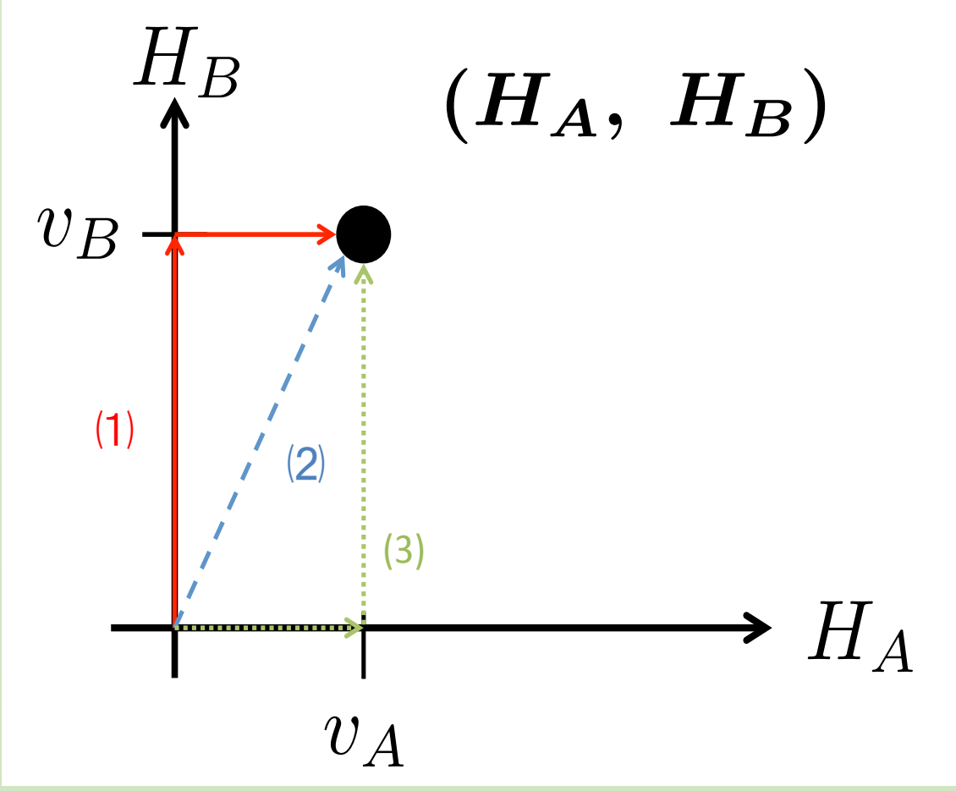
$T_B \gg T_A$

$(2)(0,\ 0) \Rightarrow (v_A,\ v_B)$

$T_A \simeq T_B$

$(3)(0,\ 0) \Rightarrow (v_A,\ 0) \Rightarrow (v_A,\ v_B)$

$T_A \ll T_B$



We consider the case (1) and analyze the U(4) breaking phase transition.

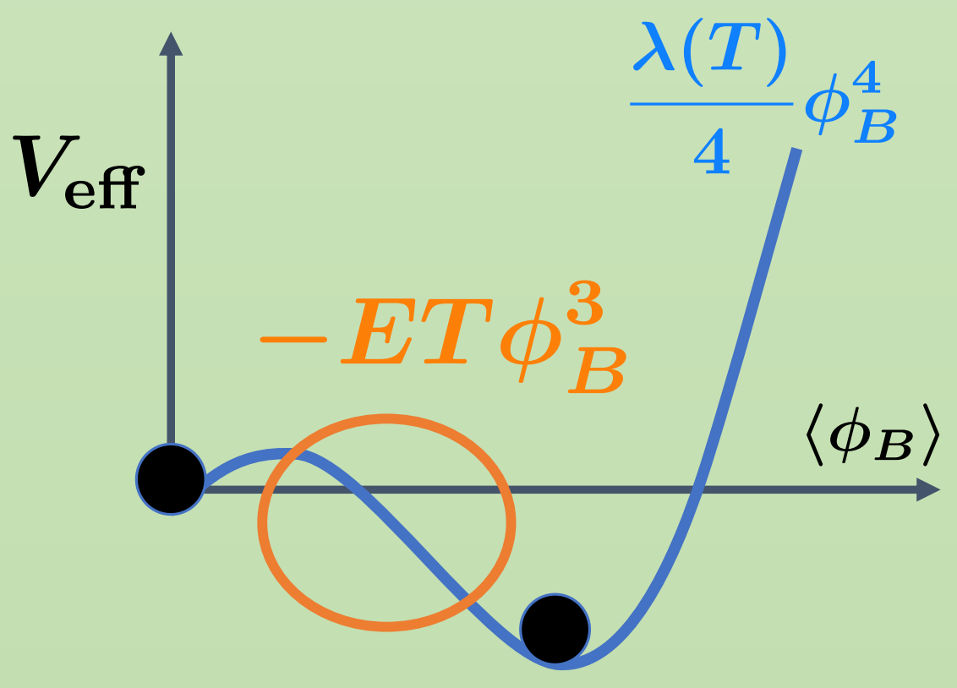
$T_{A(B)}$: critical temperatures of EW (twin EW) electroweak phase transition

Thermal mass

$$m_A^2(H_A,\ T) = (\zeta_A T^2 - (\lambda - \sigma_1)f^2)$$
$$m_B^2(H_A,\ T) = (\zeta_B T^2 - \lambda f^2)$$
$$\frac{T_A}{T_B} = \sqrt{\frac{\zeta_B}{\zeta_A}\left(1 - \frac{\sigma_1}{\lambda}\right)}$$

$\sigma_1 > 0$ is necessary condition for two-step phase transition

We consider SUSY twin Higgs models and take into account light twin stop effects.



$$V_{\rm eff} = \frac{M^2(T)}{2}\phi_B^2 - ET\phi_B^3 + \frac{\lambda + \kappa}{4}\phi_B^4$$

Potential barrier is generated by bosonic thermal loop.

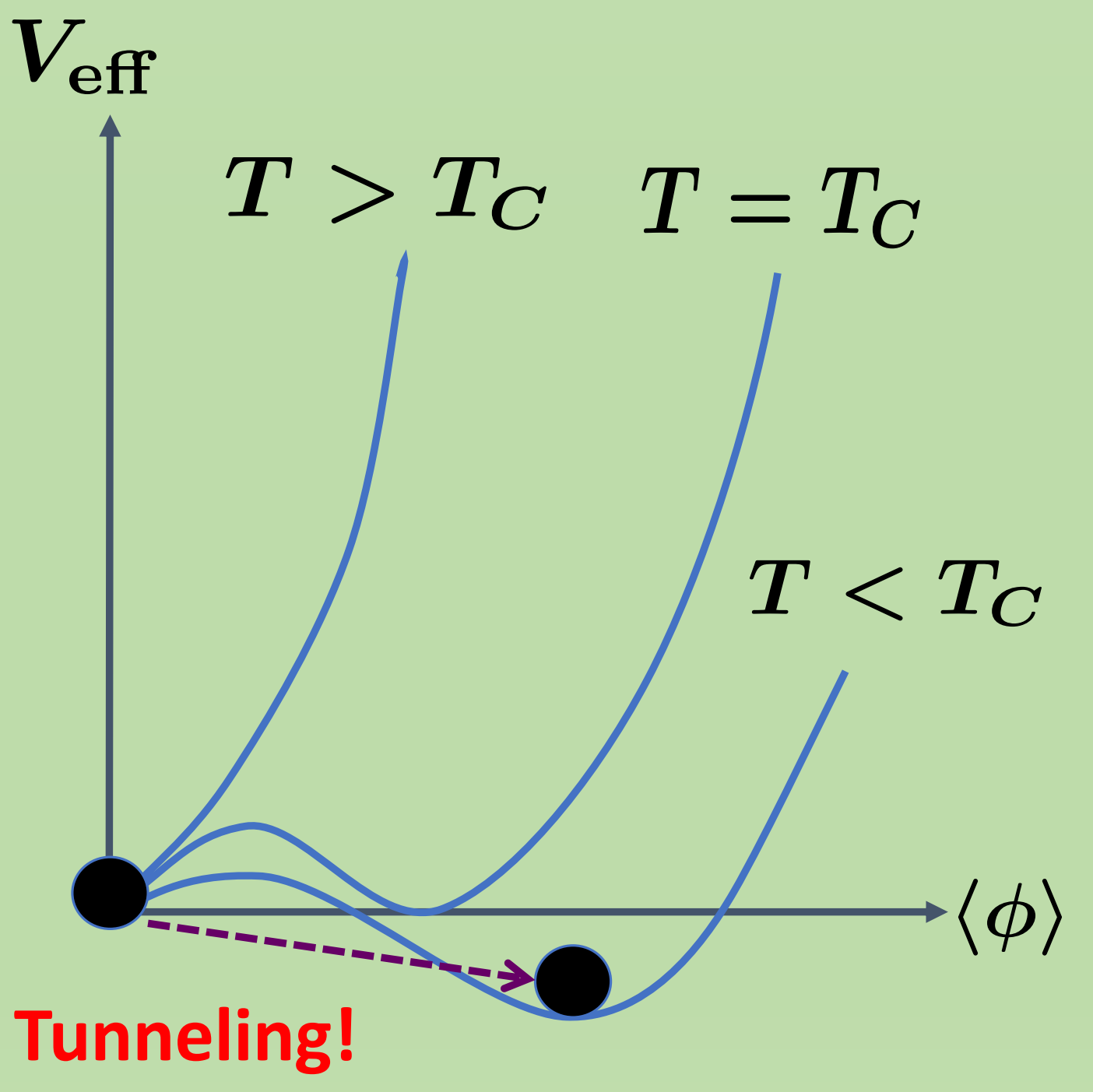
$$E \simeq \frac{3}{32\pi}\widehat{g}_2^3 + \frac{\sqrt{2}}{6\pi}\widehat{y}_t^3$$

SU(2) gauge coupling: $\widehat{g}_2 \simeq g_2$

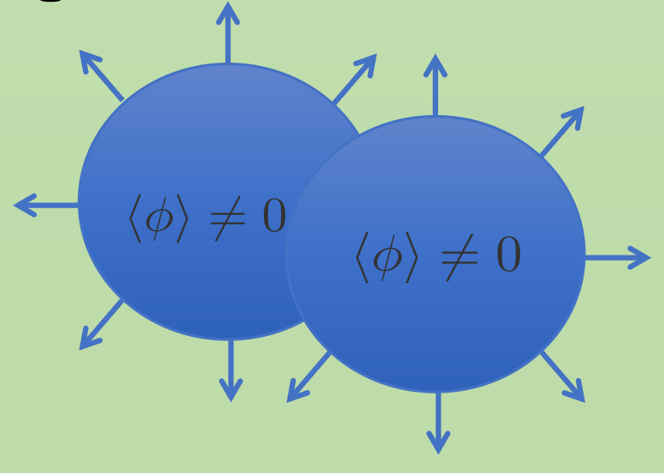
top Yukawa coupling: $\widehat{y}_t \simeq y_t$

$$M^2(T) \simeq aT^2 - \lambda f^2 \ \ (a : {\rm const.})$$

GW from a first-order phase transition



Tunneling!



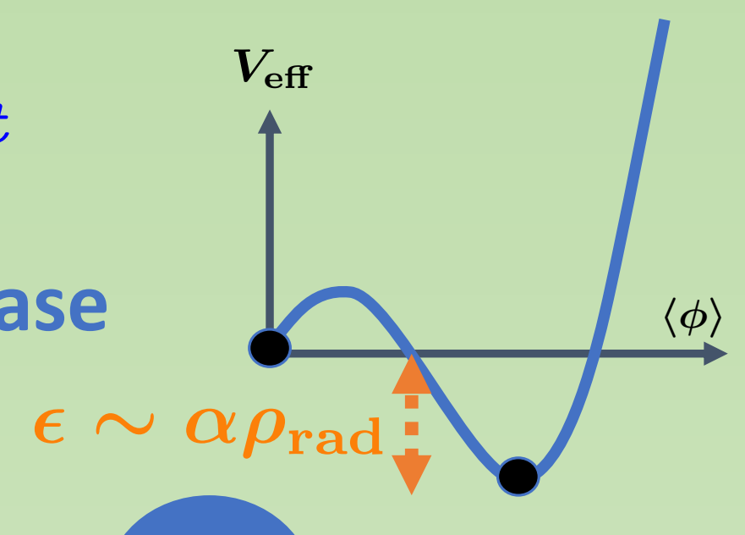
There are three sources of the GWs.

- Bubble collisions
- Sound Waves of the plasma
- Turbulence of the plasma

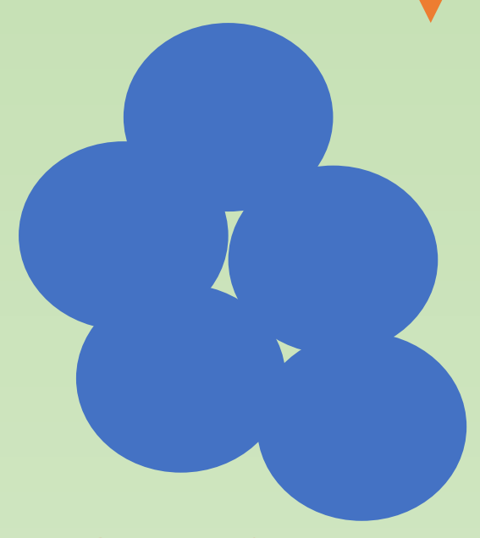
Decay rate
$\Gamma \simeq \Gamma_0 e^{\beta t}$

Duration of phase transition: β

Latent heat density: α



$\epsilon \sim \alpha\rho_{\rm rad}$



$L \simeq v_w\beta^{-1}$

Bubble size at collision: $L \simeq v_w\beta^{-1}$

Bubble wall velocity: v_w

$$\Omega_{\rm GW} \sim \frac{\rho_{\rm GW}}{\rho_{\rm crit}} \qquad \rho_{\rm crit} \simeq (1+\alpha)\rho_{\rm rad}$$

$\rho_{\rm GW} \sim E_{\rm GW}/L^3$ Bubble volume $\sim L^3$

$$E_{\rm GW} \sim \int dt P_{\rm GW} \sim P_{\rm GW}(\beta^{-1}{\rm or}\ H^{-1})$$

Quadrupole formula: $P_{\rm GW} \sim G\dot{E}_{\rm kinetic}^2$

$$\dot{E}_{\rm kinetic} \sim \beta E_{\rm kinetic} \qquad E_{\rm kinetic} \sim \kappa\epsilon L^3$$

Efficiency factor: κ $\quad G \sim \frac{H^2}{(1+\alpha)\rho_{\rm rad}}$ (Newton const.)

$$\Omega_{\rm GW} \sim \left(\frac{H}{\beta}\right)^{2\ {\rm or}\ 1}\left(\frac{\kappa\alpha}{1+\alpha}\right)^2 v_w^3$$

Large latent heat and long-duration enhance the GW amplitude!

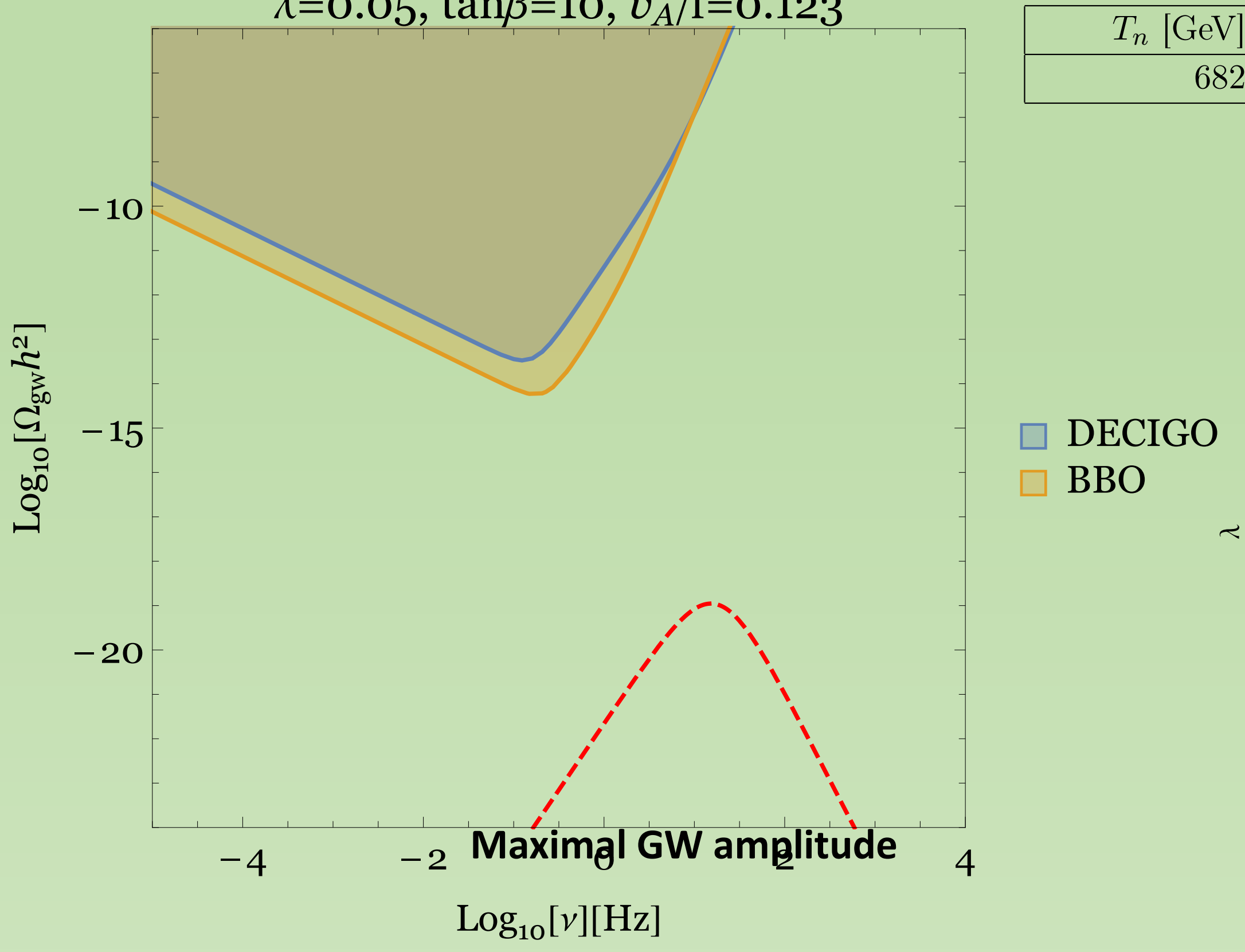
Result

We (numerically) calculate the decay rate and found the following statement.

small	$\lambda + \kappa$	Large latent heat density and long-duration	large	$\Omega_{\rm GW}$
large	$\lambda + \kappa$	Small latent heat density and short-duration	small	$\Omega_{\rm GW}$

$M_{\widehat{\rm stop}} = 0 \quad (\kappa_1 \simeq 0.05)$

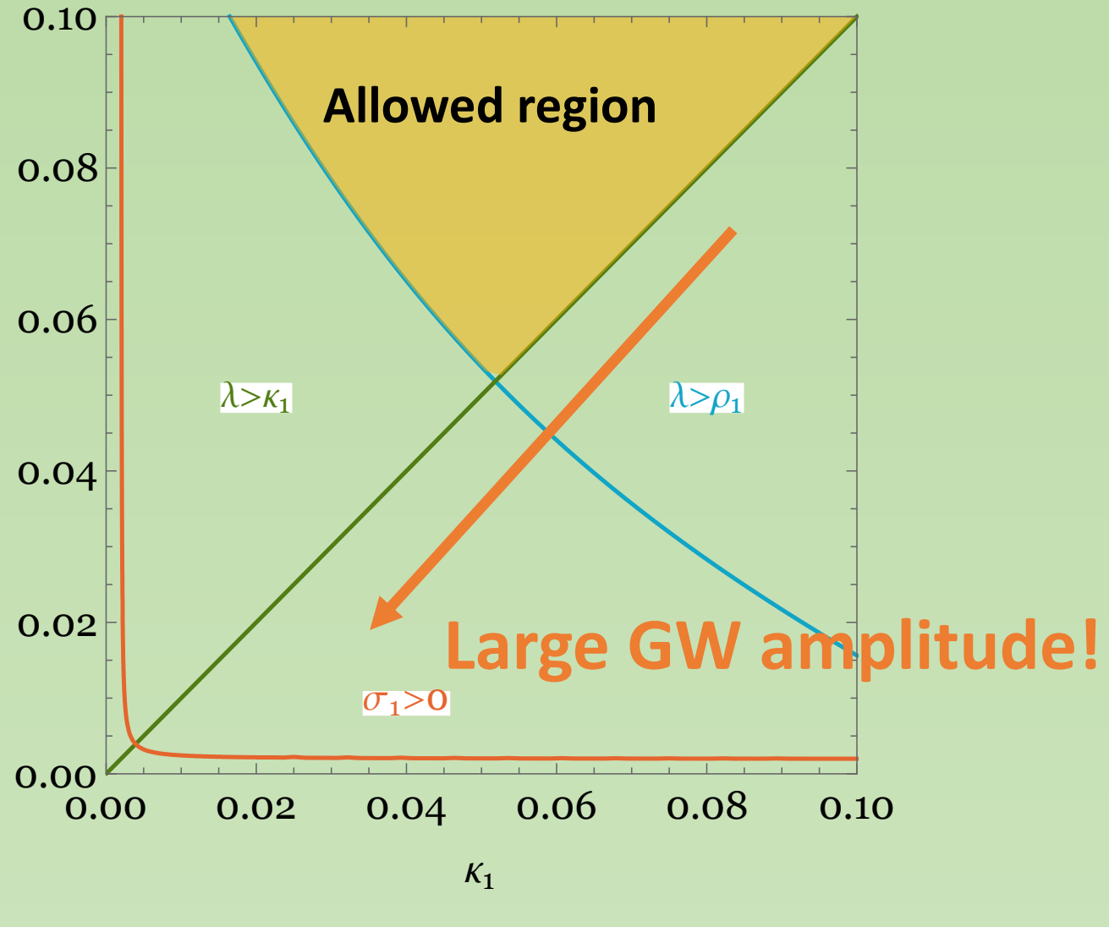
λ=0.05, tanβ=10, v_A/f=0.123



Maximal GW amplitude

T_n [GeV]	$\phi_B(T_n)/T_n$	α	$\beta/H(T_n)$
682	1	7×10^{-3}	7×10^4

$v_A/f = 0.123$



Large GW amplitude!

U(4) breaking phase transition with light twin stop is first order.
However, GW amplitude cannot be detected by DECIGO and BBO.