A Supersymmetric inert Higgs model and its phenomenological implications

Tetsuo Shindou (Kogakuin University)

S. Kanemura, E. Senaha, and T.S, Phys.Lett.B706,40

S. Kanemura, N. Machida, T.S, in preparation

S. Kanemura, E. Senaha, T.S, T. Yamada, in preparation

LCWS12@University of Texas at Arlington 24/10/2012

Supersymmetry

SUSY is an attractive candidate of New Physics

- a solution for the quadratic divergence problem
- In the MSSM, the origin of the Higgs coupling is gauge coupling
  - Light Higgs → m_h=126GeV@LHC
- Elementary scalar fields is naturally introduced
- R-parity provide a candidate for DM

Some serious problems still remain in the MSSM

- Mechanism for the Baryogenesis
- Origin of the finite tiny neutrino masses

↓

MSSM should be extended → Some modifications require extended SUSY Higgs sector

Baryogenesis

How is the baryon asymmetry of Universe produced ?

$$\eta_B = (6.21 \pm 0.16) \times 10^{-10}$$

Sakharov's three conditions

- Baryon number violation
- C and CP violation
- Interactions out of thermal equilibrium

- #B (#B-L) is produced at T >> 100GeV(e.g. Leptogenesis)

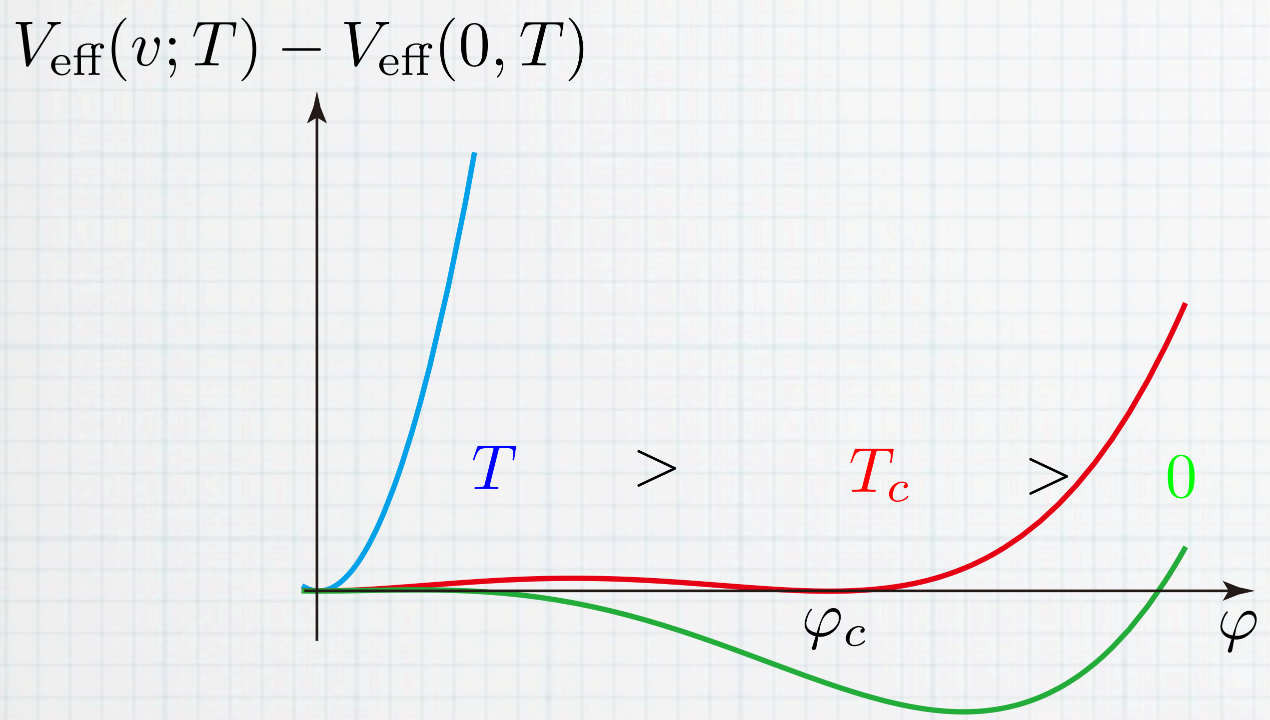
↕

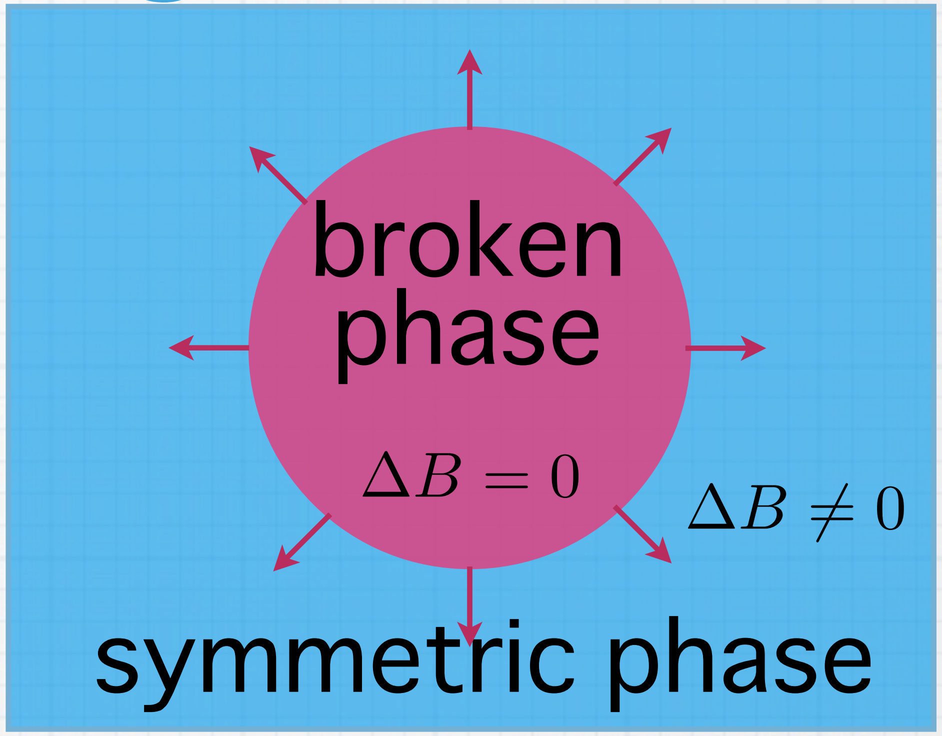
It is relevant to physics at very high energy scale

They may be out of the experimental reach

- Electroweak baryogenesis: #B is generated at the first order electroweak phase transition ⟷ Higgs physics @M_{EW}

Electroweak Baryogenesis





1st order phase transition
↓
Out of thermal equilibrium

CP violating interaction between matter and wall

Sphaleron in the SM violates #B (100GeV<T<10^{12}GeV)
↑
B+L is violated while B-L is conserved

In order to avoid too strong sphaleron washout of #B,
strong 1st order PT is required: $\varphi_c/T_c > 1$

EWBG in the SM

In the high temperature approximation,

$$V(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

$$\varphi_c/T_c = 2E/\lambda_{T_c}$$

1st order PT is possible due to the cubic term

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$

$$\lambda_T = \frac{m_h^2}{2v^2} + \log \text{ corrections}$$

$$\varphi_c/T_c \propto 1/m_h^2$$

Light Higgs is required !!

In SM, Higgs should be lighter than 50GeV

excluded by LEP data

NEW CP phases are also necessary for successful baryogenesis

Extension of the SM at TeV scale is necessary

It can be tested by experiments

- New bosonic loop contribution
- Higher dim. term in the potential
- ...

EWBG in the MSSM

Carena et al.,PLB380,81;···

Lighter stop loop can contribute

enhance

$$\varphi_c/T_c = 2E/\lambda_{T_c} > 1$$

large top Yukawa coupling

$$E \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) + \frac{m_t^3}{2\pi v^3}\left(1 - \frac{|A_t + \mu\cot\beta|^2}{M_{\tilde{q}}^2}\right)^{3/2}$$

where the maximal contribution case is considered;

$$m_{\tilde{t}_1}^2(\varphi,\beta) = M_{T_R}^2 + \frac{y_t^2 s_\beta^2}{2}\left(1 - \frac{|A_t + \mu\cot\beta|^2}{M_{\tilde{q}^2}}\right)\varphi^2$$

$M_{T_R}^2 \sim 0$

For larger M_{TR}, the effect is smaller

Light stop is necessary ⟷ No new coloured particles at LHC···

Even with such a maximal case, it's not easy to get $\varphi_c/T_c>1$

Carena et al.,NPB812,243; Funakubo,Senaha,PRD79,115024

MSSM should be also modified at TeV scale for EWBG

What kind of modification?

$\varphi_c/T_c \propto 1/m_h^2$ → Small m_h is preferable ← support m_h=126GeV@LHC

We want to keep it!

A Good point of MSSM : h^4 coupling is from gauge coupling→Light Higgs → **strong but light!**

Large bosonic loop contribution

- A strong Higgs coupling with additional bosons (h-Φ'-Φ')
- Mass of ϕ' is dominated by vev $m_{\Phi'}^2 = M^2 + \lambda^2 v^2$

A natural realization of "strong but light" in SUSY model:

MSSM Higgs Z_2 odd new fields

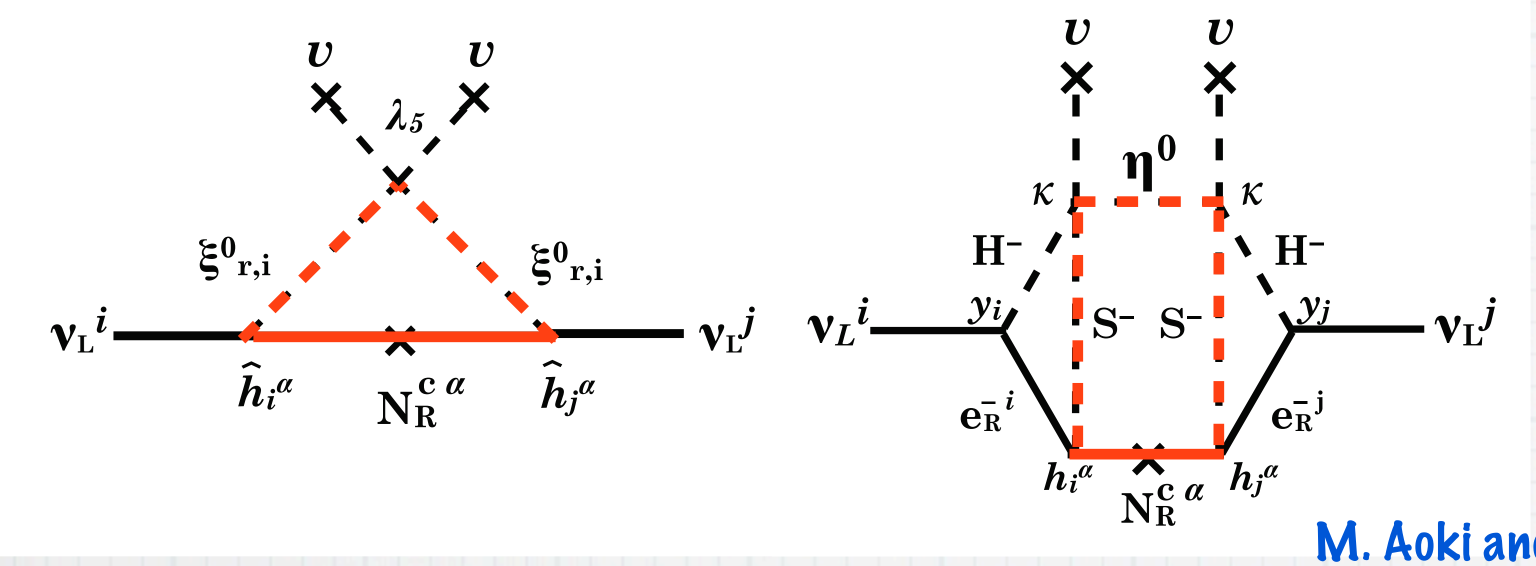
$$W = \lambda \Phi_{u,d} \Phi'_1 \Phi'_2 \rightarrow \Delta V = |\lambda|^2 h^2 \varphi'^{\dagger}_{1,2} \varphi'_{1,2}$$

It provides strong coupling but m_h is kept small!

SUSY inert model

SUSY inert model is interesting not only for EWBG but also for neutrino mass generation

Ma model　　　Aoki-Kanemura-Seto model



M. Aoki and S. Kanemura, PLB689,28

In some model for radiative m_ν generation, Z_2-odd particles run in the loop

The Higgs sector of SUSY versions of these model naturally has the form of $W = \lambda\Phi_{u,d}\Phi'_1\Phi'_2$

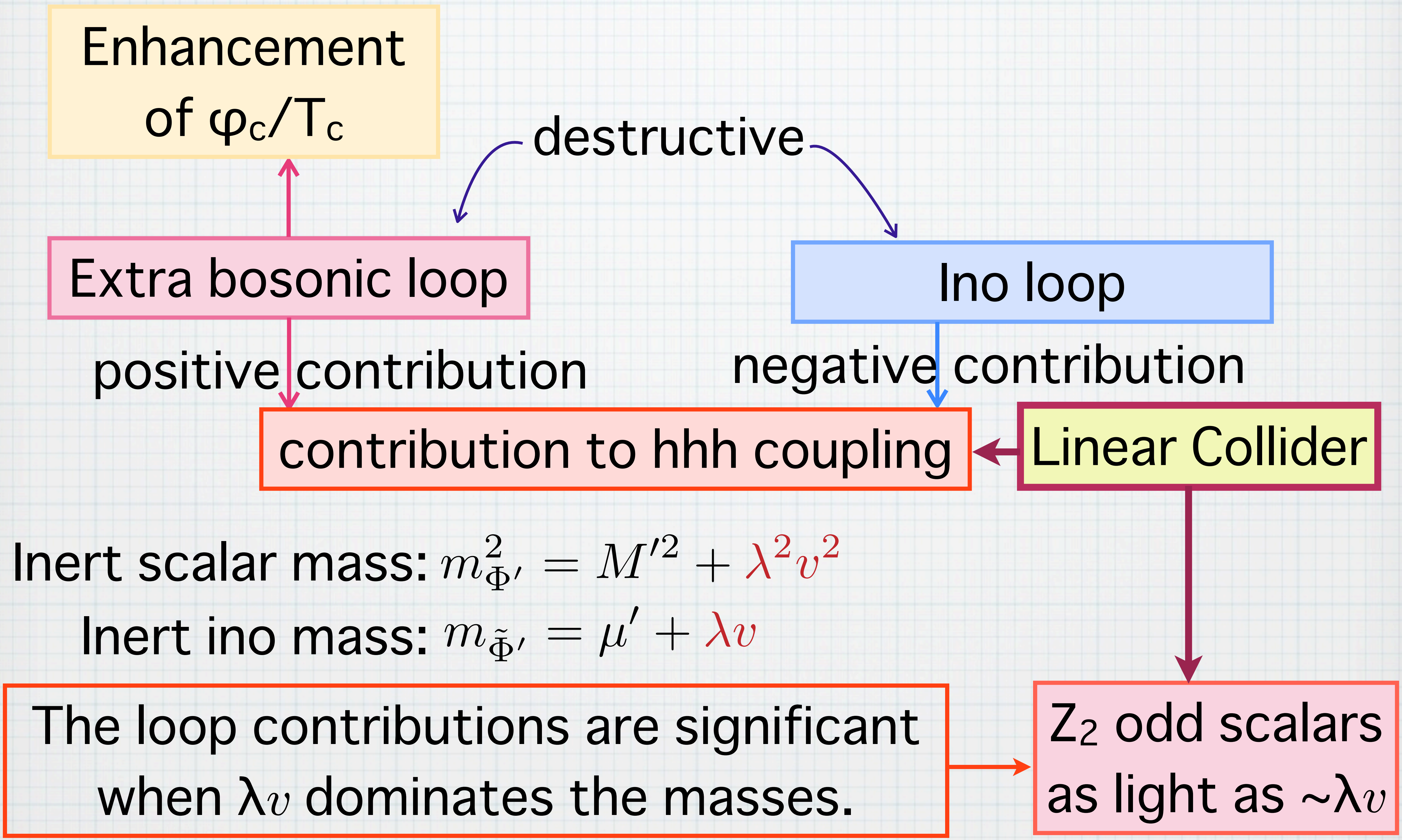
<u>In the radiative seesaw models,</u>

#L violation at O(100GeV) $\xrightarrow{\text{sphaleron}}$ #B is washed out (produced at high T)

EWBG is necessary!!　　<u>Inert model is very nice</u>

The lightest Z_2 odd particle can be a new candidate of DM

Tests of the scenario



Large μ' and small M'^2 provides large deviation in hhh and large φ_c/T_c

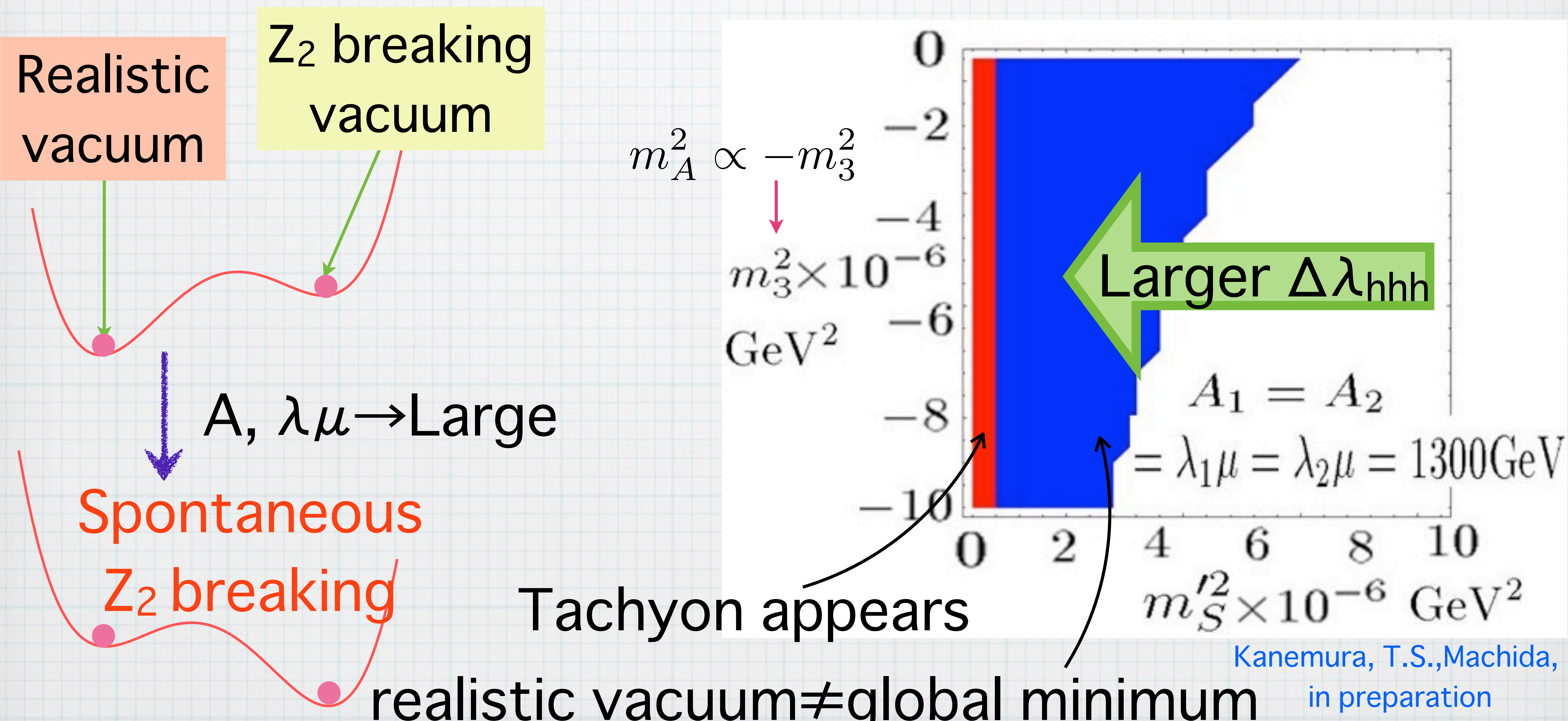
A Comment on vacuum stability

Kanemura, T.S., Machida, in preparation

For large coupling λ and small mass parameter M^2

The vacuum can be unstable

Z_2 breaking (unrealistic) vacuum can be a global minimum



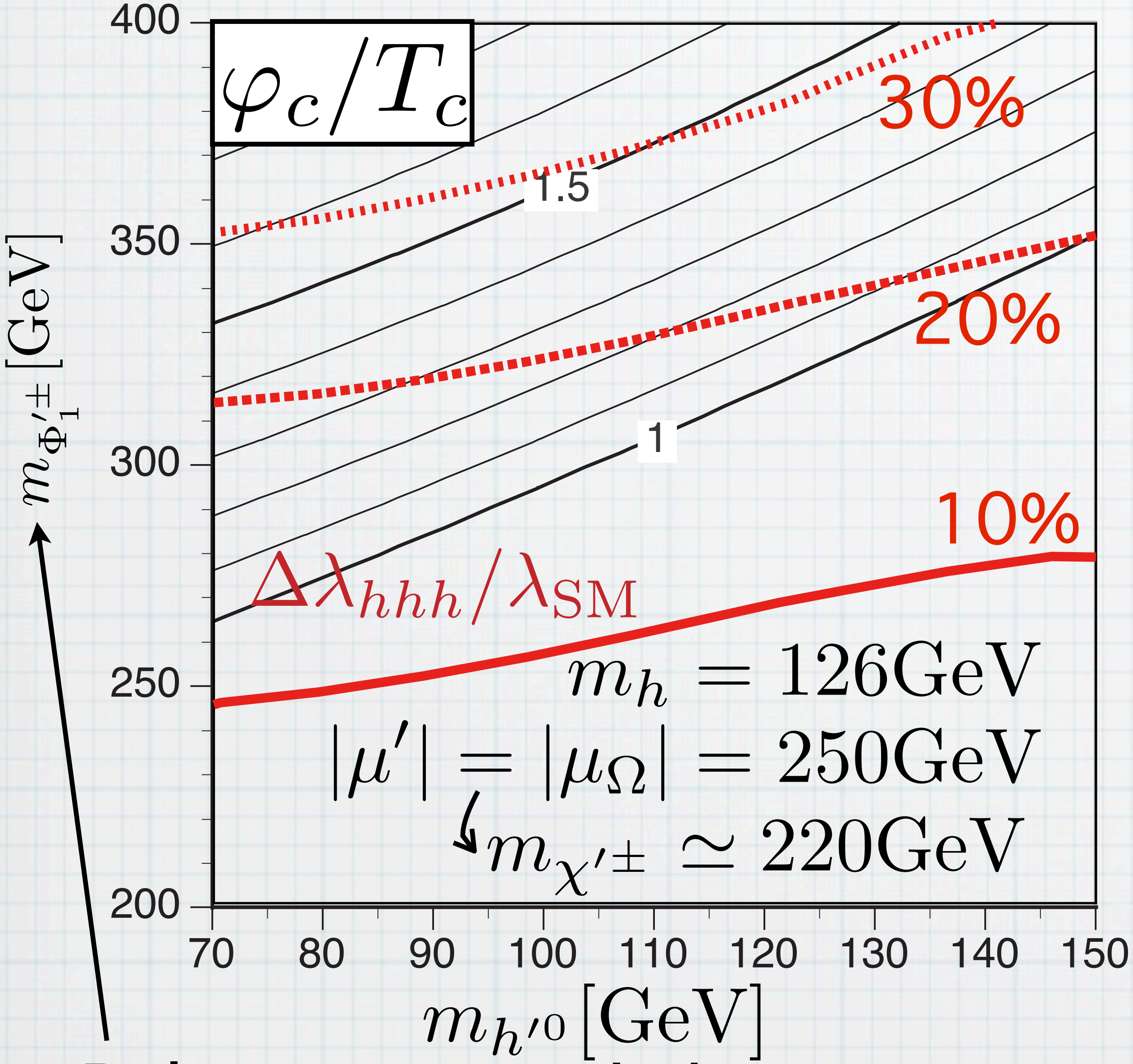
Kanemura, T.S.,Machida, in preparation

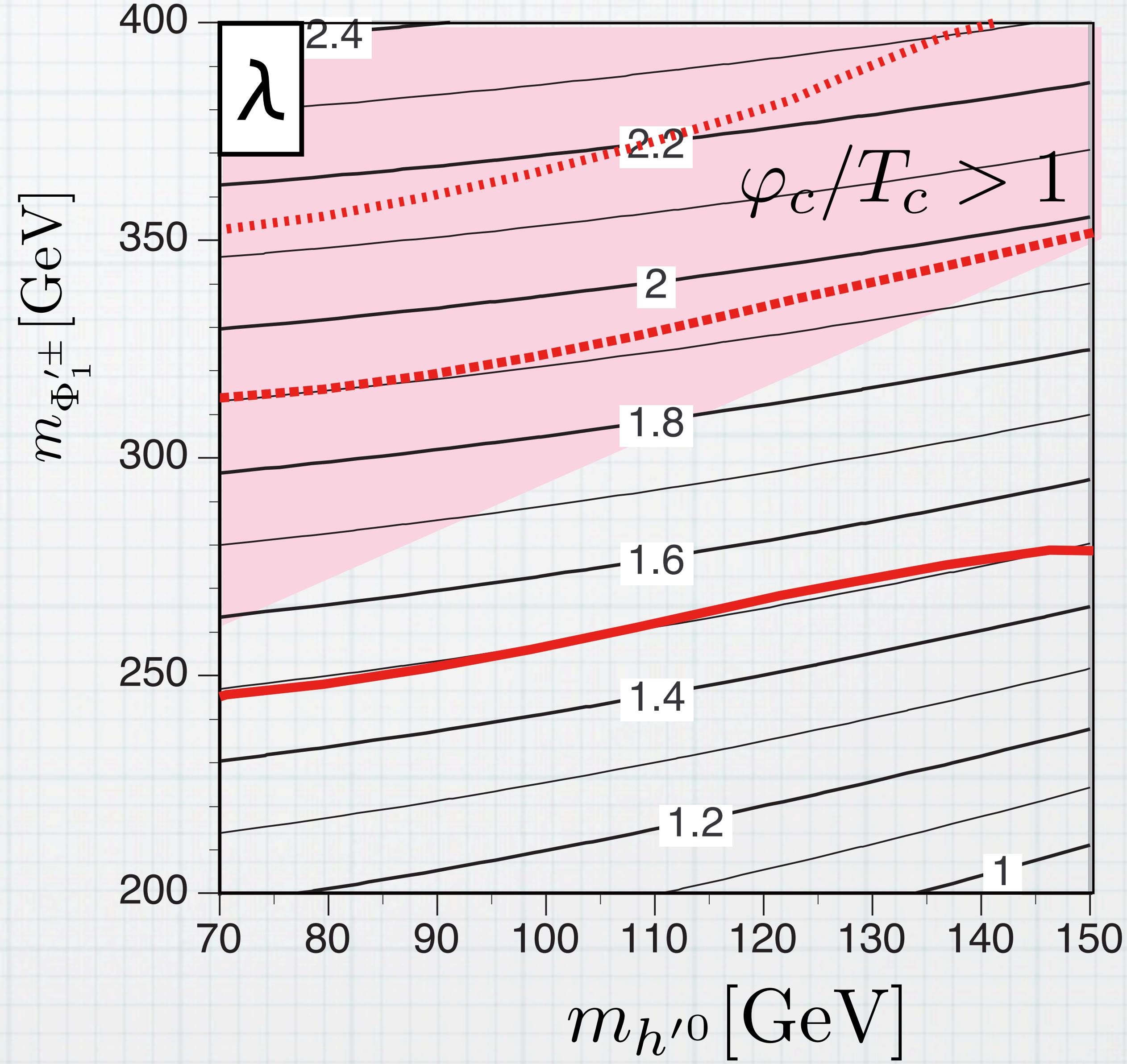
φ_c/T_c and hhh coupling

Benchmark model: Z_2-odd

Kanemura, T.S, Senaha, Yamada, in preparation

MSSM+Two doublets and Two charged singlets





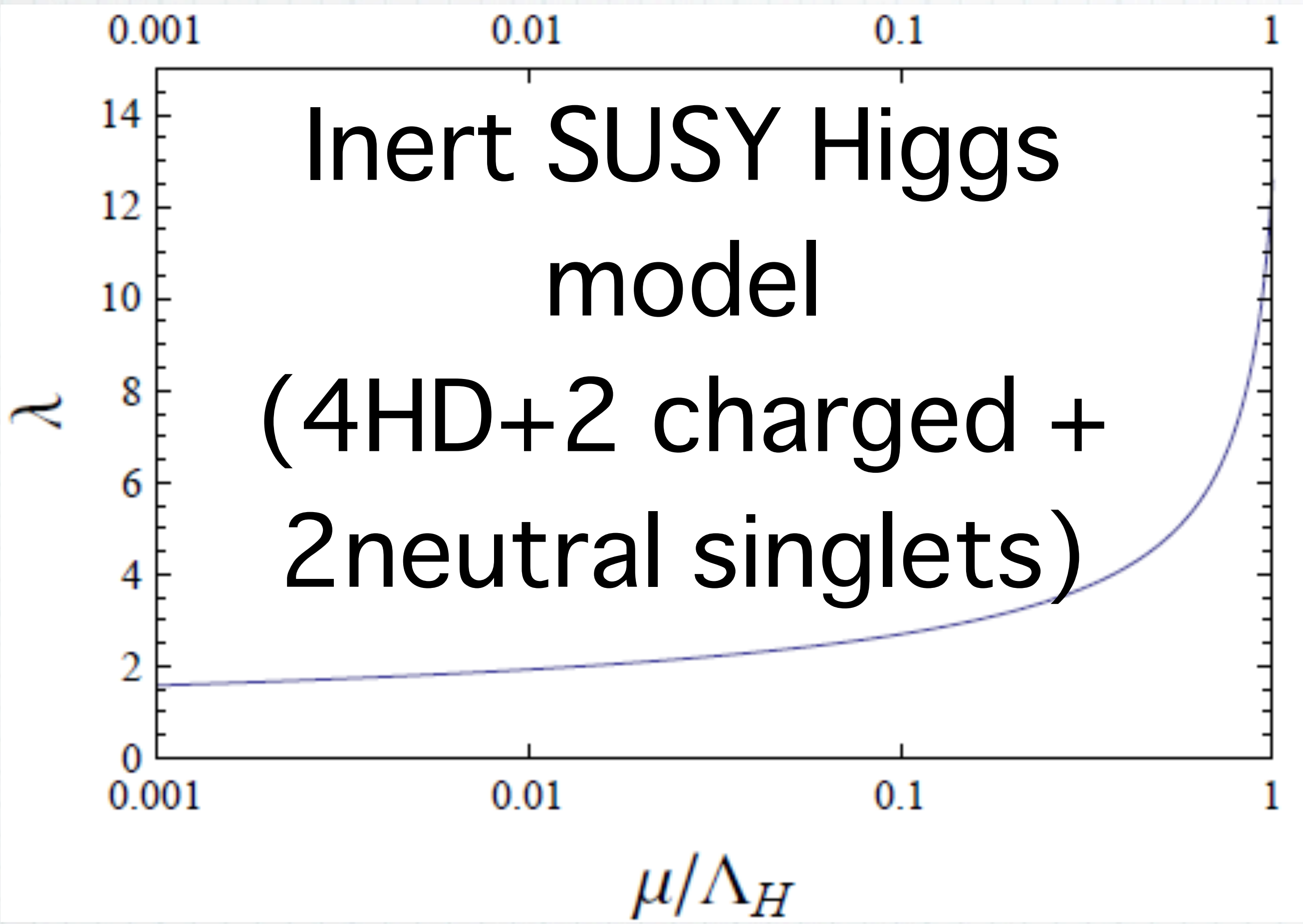
Relevant Z_2 odd charged scalar

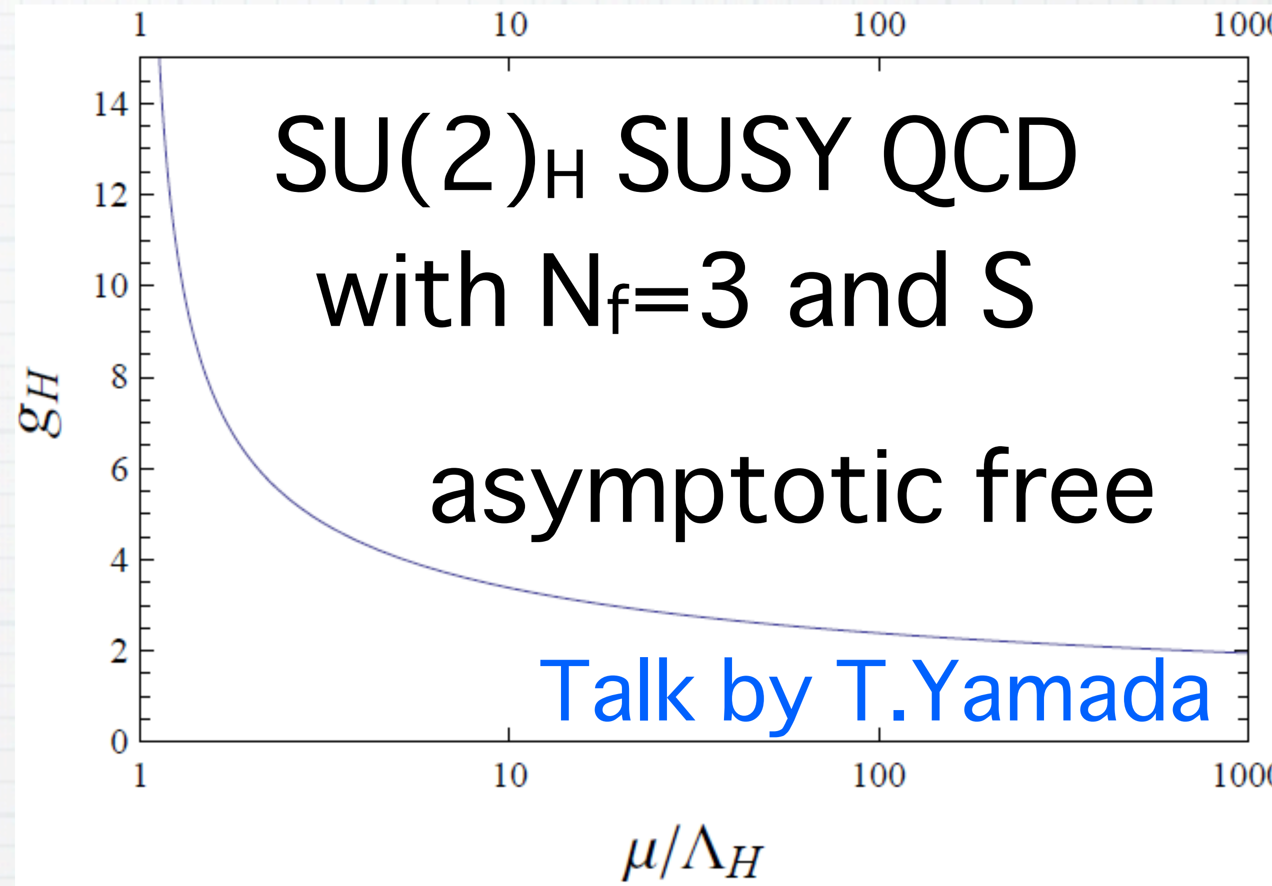
lightest Z_2 odd scalar (DM?)

For $\varphi_c/T_c>1$ and $\lambda=2$, 20-25% deviation can be found in λ_{hhh}

Towards a unified picture

$\lambda \sim 2$ ⟶ Landau pole @ ~10TeV Kanemura, T.S,Yamada, PRD86,055023





Cutoff scale appears at 10TeV for successful EWBG

Above the cutoff, SUSY QCD like theory may be realized

↑

It can be UV complete → We can go to Planck scale

Higgs fields behave as composite fields

The picture is quite different from GUT over the grand desert

EWBG and neutrino mass

With a low cut-off scale as Λ~10TeV

Higgs field may appear as a composite field below Λ

↓

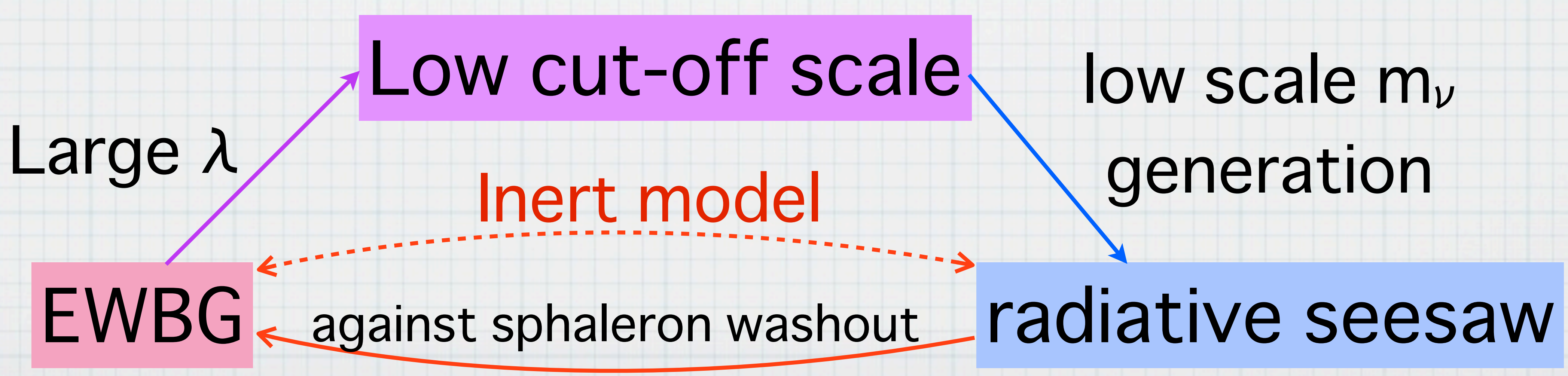
High scale generation of m_ν is un-natural in this case

$$\mathcal{L} = \frac{c}{M}(\ell \cdot \Phi_u)(\ell \cdot \Phi_u)$$

very high scale as ~10^{12}GeV ←?→ They appear only below 10TeV

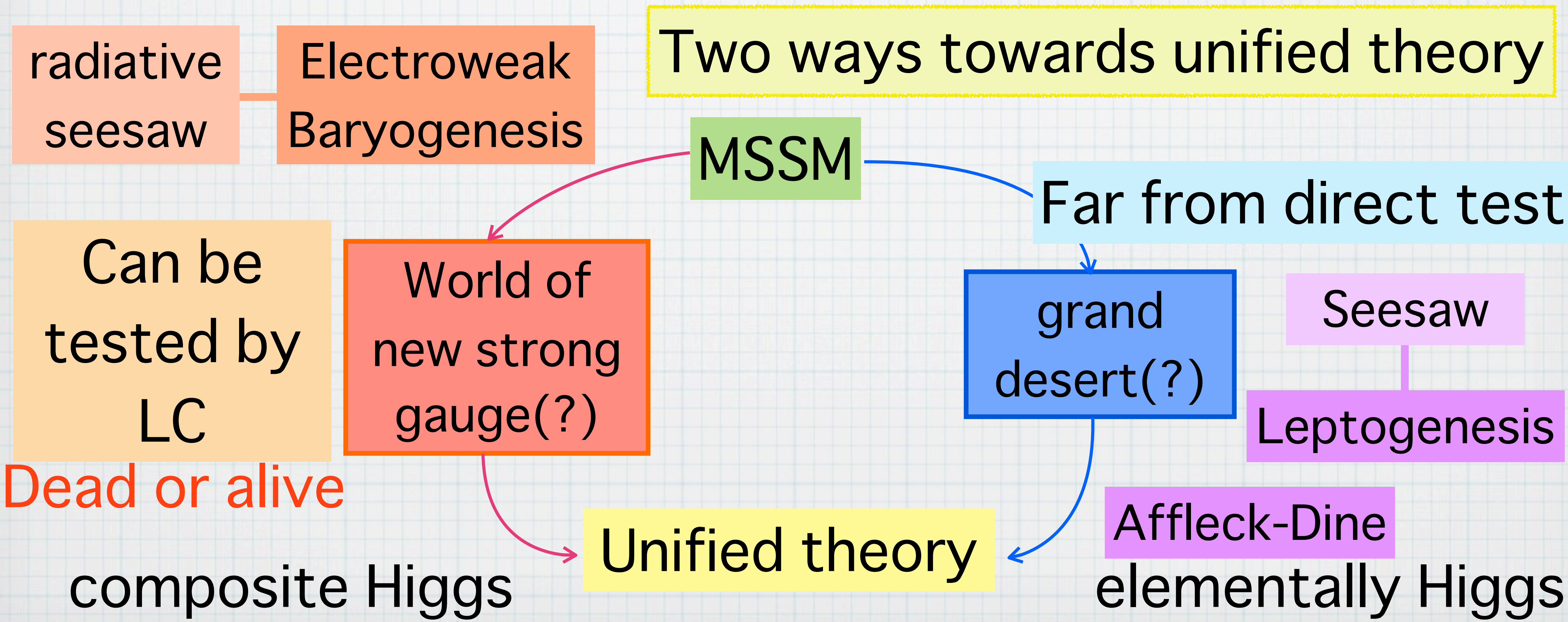
Some mechanism to generate neutrino masses below Λ

Loop induced mechanism (radiative seesaw) is attractive!



Summary

- Electroweak baryogenesis requires a light Higgs boson with strong couplings
- Large deviation (~20%) in hhh coupling and new light non-coloured particles are predicted→LC can test them!!!
- Low cutoff scale appears: Rich physics above O(10TeV)



Backup

Sphaleron Process

F.R.Klinkhamer, N.S.Manton,PRD30,2212

Baryon number violation in the SM by quantum effect

||

Chiral anomaly in (B+L) current

$$\partial_\mu j^\mu_{\mathrm{B+L}} = \frac{N_f}{16\pi^2}\left\{g_2^2 \mathrm{tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g_1^2 \mathrm{tr}(B_{\mu\nu}\tilde{B}^{\mu\nu})\right\}$$

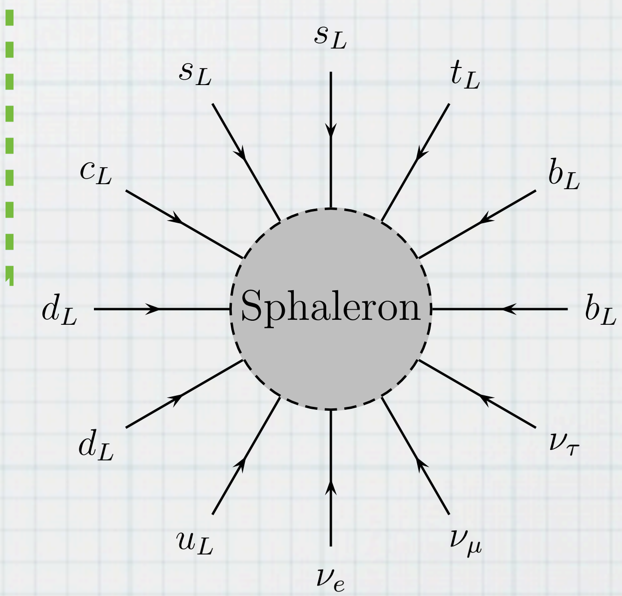
- B-L is conserved $\partial_\mu j^\mu_{\mathrm{B-L}} = 0$
- At T=0, transition rate is negligible
- At finite temperature, the rate is significant

Sphaleron is in the thermal equilibrium in

$100\mathrm{GeV} < T < 10^{12}\mathrm{GeV}$

Sphaleron is weak at low T

$\Gamma < H$



$$O_{B+L} = \prod_i (q_{Li}^{(\alpha)} q_{Li}^{(\beta)} q_{Li}^{(\gamma)} \ell_{Li})$$

W. Buchmüller, M. Plümacher, IJMP,A15,5047

Testability of EWBG

$$\varphi_c/T_c = 2E/\lambda_{T_c} > 1$$

Kanemura, Okada, Senaha,PLB606,361

THDM: $$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_H^3 + m_A^3 + 2m_{H^\pm}^3)$$

$$m_\Phi^2(\varphi) = M^2 + \lambda_i^2\varphi^2 \quad M \to 0$$

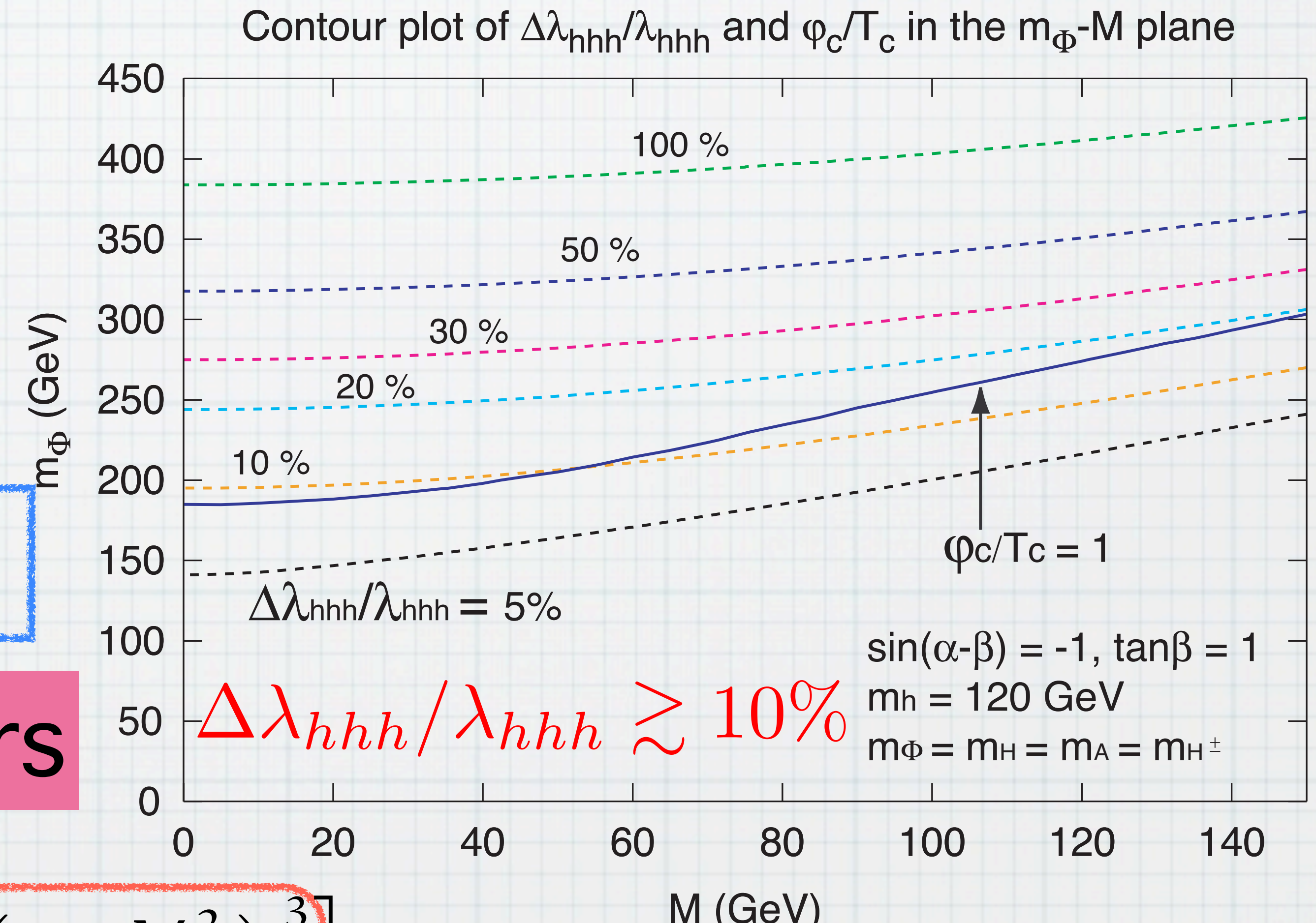
Extra bosonic loop

1st order PT

⇕ correlation

hhh coupling, h→γγ,gg,···

It can be tested at colliders



$$\lambda_{hhh}^{2HDM} \simeq \frac{3m_h^2}{v}\left[1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right]$$

SM Additional contributions

Kanemura, Okada, Senaha,PLB606,361

Benchmark model(4HDΩ)

Kanemura, T.S, Senaha,PLB706,40

Minimal SUSY model for realizing the mechanism

MSSM+Two doublets and Two charged singlets

Z_2 even

Z_2 odd

It also works in 4HD+neutral singlets

$$W = \lambda_1 \Omega_1 H_1 \cdot H_3 + \lambda_2 \Omega_2 H_2 \cdot H_4 - \mu H_1 \cdot H_2 - \mu' H_3 \cdot H_4 - \mu_\Omega \Omega_1 \Omega_2$$

$$\mathcal{L}^{\rm rel}_{\rm soft} = -\left\{ \tilde{M}^2_{H_1} \Phi_1^\dagger \Phi_1 + \tilde{M}^2_{H_2} \Phi_2^\dagger \Phi_2 + \tilde{M}^2_{H_3} \Phi_3^\dagger \Phi_3 + \tilde{M}^2_{H_4} \Phi_4^\dagger \Phi_4 + \tilde{M}^2_+ \omega_1^+ \omega_1^- + \tilde{M}^2_- \omega_2^+ \omega_2^- \right\}$$
$$- \left\{ (A_1) \omega_1^+ \Phi_1 \cdot \Phi_3 + (A_2) \omega_2^- \Phi_2 \cdot \Phi_4 + {\rm h.c.} \right\}$$
$$- \left\{ B\mu \Phi_1 \cdot \Phi_2 + B'\mu' \Phi_3 \cdot \Phi_4 + B_\Omega \mu_\Omega \omega_1^+ \omega_2^- + {\rm h.c.} \right\}$$

For $B' = B_\Omega = \mu' = \mu_\Omega = 0$ (just for simplicity)

MSSM-like(Z_2 even)

Higgs mass matrix:

$$(M_h^2)_{11} = m_Z^2 c_\beta^2 - B\mu \tan\beta + \frac{\lambda_1^4 v^2 c_\beta^2}{16\pi^2} \ln \frac{m^2_{\Omega_2^\pm} m^2_{\Phi_2'^\pm}}{m^4_{\tilde{\chi}_1^\pm}},$$

$$(M_h^2)_{22} = m_Z^2 s_\beta^2 - B\mu \cot\beta + \frac{\lambda_2^4 v^2 2_\beta^2}{16\pi^2} \ln \frac{m^2_{\Omega_1^\pm} m^2_{\Phi_1'^\pm}}{m^4_{\tilde{\chi}_2^\pm}},$$

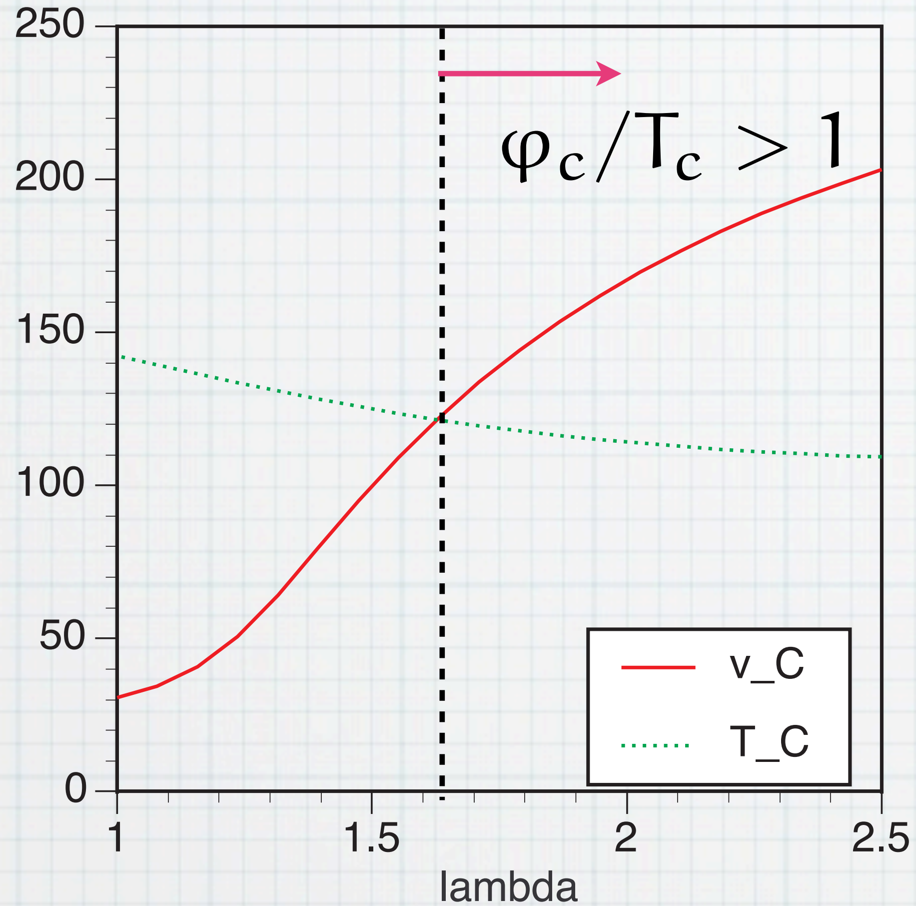
$$(M_h^2)_{12} = (M_h^2)_{21} = B\mu - m_Z^2 c_\beta s_\beta,$$

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

m_h can be pushed up

φ_c and T_c

Kanemura, T.S, Senaha, Yamada, in preparation



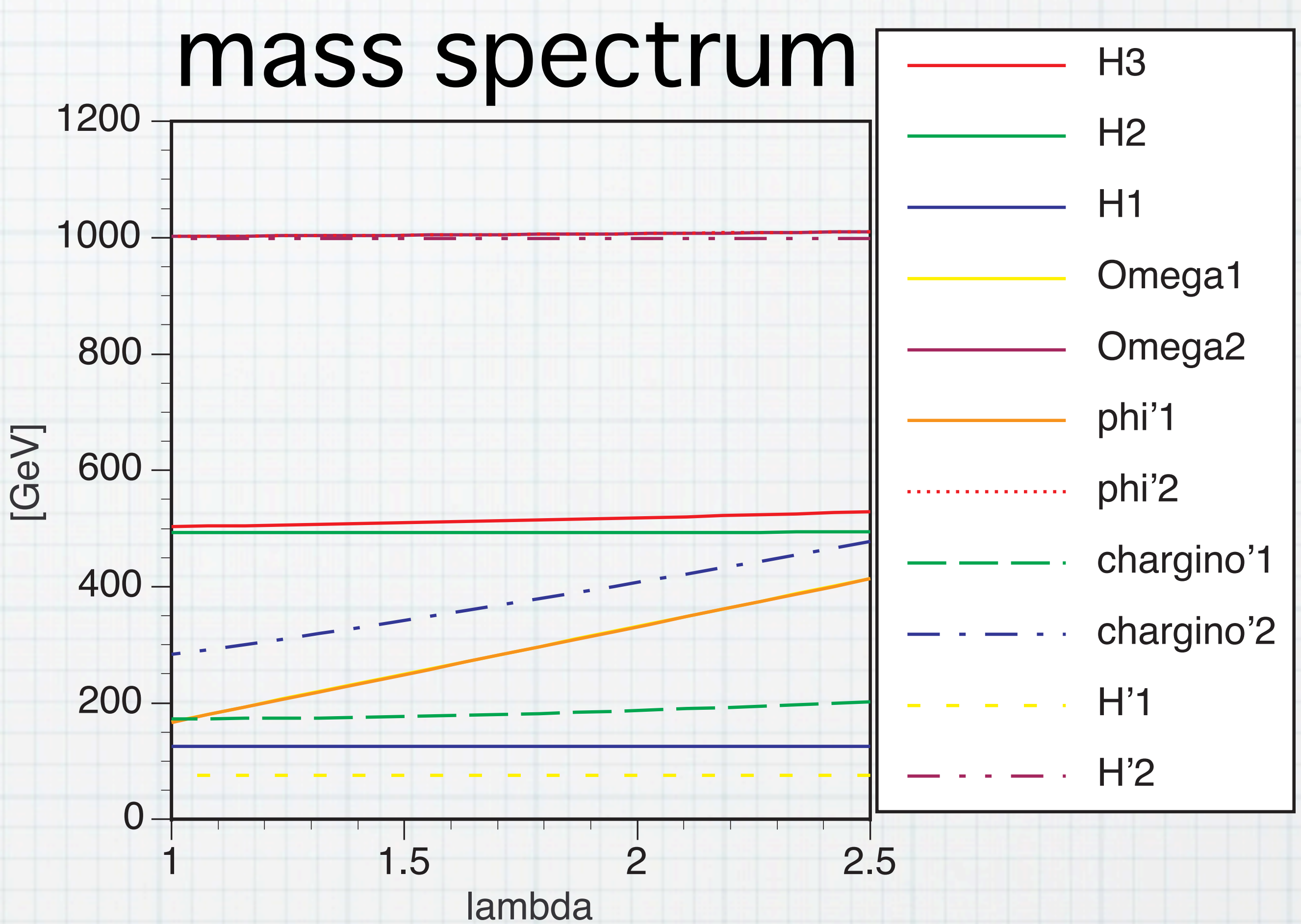


Figure 1: $\tan\beta = 3$, $m_{H^\pm} = 500$ GeV, $m_h = 126$ GeV, $\tilde{M}_{\tilde{q}} = \tilde{M}_{\tilde{t}} = \tilde{M}_{\tilde{b}} = 2000$ GeV, $X_t = 1.37 - 4.32$ TeV; $\lambda_1 = \lambda_2 \equiv \lambda$, $\bar{m}_+^2 = \bar{m}_3^2 = (1000\text{ GeV})^2$, $\bar{m}_-^2 = \bar{m}_4^2 = (50\text{ GeV})^2$, $B_\Omega = B' = 0$ GeV. $\mu_\Omega = -\mu' = 200$ GeV.

$\varphi_c/T_c > 1$ can be easily realized for $\lambda_2 > 1.6$

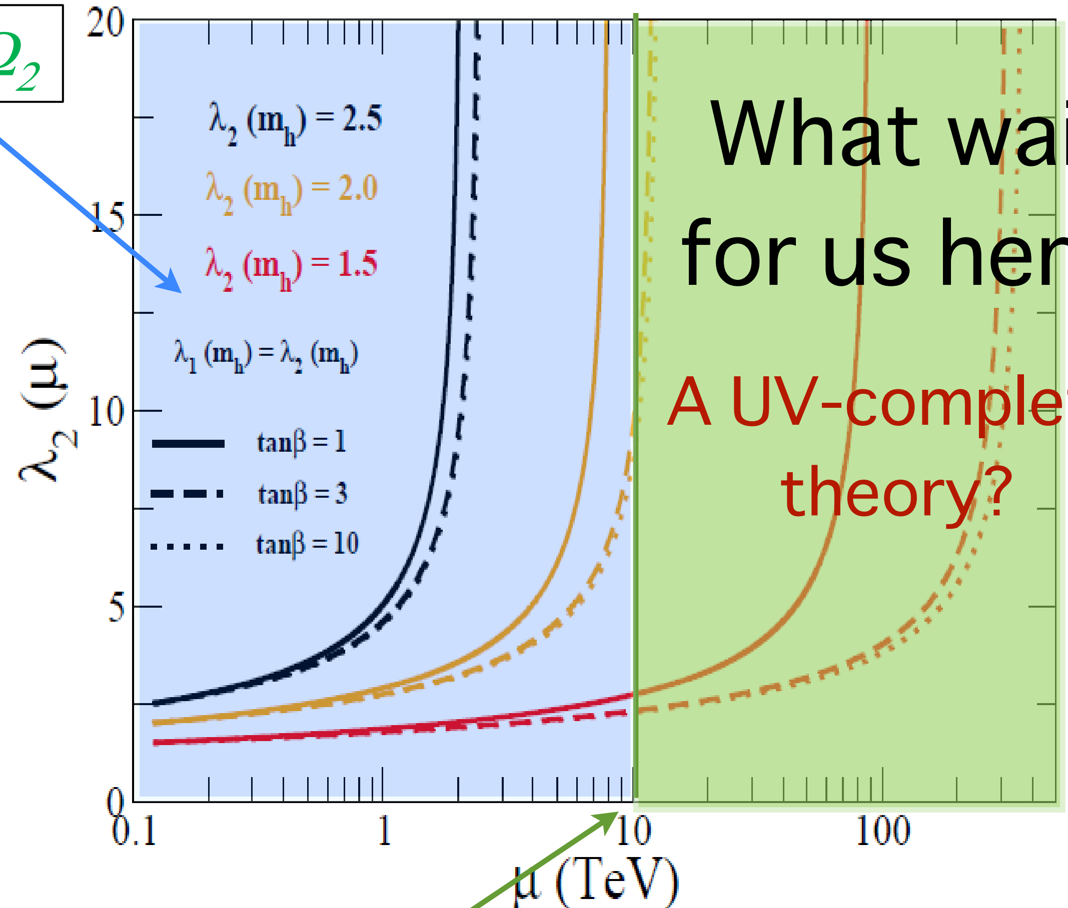
Landau pole appears at the scale of O(10TeV)

Going beyond the cutoff

$W = \lambda_1 H_u H_u' \Omega_1 + \lambda_2 H_d H_d' \Omega_2$

λ_2	Λ_{cutoff}
2.5	2 TeV
2.0	10 TeV
1.5	100 TeV

Kanemura, T.S, Yagyu, 2010



cutoff for λ=2

Landau pole at the low energy scale

↓

Cutoff scale before coming across the Landau pole

We try to build a UV-complete model above the cutoff