Singlino Resonant Dark Matter

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Phys. Rev. D 91, no. 5, 055004 (2015)

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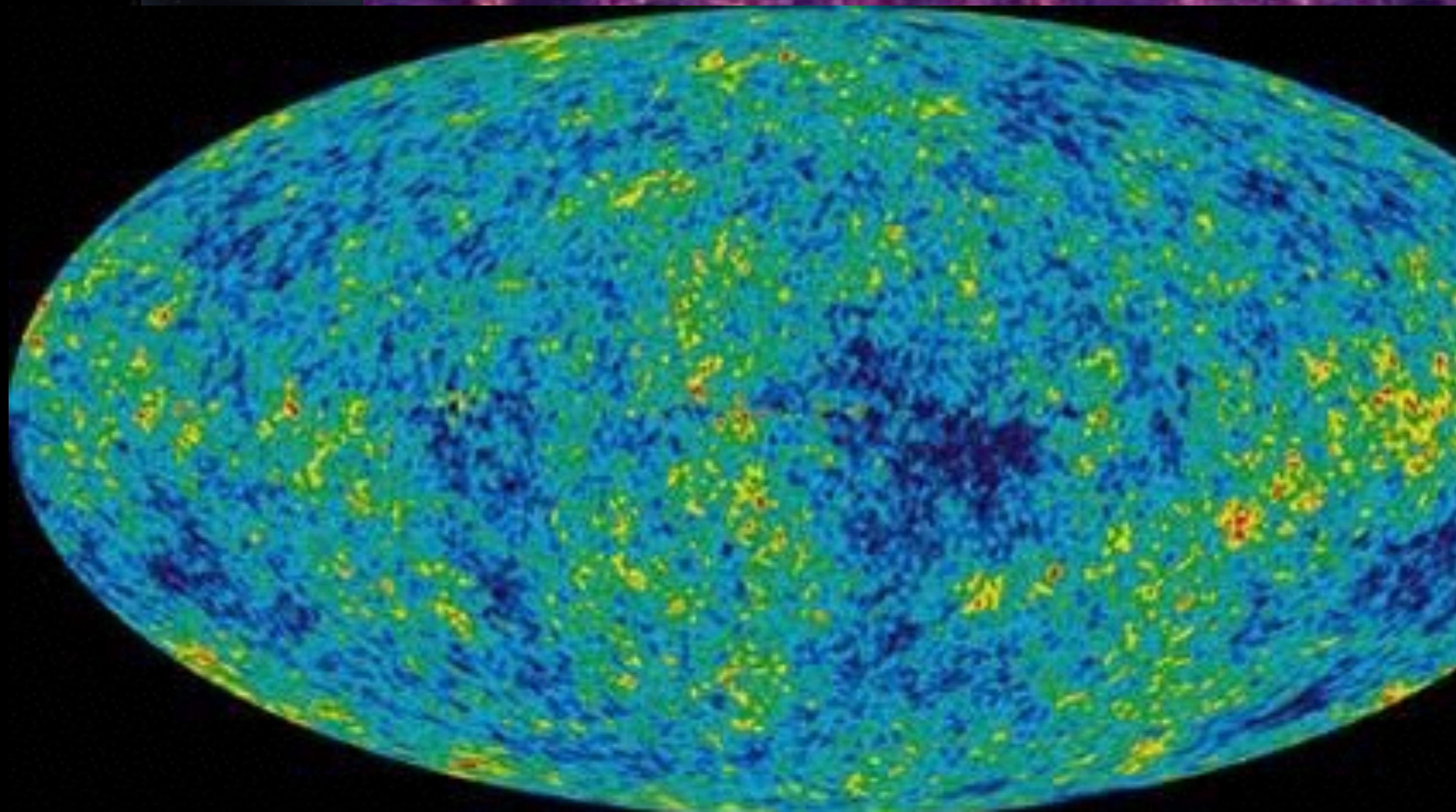
1. Introduction

There exists Dark Matter!!



1. Introduction

There may exist Supersymmetry!!

1. Introduction

Outlook of this talk.

The neutralino mass matrix is unique.

We consider a dark matter scenario
in the Nearly-Minimal Supersymmetric SM (**nMSSM**)
with TeV scale SUSY breaking soft masses.

・In this setup, the DM candidate is the **Singlino**.

・We take a radiative mass correction into account, which opens a window for the DM scenario with resonant annihilation via Higgs boson exchange.

・This scenario can be probed by future experiments!

・We also mention the possibility of the first order phase transition of the Higgs field at high temperature.

Contents

2. nMSSM

μ problem and singlet extension

MSSM has a μ term which can be any scale..

$$W_{\text{MSSM}} = \mu \hat{H}_u \hat{H}_d + \text{Yukawa terms}$$

This is a free parameter and can be Planck scale…

However…

$$\mu^2 = -\frac{1}{2}M_Z^2 + \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1-\tan^2\beta} \sim M_{\text{SUSY}}$$

μ has to be EW-SUSY breaking scale.. $\boxed{\mu \text{ Problem!}}$

If a gauge singlet field S has a vev which is order of SUSY breaking scale, μ problem can be solved.

$$W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d \qquad \mu_{\text{eff}} = \lambda\langle S\rangle \sim M_{\text{SUSY}}$$

2. nMSSM

Singlet extension models

- Next-to MSSM (NMSSM) $\mathcal{Z}_3$

  [S. Abel et.al. `95]

$$W_{\rm NMSSM} = W_{\rm Yukawa} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3$$

- Nearly-Minimal SSM (nMSSM)

  [C. Panagiotakopoulos et.al. `99]

tadpole

$$W_{\rm nMSSM} = W_{\rm Yukawa} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S}$$

$$V_{\rm soft} \supset t_S S + {\rm h.c.}$$

The size of the tadpoles can be controlled by $\mathcal{Z}_5^R$ symmetry.

2. nMSSM

nMSSM We impose the $\mathcal{Z}_5^R$ symmetry.

We can also impose the matter parity.

	H_d	H_u	S	Q	U	D	L	e
Z5 charge	1	1	4	2	3	3	2	3

$$\hat{\Phi}_i \rightarrow e^{i\frac{2\pi q_i}{5}}\hat{\Phi}_i, \quad W \rightarrow e^{i\frac{2\pi}{5}}W,$$

where "1" means charge $\omega = \exp(2\pi i/5)$, and "5" means $\omega^5 = 1$

- This discrete R symmetry is spontaneously broken by the sector $W_{\not R}$ with vev $\langle W_{\not R}\rangle = W_0$.
- To get a small cosmological constant, we need: $W_0 = m_{3/2}M_{\rm PL}^2$.
- In general, following terms exist: $K \supset \frac{c_1}{M_{\rm Pl}^2}W_{\not R}\hat{S} + \text{H.c.}, \ W \supset \frac{c_2}{M_{\rm Pl}^4}W_{\not R}^2\hat{S}.$
- As a results, at low energy, we have: $V_{\rm soft} \sim m_{3/2}^3 S + \text{H.c.}, \ W \sim m_{3/2}^2\hat{S}.$

We will concentrate on the phenomenology of nMSSM.

2. nMSSM

$$W_{\mathrm{nMSSM}} = W_{\mathrm{Yukawa}} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S}$$

$$V_{\mathrm{soft}} = t_S S + \mathrm{h.c.} + m_S^2|S|^2 + \mathrm{others}$$

$$t_S \sim \mathcal{O}(M_{\mathrm{SUSY}}^3),\ m_{12}^2 \sim \mathcal{O}(M_{\mathrm{SUSY}}^2)$$

$$\langle S \rangle \sim \mathcal{O}(M_{\mathrm{SUSY}})$$

Properties of nMSSM

- μ term is "controlled" by the discrete R symmetry.
- No domain wall problem.
- There exists a dark matter candidate **Singlino!**

2. nMSSM

nMSSM $W_{\mathrm{nMSSM}} = W_{\mathrm{Yukawa}} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S}$

Lightest SUSY particle(LSP) in nMSSM

Singlino!

Neutralino Mass matrix, basis: $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$

$$\mathcal{M}_{\mathrm{tree}} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\mathrm{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix}$$

No mass term!

$\Rightarrow$ $m_{\tilde{s}_0}^{\mathrm{tree}} \sim \lambda^2 \frac{v^2}{M_{\mathrm{SUSY}}} \sin 2\beta$ ($\tilde{s}_0$: singlino like particle)

If SUSY breaking scale is high, singlino like particle is always light and can be a DM candidate.

2.nMSSM

- $m_h = 125.7\mathrm{GeV}$

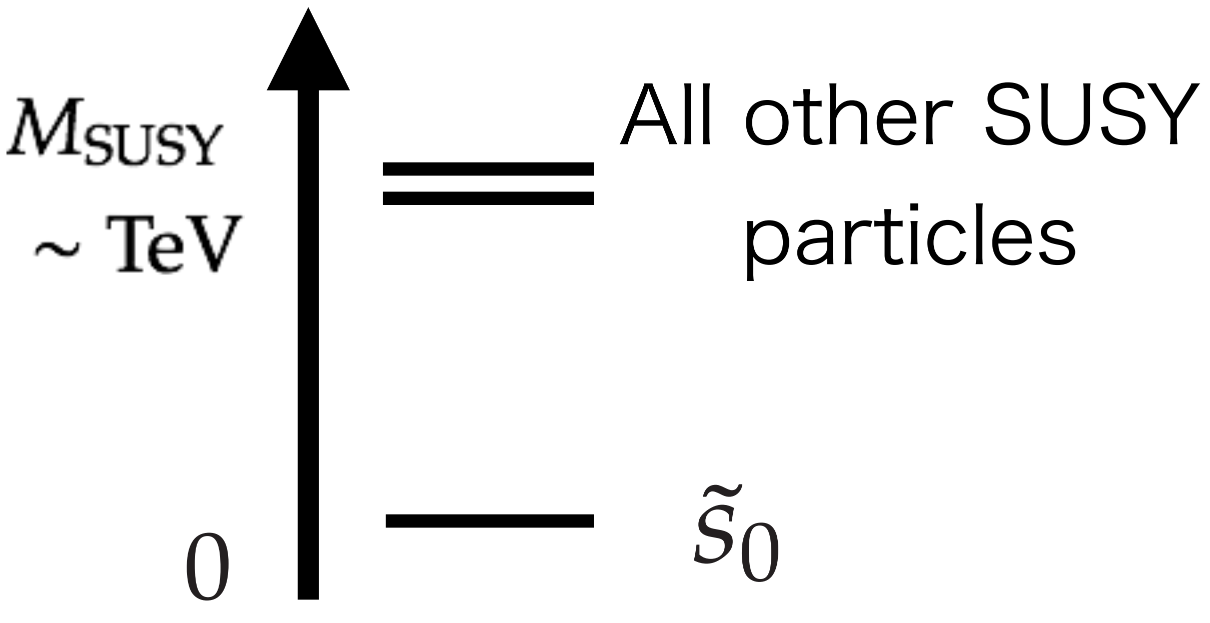
  and

- No discovery of SUSY particles at the LHC

may imply TeV scale SUSY: $M_{\mathrm{SUSY}} \sim \mathrm{TeV}$

In this case,

Singlino LSP can be DM



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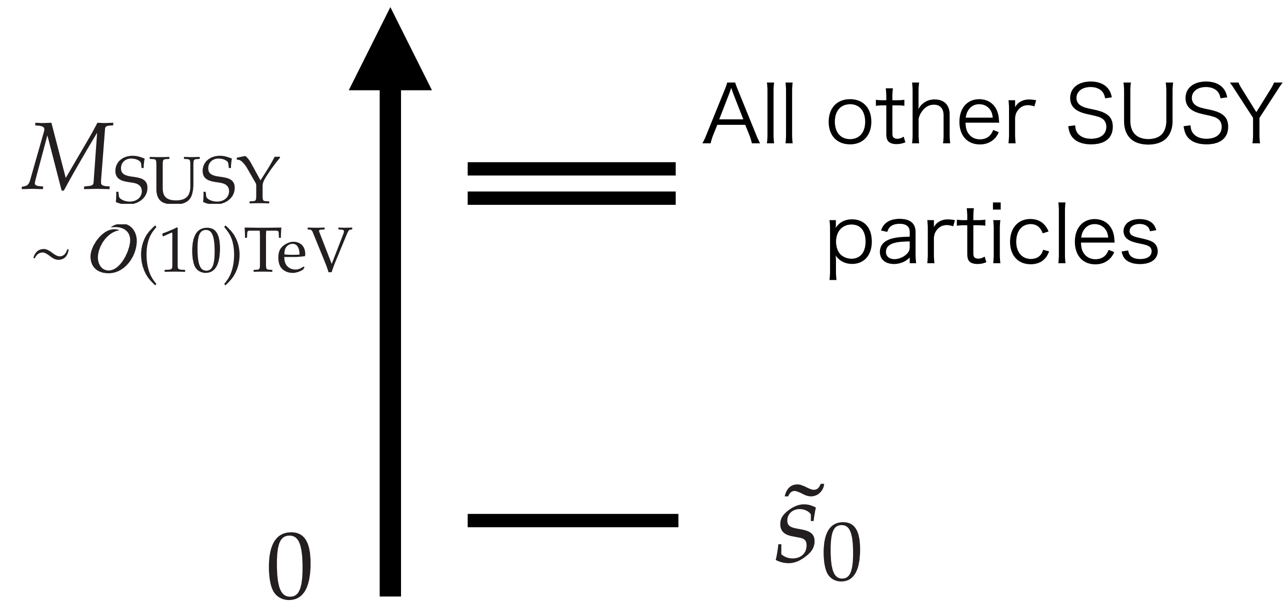
3. Singlino Dark Matter

Integrating out all heavy SUSY particles



$$\boxed{-\mathcal{L}_{\rm eff} \supset \frac{m_{\tilde{s}_0}}{2}\bar{\tilde{s}}_0\tilde{s}_0 + \frac{\lambda_{\rm eff}}{2} h\bar{\tilde{s}}_0\tilde{s}_0}$$

$\tilde{s}_0$: singlino like LSP
h : the Higgs boson

Before going to the calculation in nMSSM, let's see this effective model properties regarding $m_{\tilde{s}_0}$ and $\lambda_{\rm eff}$ as free parameters.

3. Singlino Dark Matter

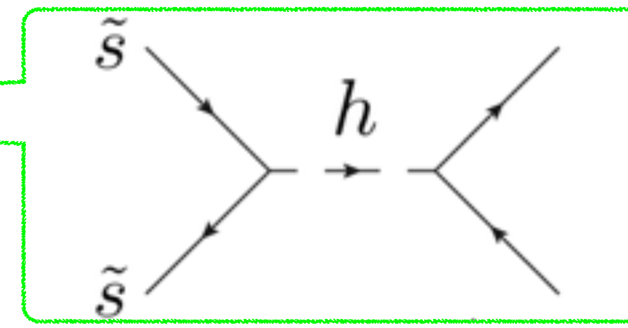
Dark Matter abundance

$$-\mathcal{L}_{\rm eff} \supset \frac{m_{\tilde{s}_0}}{2}\bar{\tilde{s}}_0\tilde{s}_0 + \frac{\lambda_{\rm eff}}{2}h\bar{\tilde{s}}_0\tilde{s}_0$$

- Annihilation cross section

$$\sigma(s) = \frac{\lambda_{\rm eff}^2}{2}\sqrt{1-\frac{4m_{\tilde{s}_0}^2}{s}}\,\frac{\sqrt{s}\Gamma_h}{(s-m_h^2)^2+s\Gamma_h^2}.$$

$(\Gamma_h \simeq 4\ \mathrm{MeV})$



・proportional to the relative velocity
→ p-wave suppressed.

・Resonantly enhanced if $s \sim m_h^2$.

- Boltzmann equation

$$\frac{dn_{\tilde{s}_0}}{dt} + 3Hn_{\tilde{s}_0} = -\langle\sigma v\rangle(T)\left(n_{\tilde{s}_0}^2 - n_{\tilde{s}_0}^{(\rm eq)2}\right) \Rightarrow \Omega_{\tilde{s}_0}h^2 \sim 0.1\times\left(\frac{0.03^2/(100\ \mathrm{GeV})^2}{\langle\sigma v\rangle(T_{\rm fr})}\right)$$

$(T_{\rm fr} \sim m_{\tilde{s}_0}/20)$

→Thermal relic abundance is roughly determined by the thermal averaged cross section $\langle\sigma v\rangle$ at freeze out $T_{\rm fr} \sim m_{\tilde{s}_0}/20$.

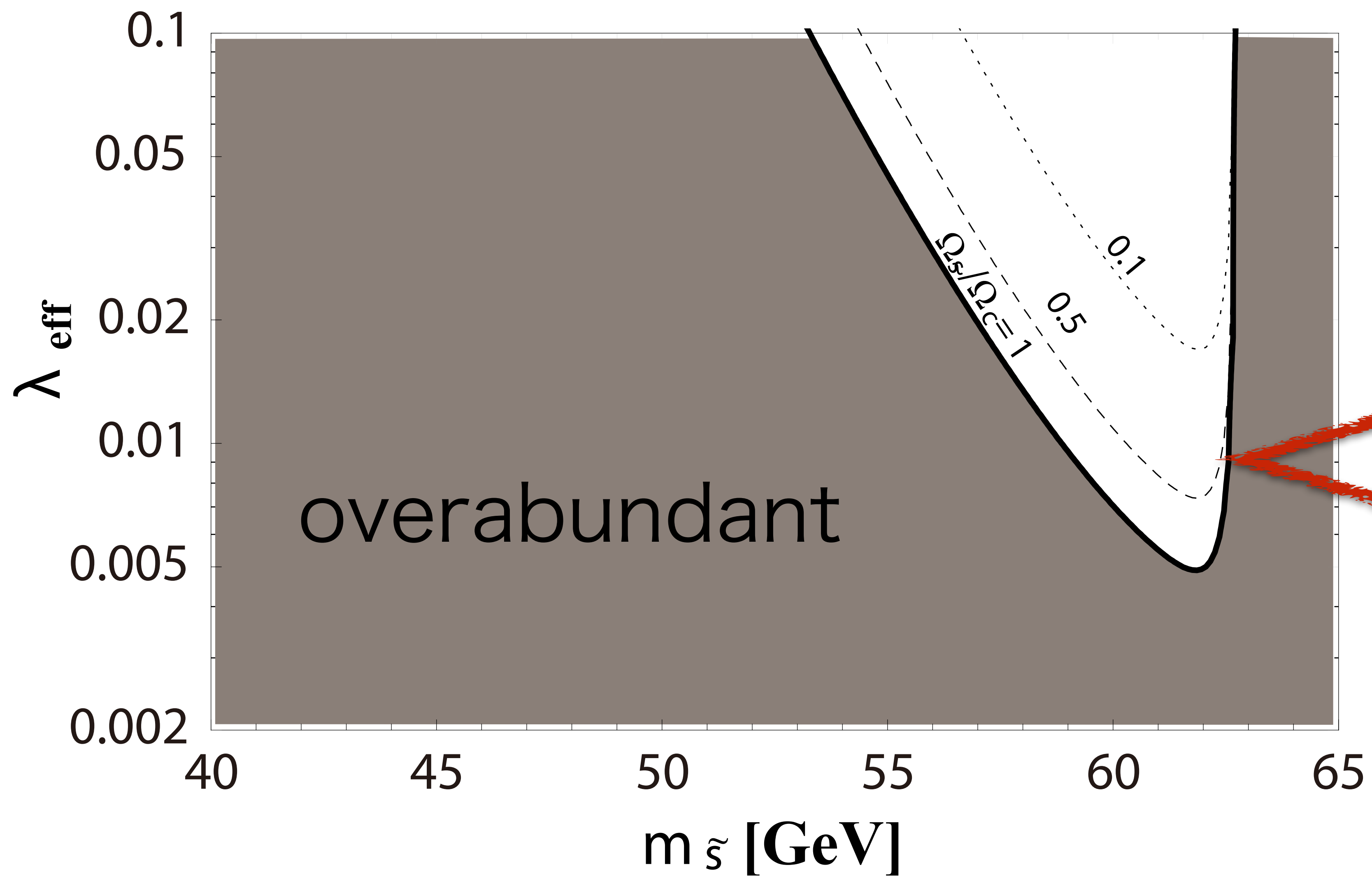
- If $2m_{\tilde{s}_0} \sim m_h$, the cross section is resonantly enhanced and the singlino can be DM with small $\lambda_{\rm eff}$.

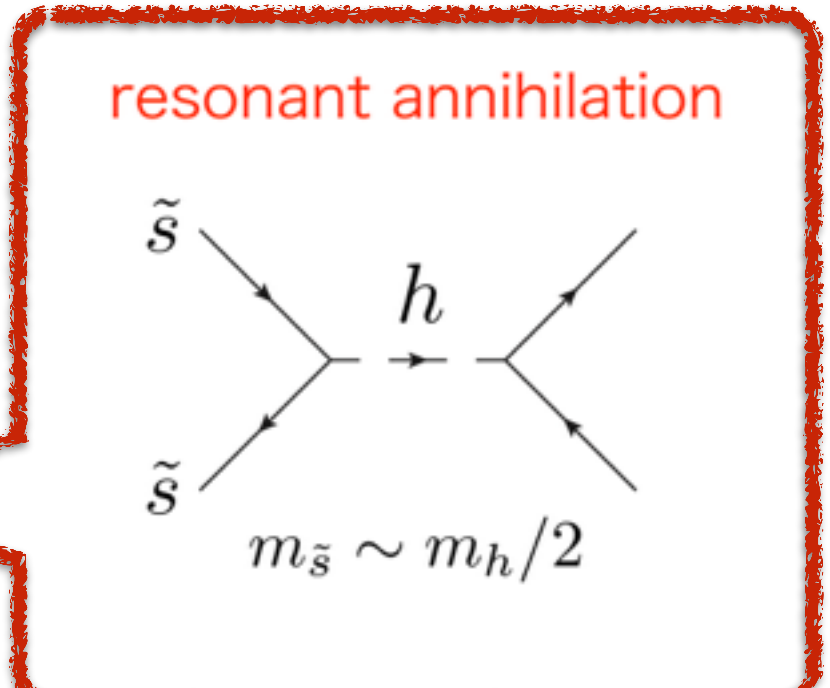
3. Singlino Dark Matter

Dark Matter abundance

$$-\mathcal{L}_{\rm eff} \supset \frac{m_{\tilde{s}_0}}{2}\bar{\tilde{s}}_0\tilde{s}_0 + \frac{\lambda_{\rm eff}}{2}h\bar{\tilde{s}}_0\tilde{s}_0$$

the ratio of thermal relic abundance to $\Omega_c h^2 = 0.1199$



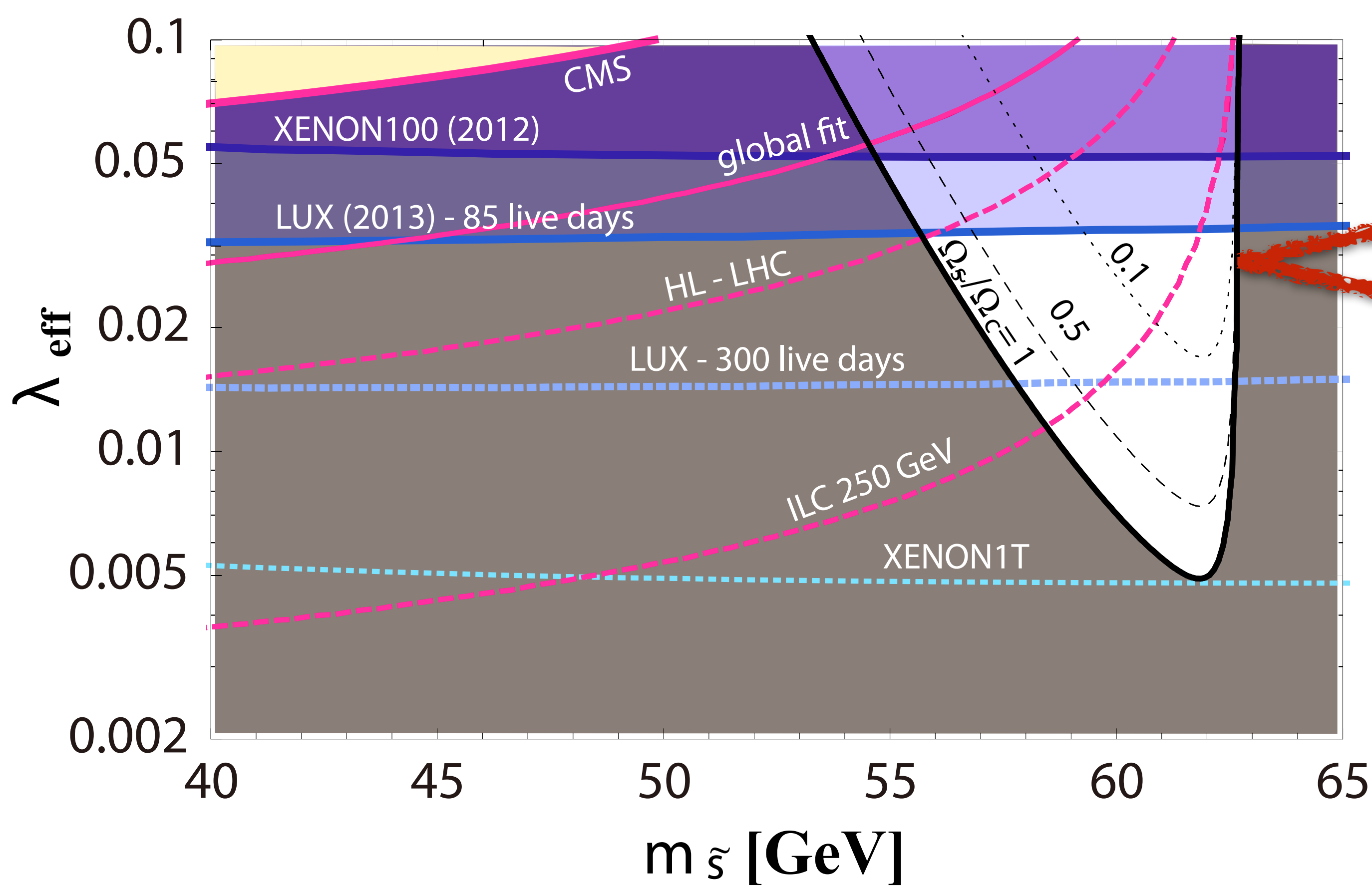


3. Singlino Dark Matter

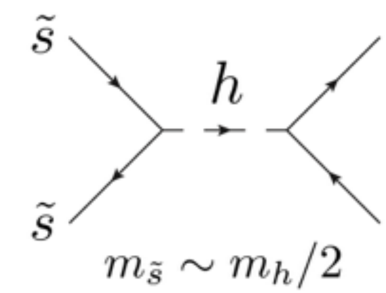
Dark Matter abundance

$$-\mathcal{L}_{\text{eff}} \supset \frac{m_{\tilde{s}_0}}{2}\bar{\tilde{s}}_0\tilde{s}_0 + \frac{\lambda_{\text{eff}}}{2}h\bar{\tilde{s}}_0\tilde{s}_0$$

Experimental constraints/future prospects.



resonant annihilation



— : current bounds

···· : future bounds

The region with $m_{\tilde{s}_0}$ ~60GeV and λ_{eff} ~0.01 is

・consistent with DM abundance and

・can be probed by XENON 1T!!

3. Singlino Dark Matter

・nMSSM analysis

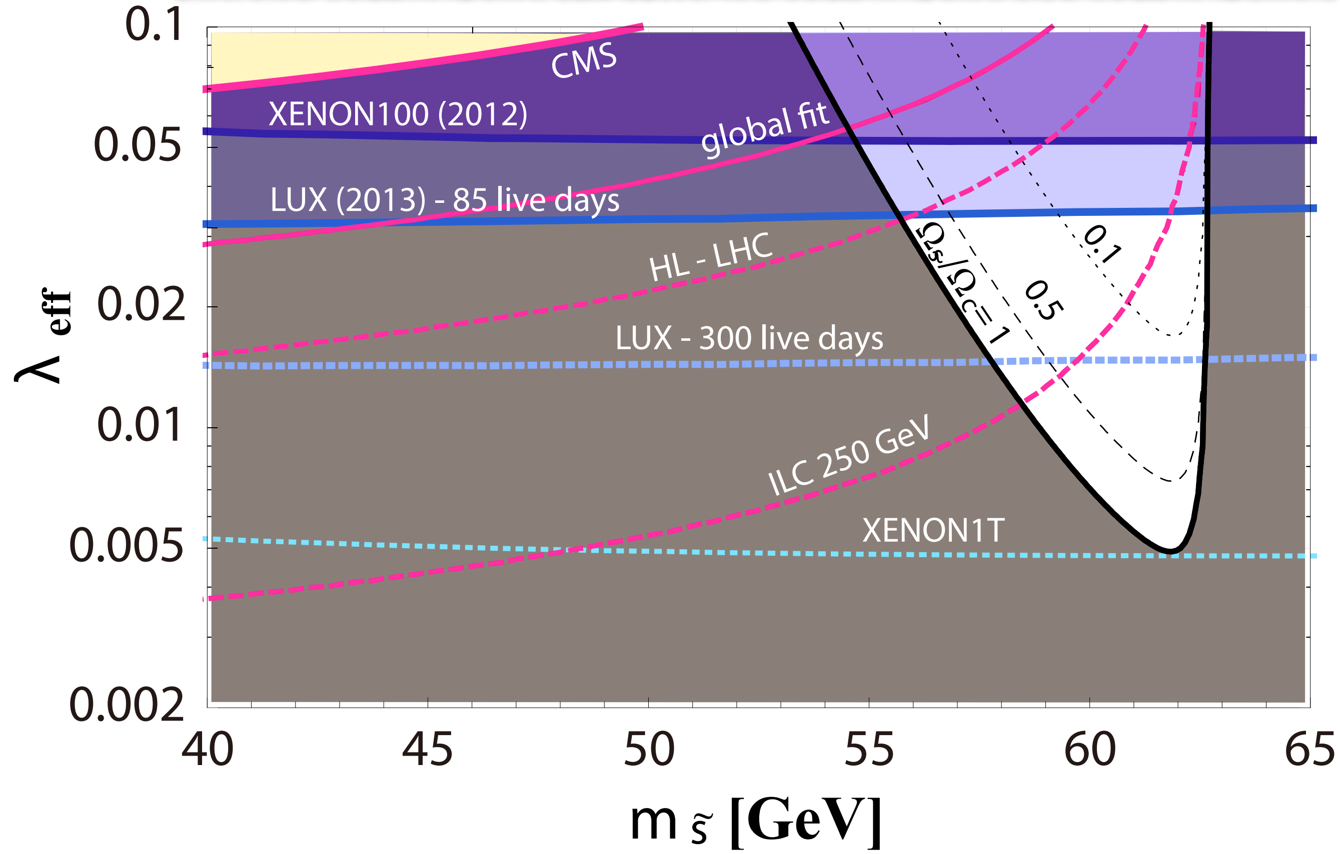
In tree level nMSSM,

$(W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d)$

$$m^{\rm tree}_{\tilde{s}_0} \sim \lambda^2 \frac{v^2}{M_{\rm SUSY}} \sin 2\beta$$

$$\lambda_{\rm eff} \sim \lambda^2 \frac{v}{M_{\rm SUSY}} \sin 2\beta$$

$$-\mathcal{L}_{\rm eff} \supset \frac{m_{\tilde{s}_0}}{2}\bar{\tilde{s}}_0\tilde{s}_0 + \frac{\lambda_{\rm eff}}{2} h\bar{\tilde{s}}_0\tilde{s}_0$$



for $\lambda_{\rm eff} \sim 0.01, \;\; m_{\tilde{s}_0} \sim 1.7{\rm GeV}....$

Actually, there has been no study about nMSSM with high scale SUSY breaking.

3. Singlino Dark Matter

However,

one-loop corrections can raise $m_{\tilde{s}_0}$!

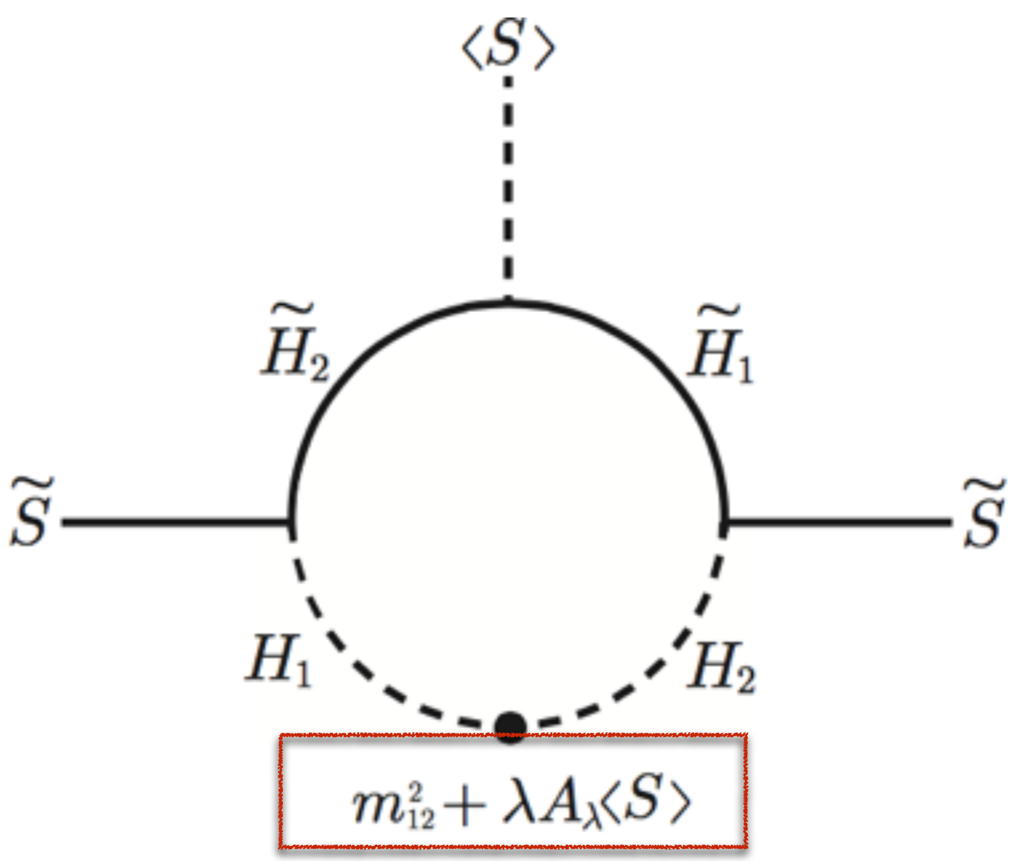
3. Singlino Dark Matter

・nMSSM analysis

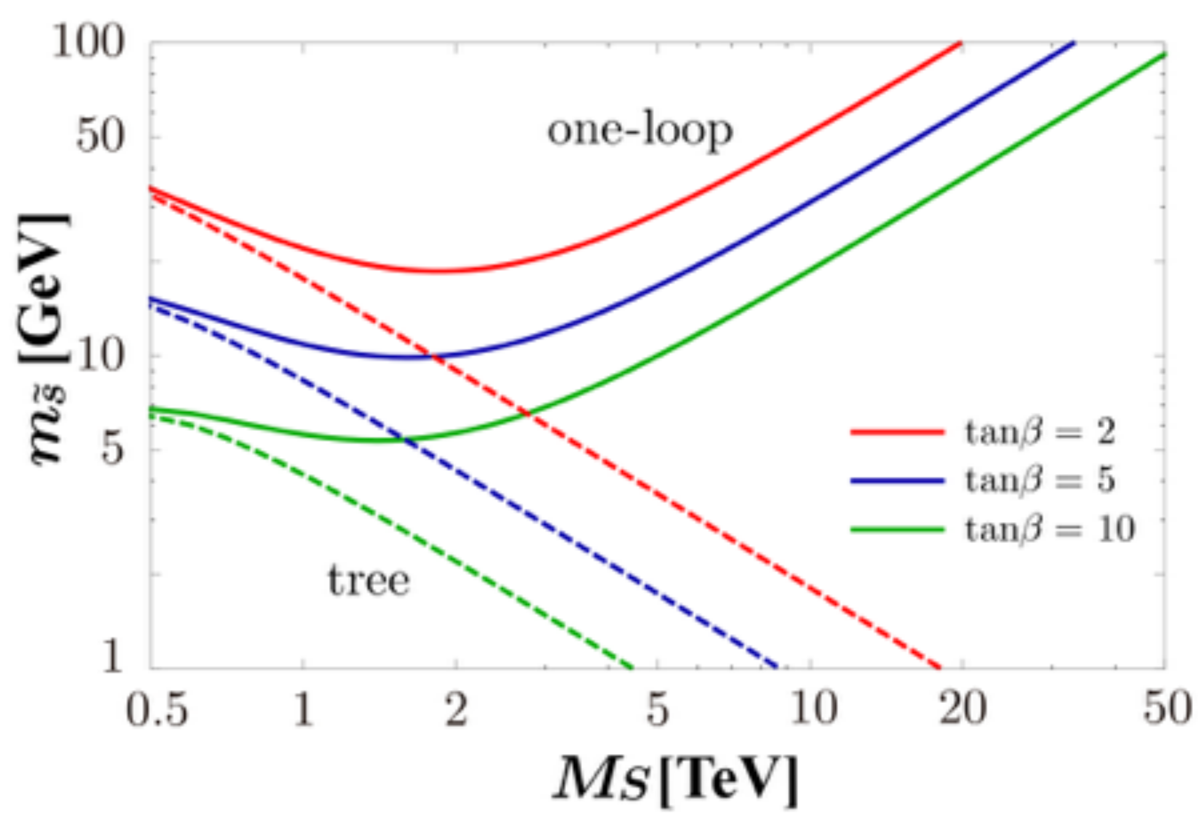
$(W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S})$

$$-\mathcal{L}_{\rm eff} \supset \frac{m_{\tilde{s}_0}}{2}\bar{\tilde{s}}_0\tilde{s}_0 + \frac{\lambda_{\rm eff}}{2}h\bar{\tilde{s}}_0\tilde{s}_0$$

One-loop corrections can raise $m_{\tilde{s}_0}$!!



$\lambda = 0.75$ All dimensionful parameters$= M_S$



$$m_{\tilde{s}_0}^{\text{1-loop}} \sim \frac{\lambda^2}{16\pi^2}M_{\rm SUSY}\sin 2\beta$$

$$m_{\tilde{s}} \simeq \frac{\lambda^2}{16\pi^2}\mu_{\rm eff}\sin 2\beta \cdot F\left(\frac{2(m_{12}^2 + A_\lambda\mu_{\rm eff})}{\mu_{\rm eff}^2\sin 2\beta}\right)$$

$$F(x) \equiv \frac{x\log x}{x-1}$$

3. Singlino Dark Matter

・nMSSM analysis

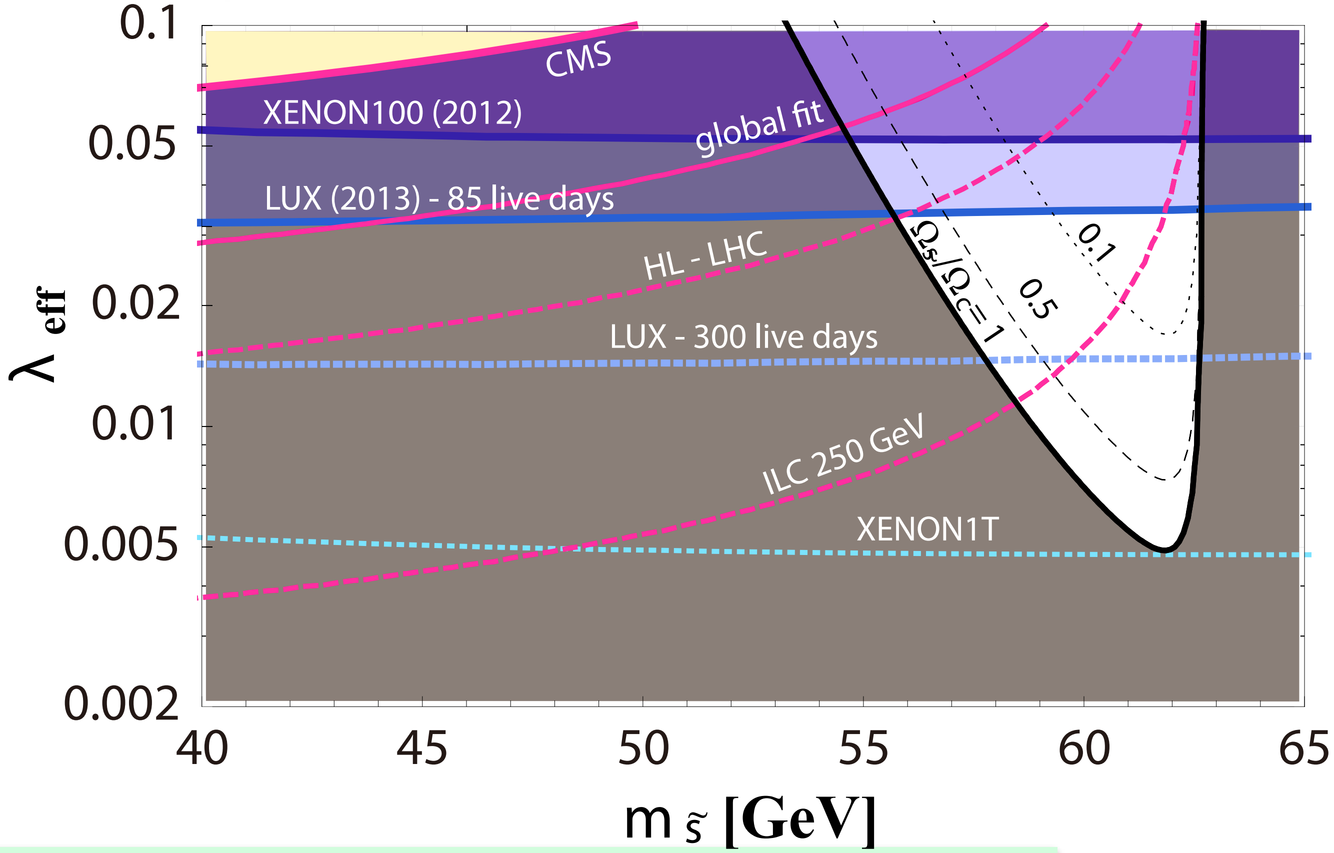
$(W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S})$

$$\boxed{-\mathcal{L}_{\rm eff} \supset \frac{m_{\tilde{s}_0}}{2}\bar{\tilde{s}}_0\tilde{s}_0 + \frac{\lambda_{\rm eff}}{2}h\bar{\tilde{s}}_0\tilde{s}_0}$$

With 1-loop effects:

$$m_{\tilde{s}_0}^{\text{1-loop}} \sim \frac{\lambda^2}{16\pi^2}M_{\rm SUSY}\sin 2\beta$$

$$\lambda_{\rm eff} \sim \lambda^2\frac{v}{M_{\rm SUSY}}\sin 2\beta$$



$$\lambda_{\rm eff} \sim 0.01, \;\; m_{\tilde{s}_0} \sim 60\text{GeV}$$

seems to be possible if

$$M_{\rm SUSY} \sim \mathcal{O}(10)\text{TeV}, \;\; \tan\beta \sim \mathcal{O}(1), \; \lambda \sim \mathcal{O}(1)$$

3. Singlino Dark Matter

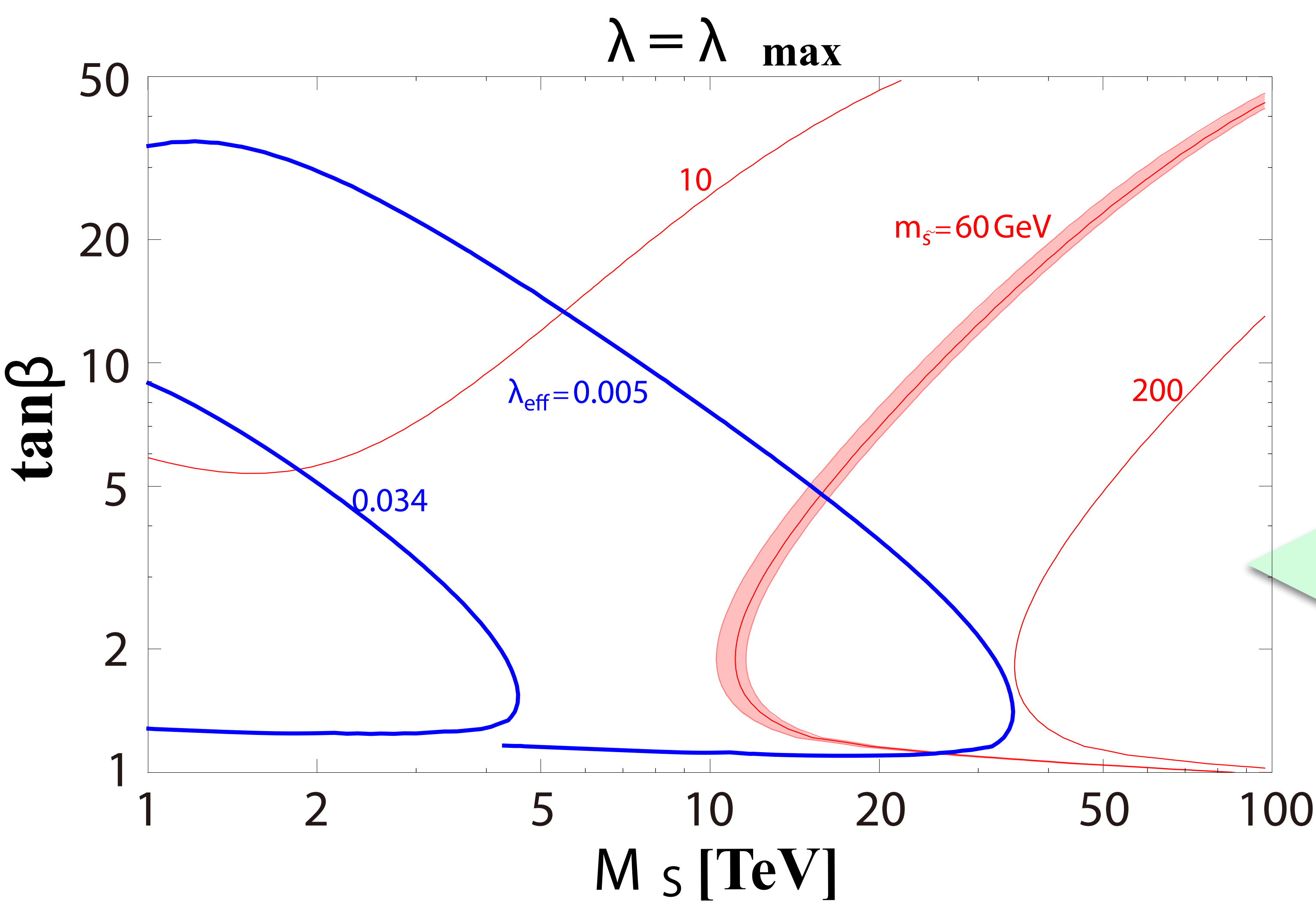
- Numerical results of nMSSM singlino DM $(W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d)$

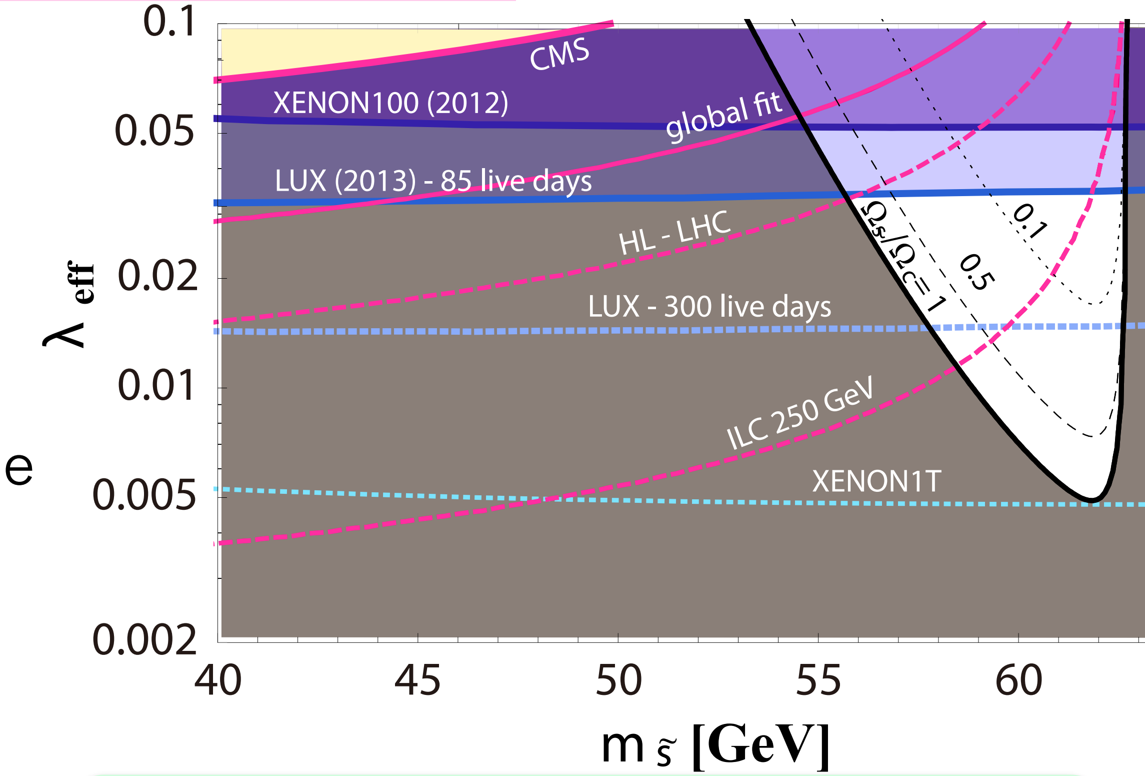
Let's see a typical situation.

We set

$A_\lambda^2 = \frac{2}{5}M_S^2$,other dimensionful parameters= M_S

$\lambda_{\rm max}$: maximal λ avoiding the Landau pole at GUT scale





The region which is consistent with DM exists around

$M_S \sim \mathcal{O}(10)\mathrm{TeV}$,

$\tan\beta \sim \mathcal{O}(1)$

3. Singlino Dark Matter

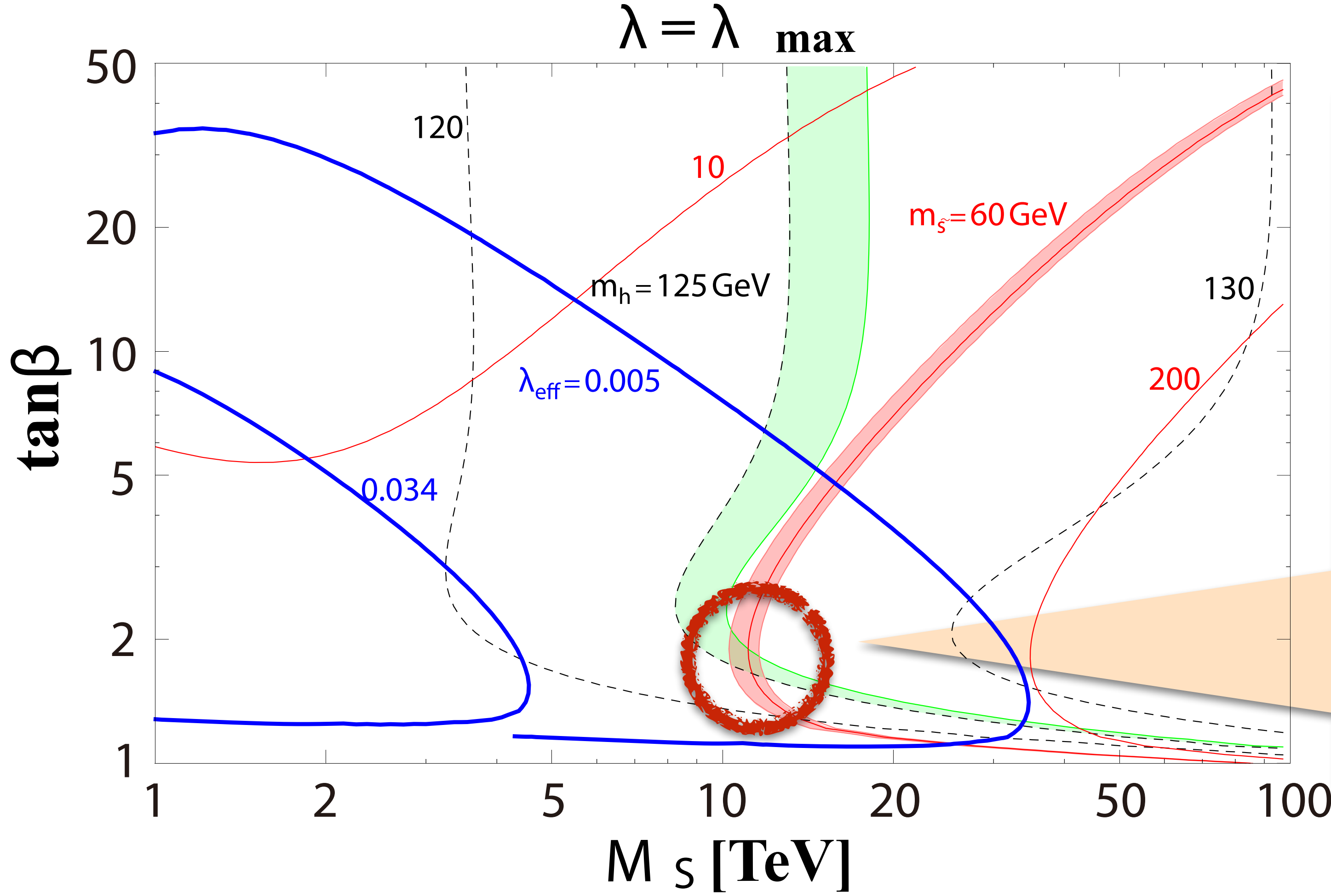
- Numerical results of nMSSM singlino DM $(W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d)$

The Higgs mass of 125 GeV can be explained simultaneously!!

$$\lambda_H \simeq \lambda_{\rm MSSM} + \frac{\lambda^2}{2}\frac{m_S^2 - A_\lambda^2}{m_S^2}\sin^2 2\beta$$

$A_\lambda^2 = \frac{2}{5}M_S^2$,other dimensionful parameters= M_S

$\lambda_{\rm max}$: maximal λ avoiding the Landau pole at GUT scale



In this region,
- DM abundance

and
- the Higgs mass

can be both explained!!

3. Singlino Dark Matter

・Summary of nMSSM singlino DM

Thanks to the radiative correction to the singlino mass

Singlino Dark Matter in nMSSM
with supersymmetry breaking scale $M_S \sim \mathcal{O}(10)$ TeV

- can explain the Dark Matter relic abundance. via the resonant annihilation with Higgs boson.
- can explain the Higgs boson mass simultaneously.
- can be probed by the future experiments.

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2. nMSSM
3. Singlino Dark Matter
4. **High Temperature Phase Transition**
5. Conclusion

4. High Temperature Phase Transition

- The nMSSM has a unique scalar potential:

$$V \supset m_S^2|S|^2 + \lambda^2|H|^2|S|^2 + t_S S + h.c$$

Tadpole!

- If there exist vector like multiplets coupling to S: $W \supset \lambda_1 \hat{S}\hat{\bar{X}}\hat{X}$, the high temperature scalar potential becomes non-trivial due to the thermal effects.

$$V \supset m_S^2|S|^2 + y_s^2 T^2|S|^2 + \lambda^2|H|^2|S|^2 + t_S S + h.c.$$

- As a result, the first order phase transition of the Higgs field can occur at high temperature $T \sim M_{\mathrm{SUSY}}$!

This may open the possibility of high scale electroweak baryogenesis. See Phys. Rev. D 91, no. 5, 055004 (2015), if you are interested in.

In this talk, we will show first order PT can actually occur.

4. High Temperature Phase Transition

After solving E. O. M. of S, the potential at T becomes

$$V = -M^2\phi^2 + y_\phi^2 T^2\phi^2 + \bar{\lambda}\phi^4 - \frac{t_s^2}{m_s^2 + y_S^2 T^2 + \lambda^2\phi^2},$$

$$M^2 = -m_d^2\cos^2\beta - m_u^2\sin^2\beta - m_{12}^2\sin 2\beta,$$

Important!!

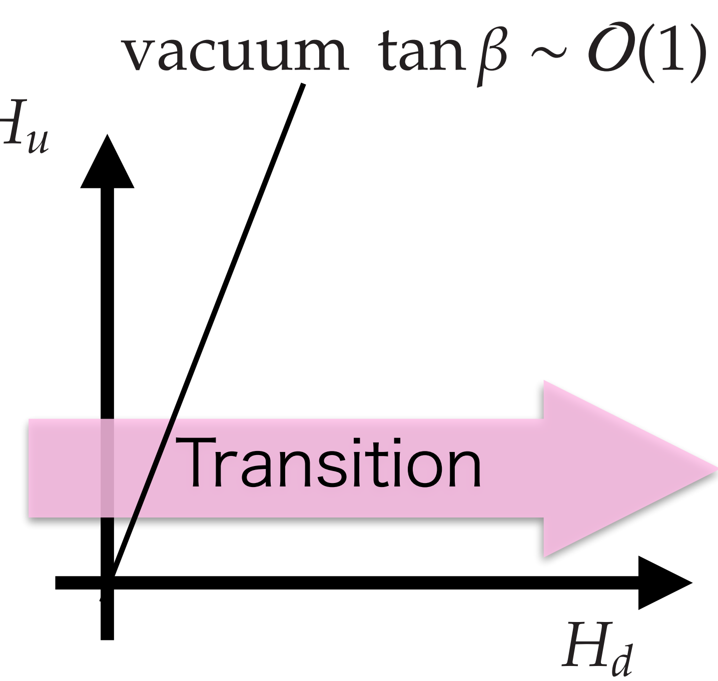
$$\bar{\lambda} = \frac{\lambda^2}{4}\sin^2 2\beta + \frac{g'^2 + g_2^2}{2}\cos^2 2\beta,$$

$$\phi^2 \equiv |H_d|^2 + |H_u|^2,$$

$$y_S^2,\ y_\phi^2 \sim \mathcal{O}(1)$$

tan β~0 direction has smaller V because

- the quartic coupling is small
- no thermal mass from top quarks



Let's consider the phase transition for tan β~0 direction.

4. High Temperature Phase Transition

Let's consider the phase transition for $\tan\beta \sim 0$ direction.

Parameterize the potential as:

$$V \propto (1 + c^2 - b^2)X + \left(a^2 - \frac{1}{1+X}\right)X^2,$$

$$(X \propto \phi^2 = |H_u|^2 + |H_d|^2)$$

$$m_S(T)^2 \equiv m_S^2 + y_S^2 T^2,$$

$$f(T) \equiv \frac{m_S^2 + y_S^2 T^2}{m_S^2} \geq 1,$$

$$X \equiv \frac{\lambda\phi^2}{m_S(T)^2},$$

$$a^2 \equiv \frac{\bar{\lambda}^2 m_S(T)^6}{\lambda^4 t_S^2} \propto f(T)^3,$$

$$b^2 \equiv \frac{M^2 m_S(T)^4}{\lambda^2 t_S^2} \propto f(T)^2,$$

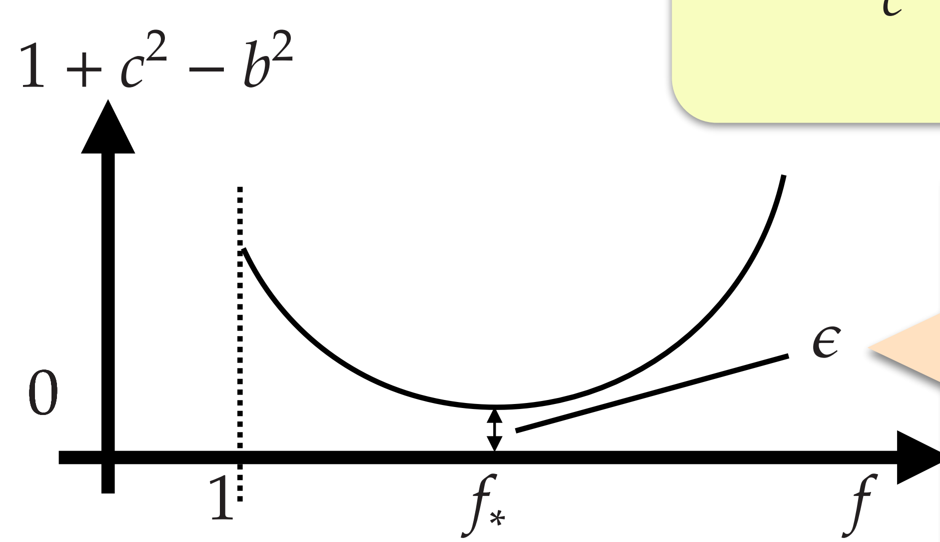
$$c^2 \equiv \frac{y_\phi^2 T^2 m_S(T)^4}{\lambda^2 t_S^2}.$$

$$1 + c^2 - b^2 = 1 - b_0^2 f^2(1+\eta) + b_0^2 \eta f^3,$$

$$\eta \equiv \frac{y_\phi^2 m_S^2}{y_S^2 M^2},$$

$$b_0 = b(T=0).$$

We can fix $1 + c^2 - b^2$ as the right figure→.



It can be always positive and have minimal value ε at $f_* = 2(\eta+1)/3\eta$

ε can be any value if $b_0 < 1,\ \eta < 2.$

4. High Temperature Phase Transition

Let's consider the phase transition for $\tan\beta \sim 0$ direction.

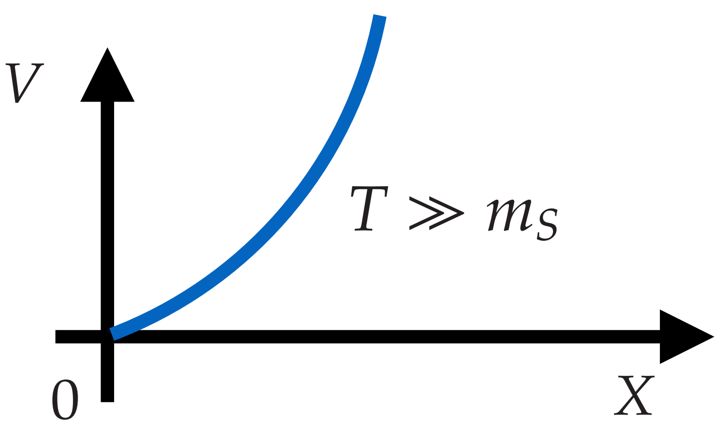
$$V \propto (1 + c^2 - b^2)X + \left(a^2 - \frac{1}{1+X}\right)X^2,$$

$$\eta \equiv \frac{y_\phi^2 m_S^2}{y_S^2 M^2},\ f \equiv \frac{y_S^2 T^2 + m_S^2}{m_S^2}. \qquad (X \propto \phi^2 = |H_u|^2 + |H_d|^2)$$

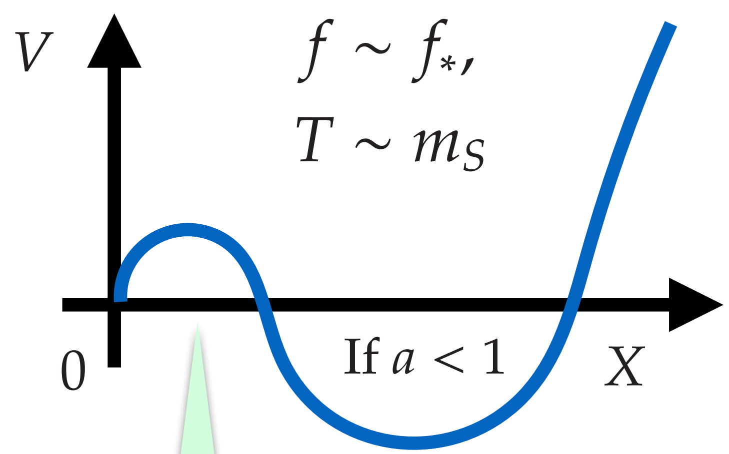
$1 + c^2 - b^2$ can be always positive
and have minimal value ε
at $f_* = 2(\eta+1)/3\eta$
ε can be arbitrarily small
if $b_0 < 1,\ \eta < 2$.

The following situation can occur.

At Huge temperature,

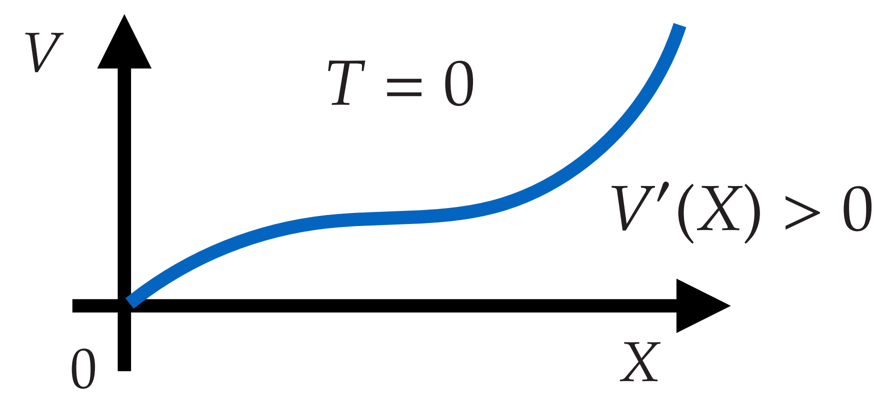


At High temperature,



$V \sim \epsilon X - (1 - a^2)X^2$

At zero temperature,



The first order phase transition can occur at $T \sim m_S$.

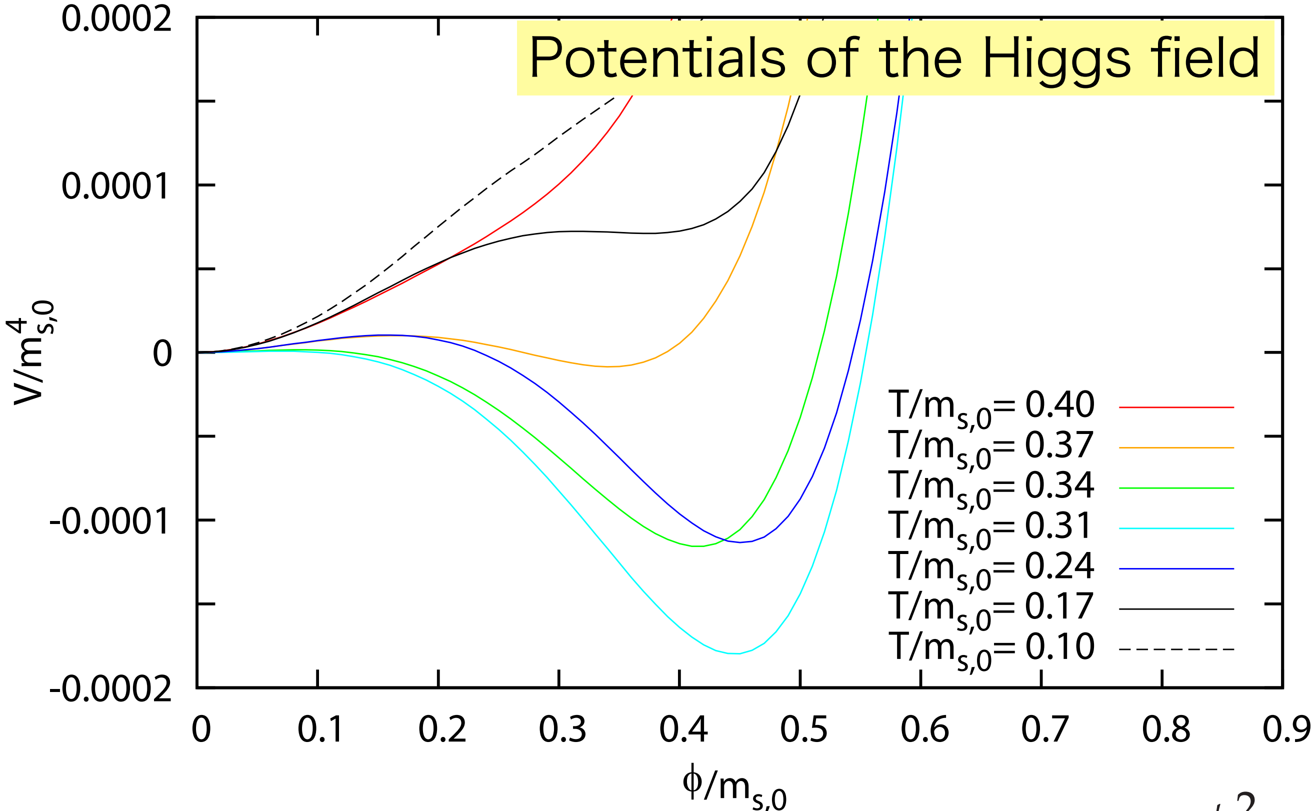
The EW vacuum be realised for $\tan\beta = \mathcal{O}(1)$ direction.

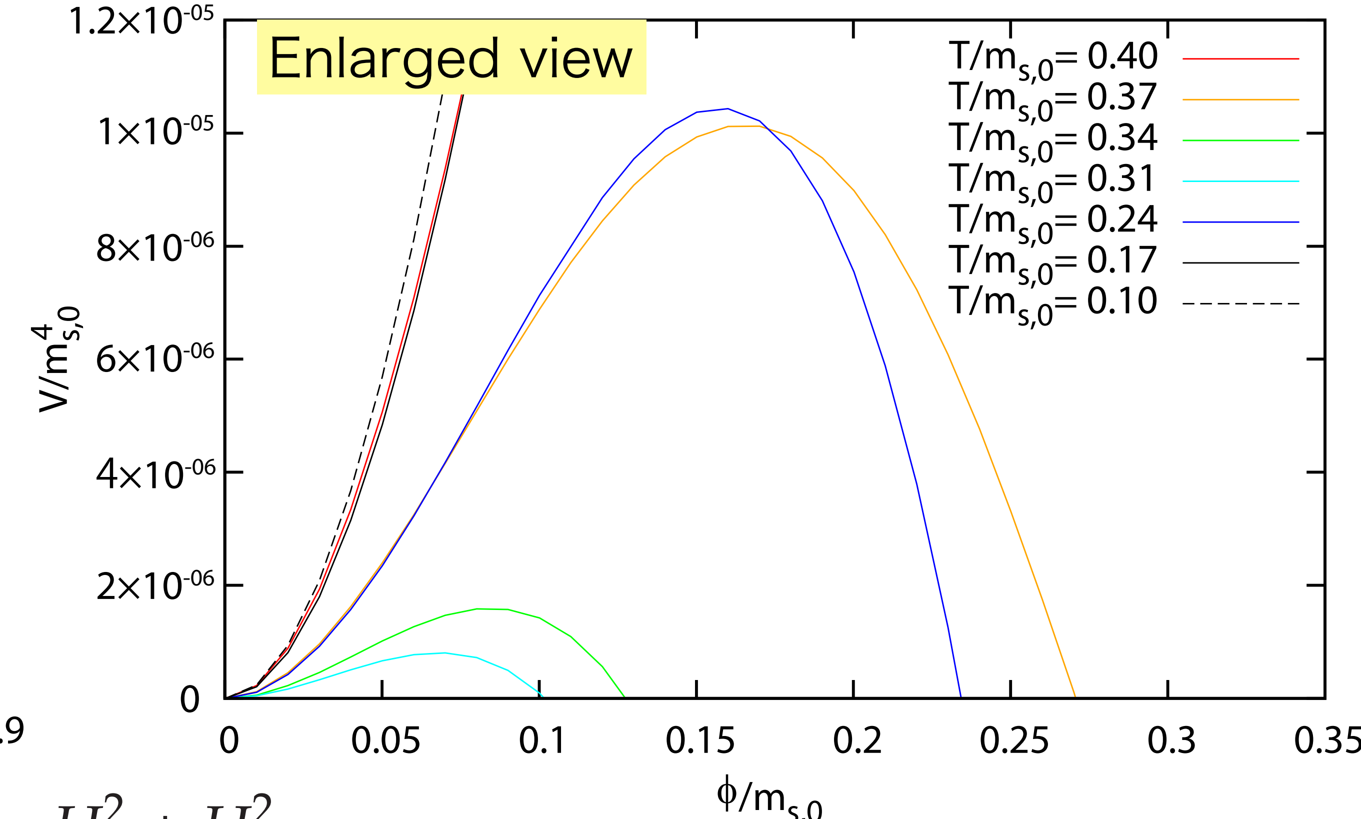
4. High Temperature Phase Transition

・Numerical results of a typical bench mark point.

Figures show the Higgs potential with minimising $\tan\beta$. $\tan\beta \sim 0$ holds. We use one-loop level potential.

The first order phase transition occur at $T \sim 0.3 m_S$.





$$\phi^2 = H_u^2 + H_d^2$$

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5. Conclusion

Thanks to the radiative correction to the singlino mass

Summary of this talk

★Singlino Dark Matter in nMSSM
with supersymmetry breaking scale $M_S \sim \mathcal{O}(10)$ TeV

- can explain the Dark Matter relic abundance.
  via the resonant annihilation with Higgs boson.
- can explain the Higgs boson mass simultaneously.
- can be probed by the future experiments.

★In nMSSM with vector like matters,

- the first order phase transition of the Higgs field can occur at $T \sim M_S$, which may induce the electroweak baryogenesis at high temperature.

Back up!!

nMSSM

$$W_{\rm nMSSM} = W_{\rm Yukawa} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S}$$

$$V_{\rm soft} = t_S S + \text{h.c.} + m_S|S|^2 + \text{others}$$

$$t_S \sim \mathcal{O}(M_{\rm SUSY}^3),\ m_{12}^2 \sim \mathcal{O}(M_{\rm SUSY}^2)$$

$$\langle S\rangle \sim \mathcal{O}(M_{\rm SUSY})$$

This model can be obtained as a effective theory of several UV models.

Examples of UV models

- The discrete R-symmetry(Z_5^R or Z_7^R) imposed model [C. Panagiotakopoulos et.al. `99]
  →tadpole term is induced with loop suppression.
- PQ invariant NMSSM [K. S. Jeong, et.al. `99]
- U(1)'-extended MSSM [V. Barger, et.al. `99]
- Fat Higgs model [R. Harnik, et.al. `99]

We will consider the phenomenology of nMSSM.

nMSSM $W_{\text{nMSSM}} = W_{\text{Yukawa}} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S}$

Higgs Mass in nMSSM

$$V_{\text{soft}} = V_{\text{soft}}^{\text{MSSM}} + m_s^2|S|^2 + (\lambda A_\lambda S H_u H_d + t_s S + h.c.)$$

Integrate out

$$V(H) = \frac{\lambda_H}{2}(|H|^2 - v^2)^2$$

$$\lambda_H \simeq \lambda_{\text{MSSM}} + \frac{\lambda^2}{2}\frac{m_S^2 - A_\lambda^2}{m_S^2}\sin^2 2\beta$$

additional contribution to the Higgs mass

DM constraints

Invisible decay

- CMS: Br<58% (95% C.L.)
- Global fit: Br<19% (95% C.L.)
- HL LHC: Br<6.2% (95% C.L.) ~5 years?
- ILC: Br< 0.4% (95% C.L.)(1150fb-1 at sqrt{s}:250GeV

Direct search

$$\sigma(\tilde{s}N \to \tilde{s}N) = \frac{\lambda_{\rm eff}^2}{2\pi v_{EW}^2} f_N^2 \frac{m_N^4 m_{\tilde{s}}^2}{m_h^4 (m_{\tilde{s}} + m_N)^2},$$

XENON1T: from 2015(?)
takes 2 years(?)

$$f_N m_N \equiv \langle N | \sum_q m_q \bar{q} q - \frac{\alpha_s}{4\pi} G_{\mu\nu} G^{\mu\nu} | N \rangle$$

From lattice

$$f_N = 0.326,\ 0.15 < f_N < 0.66 \quad (2\sigma?)$$

$$\sigma(\tilde{s}N \to \tilde{s}N) \simeq (0.15 \text{ - } 3.3) \times 10^{-46} \left(\frac{\lambda_{\rm eff}}{0.01}\right)^2 \quad [{\rm cm}^2]$$

no constraint from inv. decay

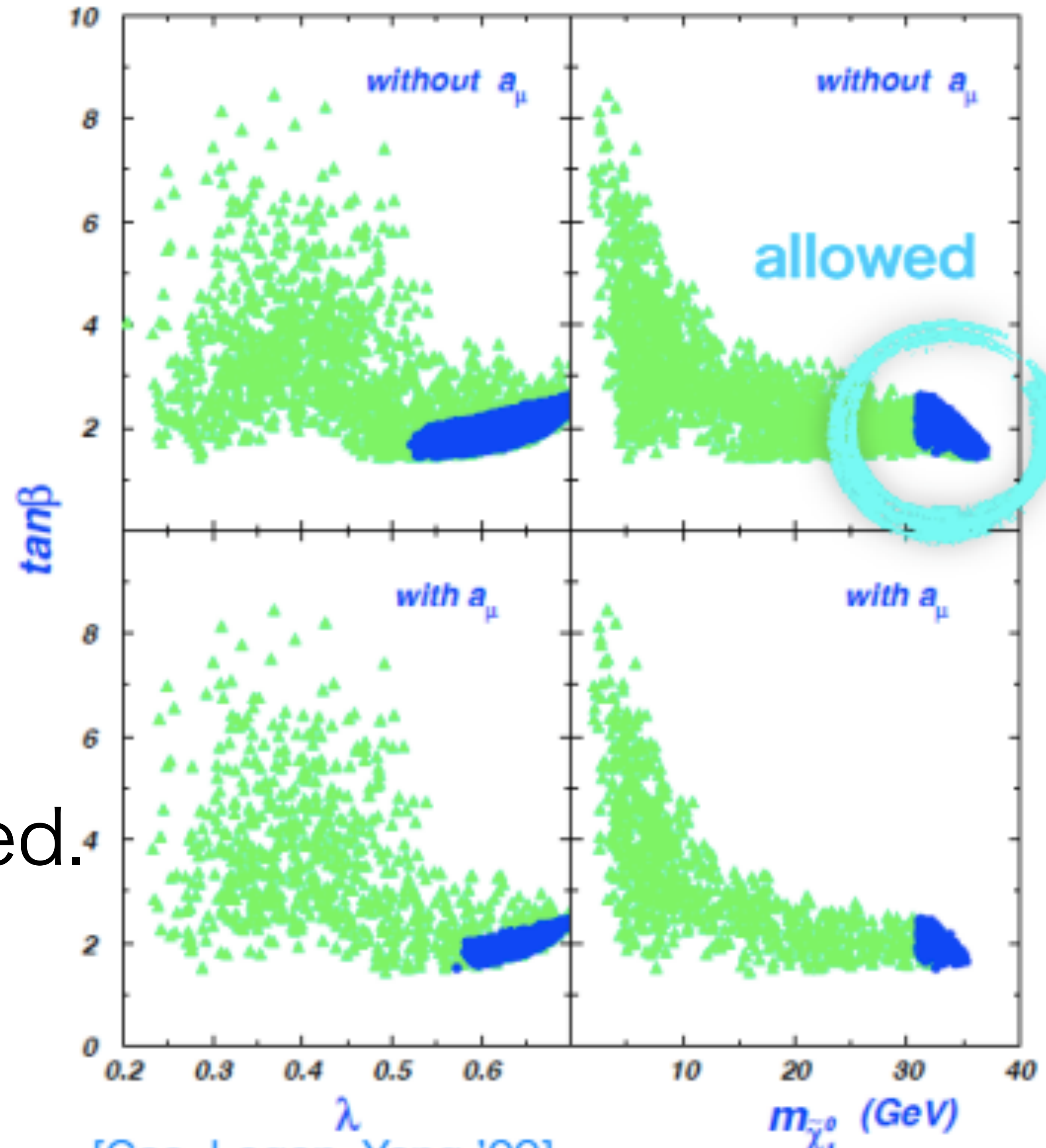
DM so far

nMSSM study so far.

10GeV<m<40GeV

is allowed.

Low scale SUSY is needed.



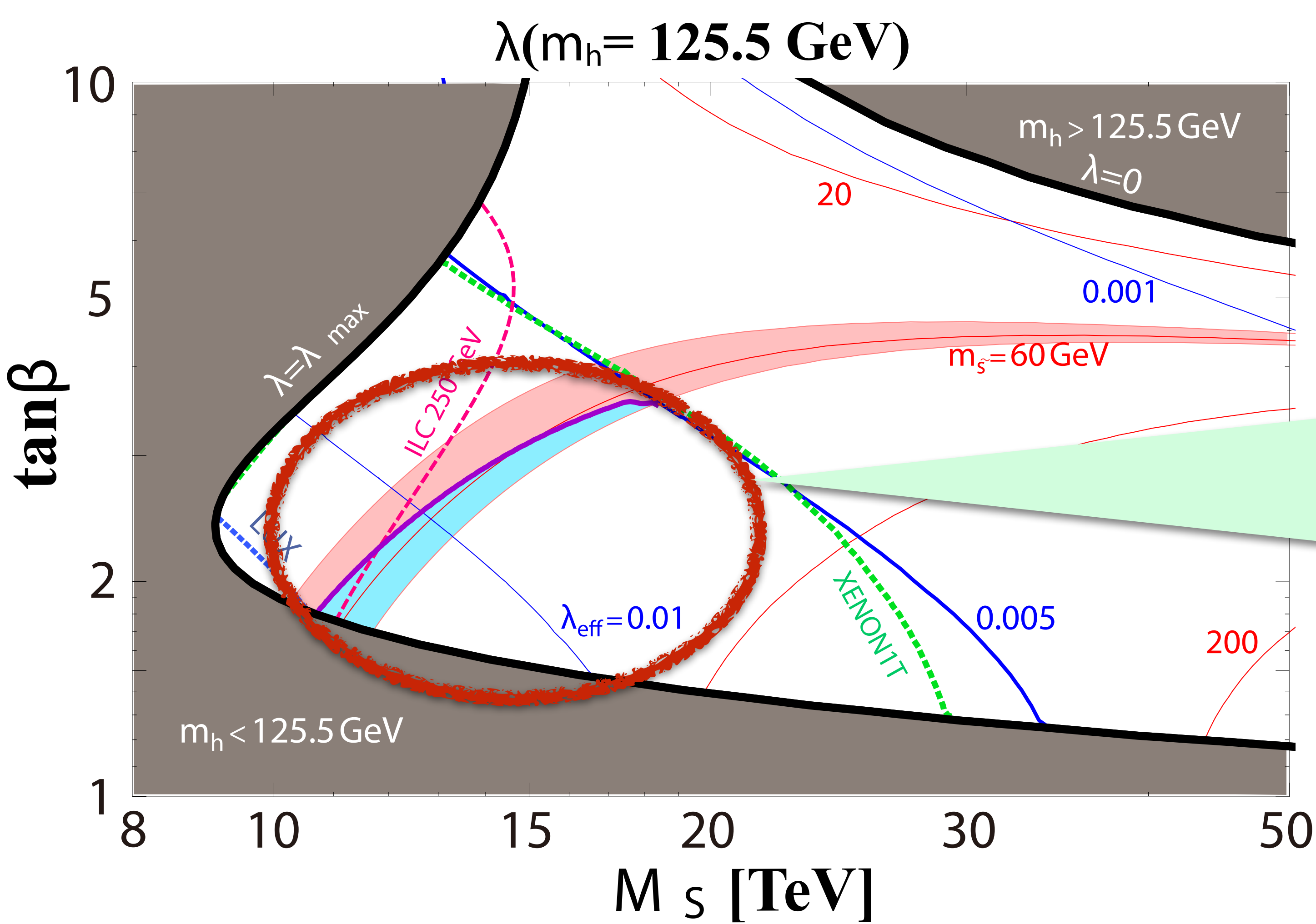
[Cao, Logan, Yang '09]

3. Singlino Dark Matter

- Numerical results of nMSSM singlino DM $(W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d)$

  - The higgs boson mass is fixed to 125.5 GeV
  by changing λ: $0 \le \lambda \le \lambda_{\max}$

$A_\lambda^2 = \frac{2}{5}M_S^2$,other dimensionful parameters= M_S
$\lambda_{\max}$: maximal λ avoiding the Landau pole at GUT scale



This region can be probed by proposed future experiments

EDM

In nMSSM, we have one extra CP phase.

chargino/neutralino-slepton loops give:

$$\left|\frac{d_e}{e}\right| = \frac{5g^2+g'^2}{384\pi^2}\frac{m_e}{{M_{\rm SUSY}}^2}\sin\phi\tan\beta \;\; [\mathrm{GeV}^{-1}]$$
$$\sim 6\times 10^{-29}\left(\frac{10\,\mathrm{TeV}}{M_{\rm SUSY}}\right)^2\sin\phi\tan\beta \;\; [\mathrm{cm}],$$

$\phi = \arg\left(\mu_{\rm eff} M_{\rm gaugino}\right)$ with universal masses.

Current bound: $8.7\times 10^{-29}[cm]$ (90% C.L.)

From ACMC Collaboration

FCNC

Roughly the same with MSSM

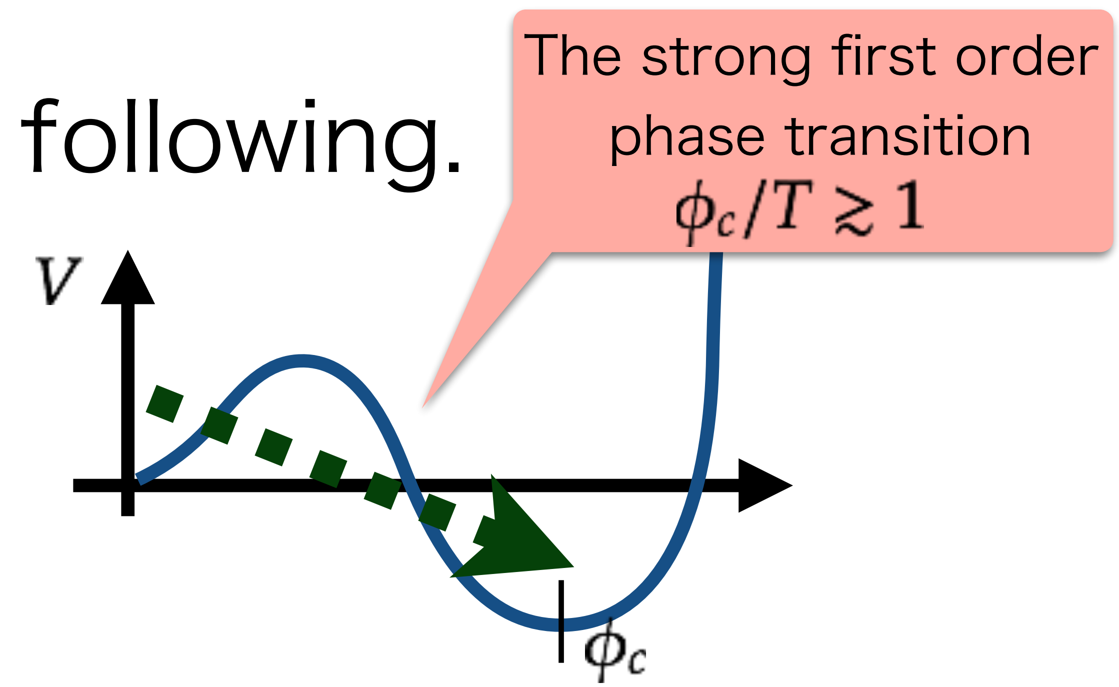
Minimal review of EWGB

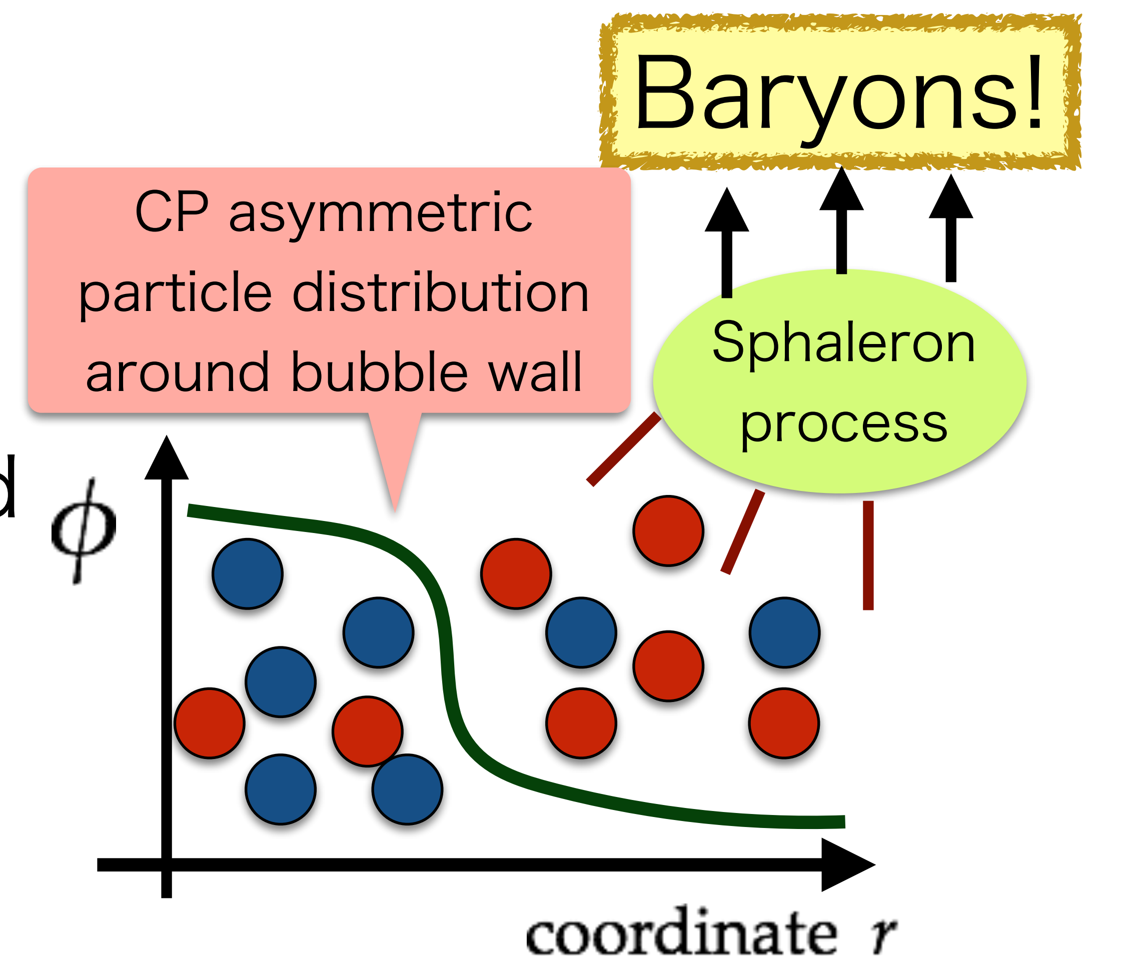
The mechanism of EWGB is the following.

・At first, the strong first order phase transition of the Higgs field occurs.

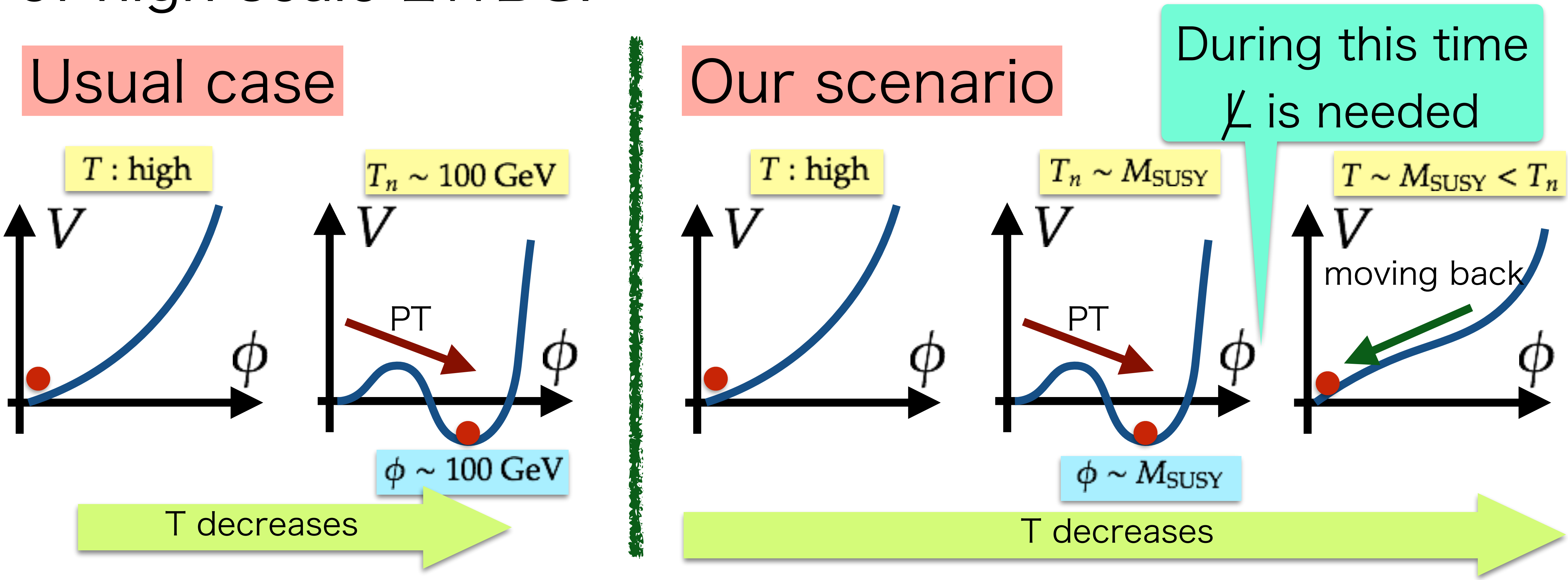
・Then, the space-time depending Higgs field configuration generates CP asymmetric particle distributions.

・Finally, CP asymmetry is converted into baryon number asymmetry by the EW sphaleron process.





We would like to see the typical thermal history of high scale EWBG.



In our scenario, EWBG occurs at $T \sim M_{\rm SUSY}$.
The potential is deformed by thermal effects
and a potential minimum appears only around $T \sim M_{\rm SUSY}$.

About L violation

Table 5.1: The charge assignment.

$\mathbb{Z}_2$-even	$\hat{H}_1$	$\hat{H}_2$	$\hat{S}$	$\hat{Q}_i$	$\hat{\bar{U}}_i$	$\hat{\bar{D}}_i$	$\hat{L}_i$	$\hat{\bar{E}}_i$							
$\mathbb{Z}_2$-odd				$\hat{Q}'$	$\hat{\bar{U}}'$	$\hat{\bar{D}}'$	$\hat{L}'$	$\hat{\bar{E}}'$	$\hat{\bar{Q}}'$	$\hat{U}'$	$\hat{D}'$	$\hat{\bar{L}}'$	$\hat{E}'$	$\hat{N}'$	$\hat{\bar{N}}'$
$\mathbb{Z}_5^R$	1	1	4	2	3	3	2	3	0	4	4	0	4	0	2
$\mathbb{Z}_3$	0	0	0	2	1	1	2	1	1	2	2	1	2	2	1

$$W_{\rm sym} = \lambda_1 \hat{S}\left(\hat{\bar{Q}}'\hat{Q}' + \hat{\bar{U}}'\hat{U}' + \hat{\bar{D}}'\hat{D}' + \hat{\bar{L}}'\hat{L}' + \hat{\bar{E}}'\hat{E}' + \hat{\bar{N}}'\hat{N}'\right)$$
$$+ k_1 \hat{L}'\hat{H}_1\hat{\bar{E}}' + k_2 \hat{\bar{L}}'\hat{H}_1\hat{N}' + k_3 \hat{Q}'\hat{H}_1\hat{\bar{D}}' + k_4 \hat{Q}'\hat{H}_2\hat{\bar{U}}' ,$$

$$W_{\not{\mathbb{Z}}_2} = \epsilon_S^i \hat{S}\left(\hat{\bar{Q}}'\hat{Q}_i + \hat{\bar{U}}_i\hat{U}' + \hat{\bar{D}}_i\hat{D}' + \hat{\bar{L}}'\hat{L}_i + \hat{\bar{E}}_i\hat{E}'\right)$$
$$+ \epsilon^i\left(\hat{Q}_i\hat{H}_1\hat{\bar{D}}' + \hat{Q}'\hat{H}_1\hat{\bar{D}}_i + \hat{Q}_i\hat{H}_2\hat{\bar{U}}' + \hat{Q}'\hat{H}_2\hat{\bar{U}}_i + \hat{L}_i\hat{H}_1\hat{\bar{E}}' + \hat{L}'\hat{H}_1\hat{\bar{E}}_i\right)$$
$$+ \epsilon_N \hat{\bar{N}}'^3 .$$

Boltzmann suppressed for T<M

$$\Gamma_{\not{N}'}(T) \sim \frac{\epsilon_N^2}{16\pi}\frac{(M_{\rm SUSY}T)^{3/2}}{M_{\rm SUSY}^2}\exp\left(-\frac{M_{\rm SUSY}}{T}\right)$$

$$\tau_{\tilde{s}} \simeq 0.8\times 10^{36}\left(\frac{10^{-5}}{\epsilon_N}\right)^2\left(\frac{10^{-5}}{\epsilon}\right)^6\left(\frac{10^{-4}}{f_{\tilde{s}\nu\nu\nu}}\right)^2\left(\frac{M_{\rm SUSY}}{10\ {\rm TeV}}\right)^4\left(\frac{60\ {\rm GeV}}{m_{\tilde{s}}}\right)^5 \ [{\rm sec}] .$$

We consider the following model.

・nMSSM

$$W_{\mathrm{nMSSM}} = \lambda \hat{S}\hat{H}_u\hat{H}_d,$$

$$V_{\mathrm{soft}} = m_d^2|H_d|^2 + m_u^2|H_u|^2 + m_s^2|S|^2 + t_s S + h.c..$$

・plus vector like multiplets

$$W = \lambda_1 \hat{S}\left[\hat{\bar{Q}}'\hat{Q}' + \hat{\bar{U}}'\hat{U}' + \hat{\bar{D}}'\hat{D}' + \hat{\bar{L}}'\hat{L}' + \hat{\bar{E}}'\hat{E}' + \hat{\bar{N}}'\hat{N}'\right]$$

$$+ k\hat{H}_d\left[\hat{L}'\hat{E}' + \hat{\bar{L}}'\hat{N}'\right]$$

- $16 + \bar{16}$ in SO(10) GUT notation.
- This choice is not crucial.
- We can impose Z_5^R as a example.
- We neglect other possible terms.
- We neglect A-terms and CP phases for simplicity.

At high temperature,

S gets thermal mass term

$$\boxed{V \supset y_s^2 T^2 |S|^2}$$

Important!!

4. High Temperature Phase Transition

・Numerical results of a typical bench mark point.

BM

$$
\begin{aligned}
y_t^2 &= 0.753324,\\
g'^2 + g_2^2 &= 0.528998,\\
g_2^2 &= 0.3994144,\\
\tan\beta_{\text{vacuum}} &= 2,\\
\lambda^2 &= 0.5,\\
\lambda_1^2 &= 0.5,\\
k &= 1,\\
M_{\text{sfermions}} &= m_S,\\
t_S/m_S^3 &= 0.58,\\
m_1^0/m_S^2 &= 0.167621,\\
m_2^2/m_S^2 &= -0.167621,\\
m_{12}^2/m_S^2 &= 0.001226.
\end{aligned}
$$

nMSSM

$$W_{\text{nMSSM}} = \lambda \hat{S}\hat{H}_u\hat{H}_d,$$

$$V_{\text{soft}} = m_d^2|H_d|^2 + m_u^2|H_u|^2 + m_s^2|S|^2 + t_s S + h.c..$$

vectors

$$W = \lambda_1 \hat{S}\left[\hat{Q}'\hat{Q}' + \hat{U}'\hat{U}' + \hat{D}'\hat{D}' + \hat{L}'\hat{L}' + \hat{E}'\hat{E}' + \hat{N}'\hat{N}'\right] + k\hat{H}_d\left[\hat{L}'\hat{E}' + \hat{L}'\hat{N}'\right]$$

・SM couplings are taken at 10 TeV.

・If you add $\mathcal{O}(v_{\text{EW}}^2/m_S^2)$ corrections to mass parameters, EW vacuum can be realised.

Note: m_S is roughly a free parameter!!! This scenario is scale free.

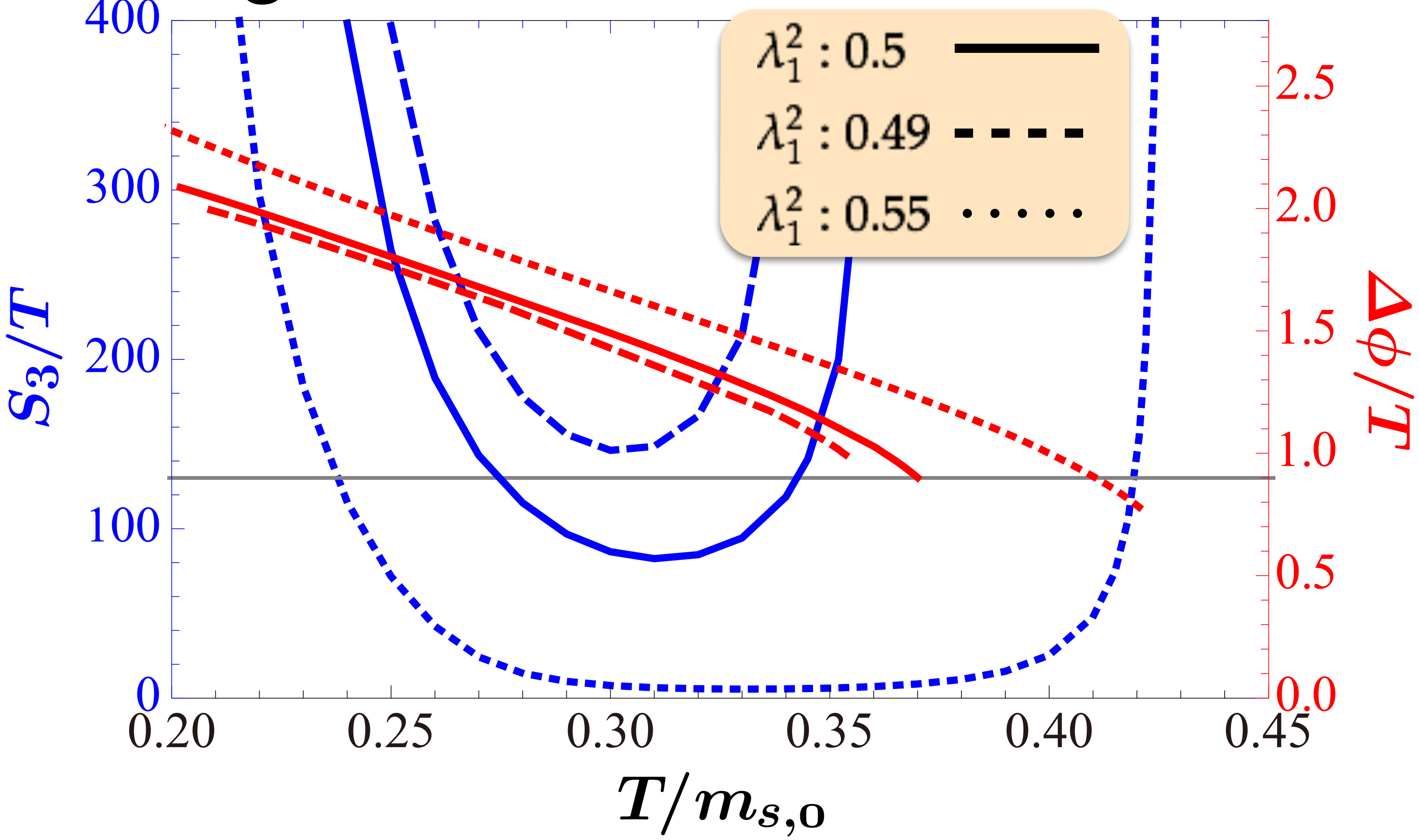
Up to small corrections of $\mathcal{O}(v_{\text{EW}}^2/m_S^2)$ and SM coupling running.

4. High Temperature Phase Transition

・Numerical results of a typical bench mark point.

Important for EWBG

The figure shows bounce action S_3/T and $\Delta\phi/T$.



The first order phase transition occur when

$$S_3/T \simeq 137 + 4\log\frac{100\text{GeV}}{T} \sim 120.$$

- The first order phase transition will occur at $T/m_S \simeq 0.34$.
- Action value is sensitive to λ_1 $(m_S(T)^2 \supset \lambda_1^2 T^2)$.

Summary of this section

The first order phase transition of the Higgs field can occur at any high temperature $T \sim m_S$. Considering singlino DM, $m_S \sim \mathcal{O}(10)\text{TeV}$ is good.

$$V = V_0 + V_{\rm CW} + V_{\rm th}.$$

The H_1 direction is important and we neglect terms which do not much affect it.

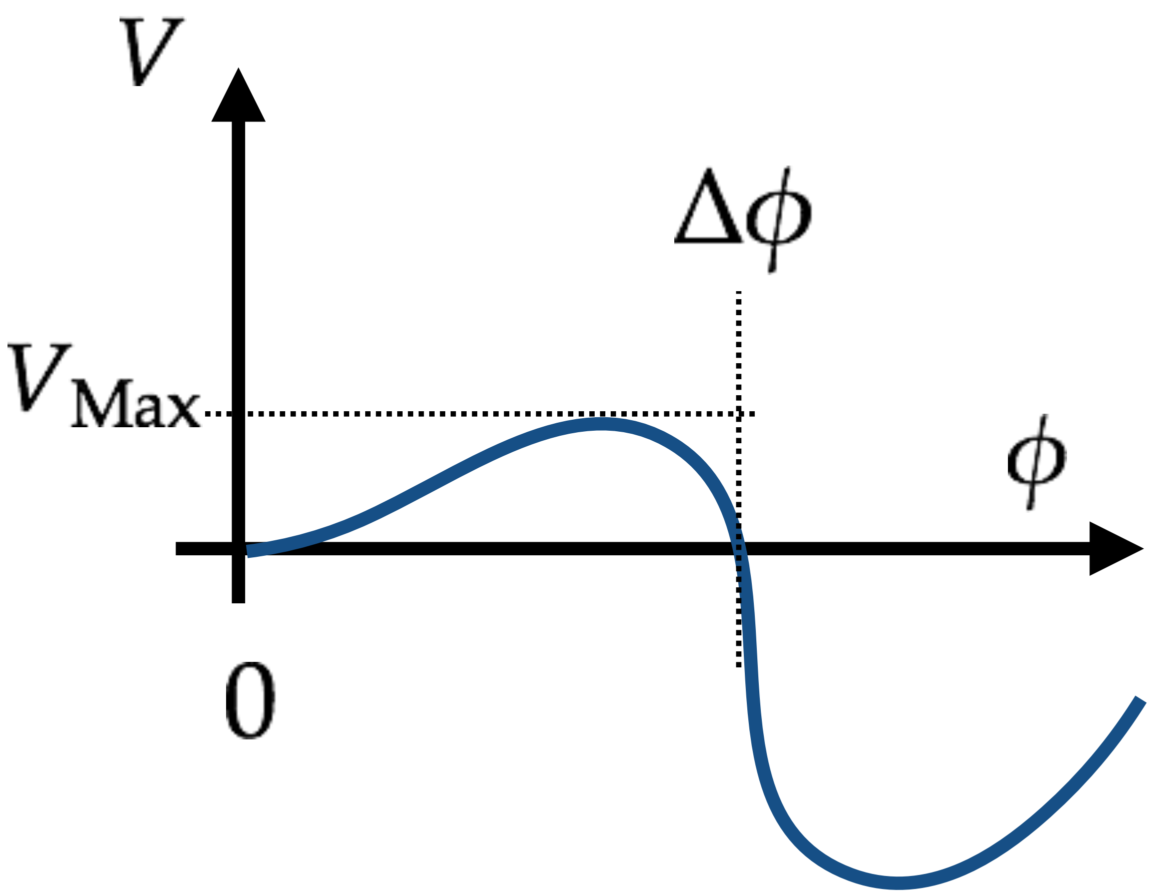
$V_{\rm CW}$ ・We take CW from top-stop sector.

・We take CW from vector multiplets which have H_1 dependence.

$V_{\rm th}$ We take thermal potential from top, vector bosons, vector-like fermions, color non charged vector-like bosons ,higgsino (neglecting higgsino-gaugino-singlino mixing) and charged/CP-odd Higgs.

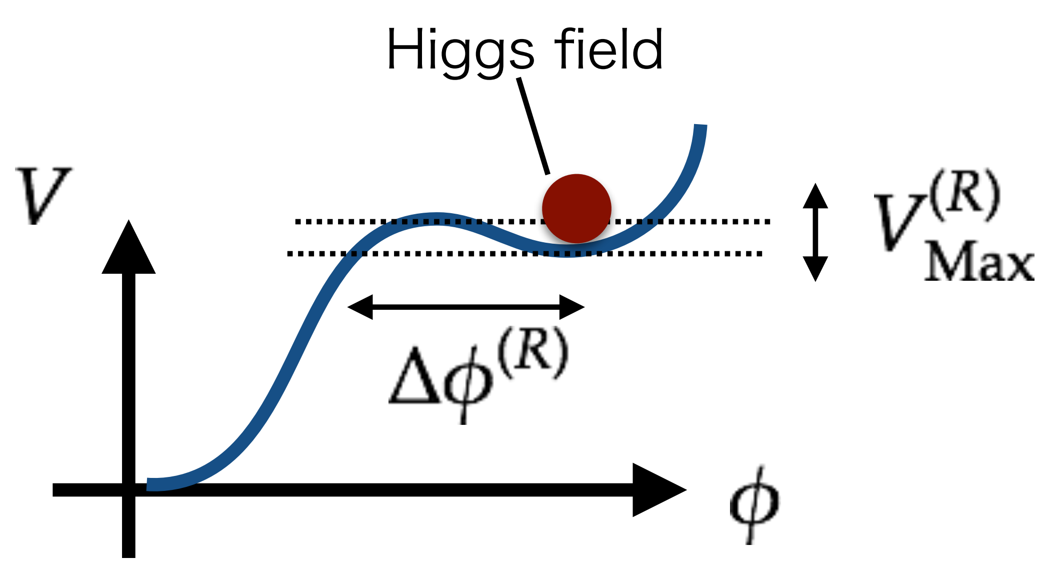
The thermal self energy is estimated by neglecting sboson effects.

Note that



$$S \propto \sqrt{\frac{\Delta\phi^4}{V_{\mathrm{Max}}}} \quad .$$

With larger λ_1 ,
$\Delta\phi$ becomes small
and S becomes small.
in our scenario.



In return way,
the action S is
large (large $\Delta\phi^{(R)4}/V^{(R)}_{\mathrm{Max}}$).