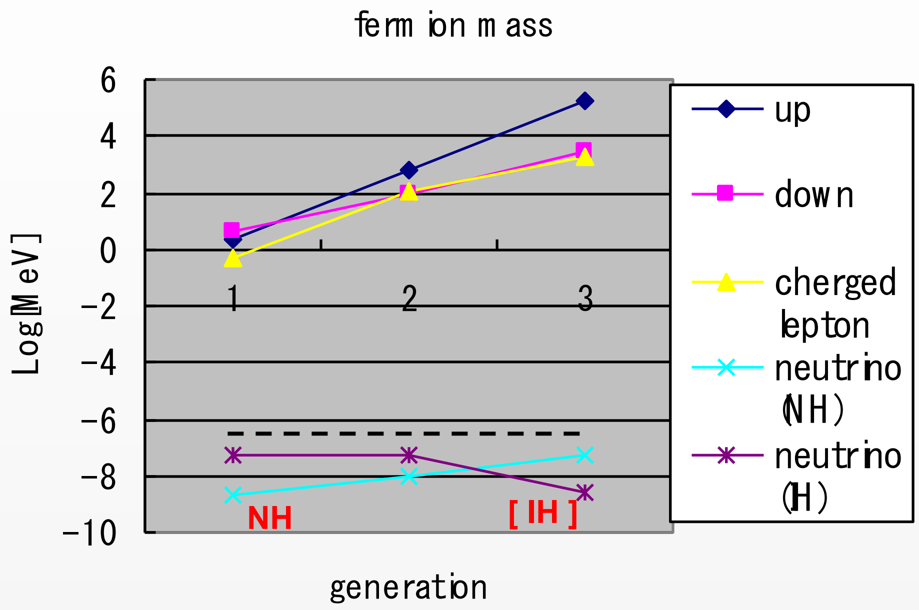
# Why $TeV^2 \sim m_\nu \times M_{GUT}$?

BENE2012, 17 – 21 Sep. 2012

Naoyuki Haba (Hokkaido U, Japan)

Based on
NH, Europhys. Lett. 96, 21001 (2011).
NH, K. Kaneta and Y. Shimizu,
Phys. Rev. D 86, 015019 (2012).

# Smallness of $\nu$ mass is one of the greatest hint of BSM!



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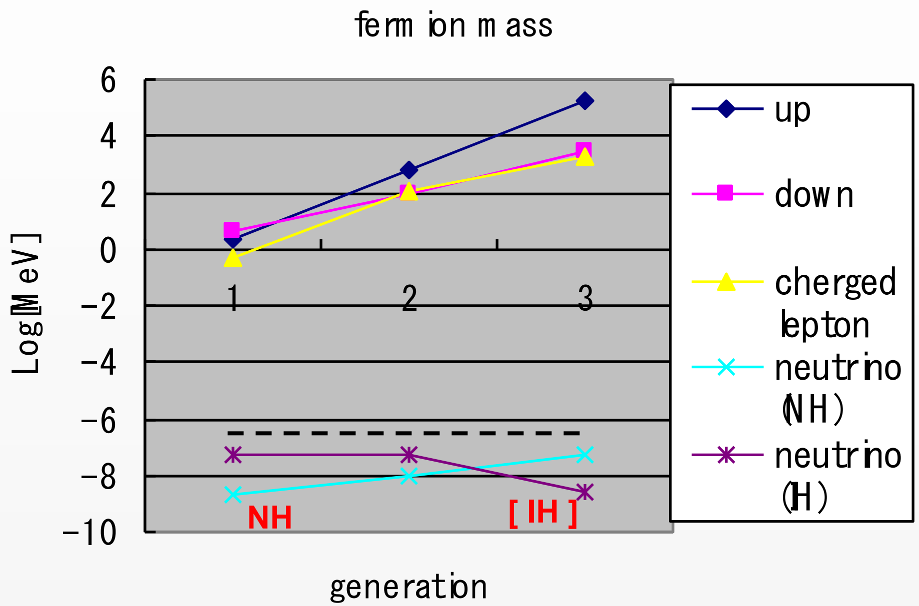


- Many trials have been suggested.

☆ Majorana ν

**BSM (BeNe): See-Saw (I, II, III), Radiative induced mass, .....**

*Behind ν mass*

☆ Dirac ν

**BSM (BeNe): Large Extra Dimension, .......**

# ☆ Majorana ν:

$$m_\nu \sim y_\nu^2 \frac{\langle \Phi \rangle \langle \Phi \rangle}{M}$$

**effective OP in the SM (dim5)：**

$$L_{\dim 5OP} \sim \gamma \frac{\overline{L^c} L \langle \phi \rangle \langle \phi \rangle}{M}$$

lepton # violating ( Δ L=2)

SM renormalizability

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$M \gg M_Z$ and/or $\gamma \ll 1$

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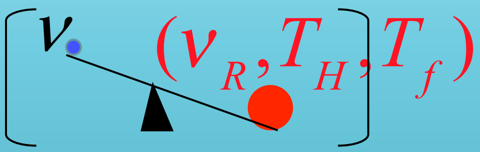
BSM (BeNe, underlying theory)

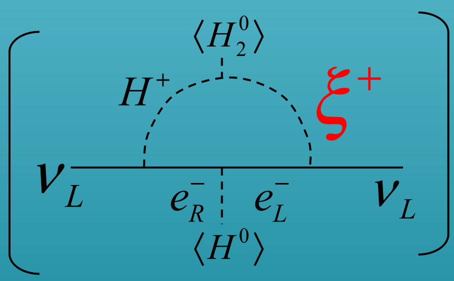
**☆ See-Saw (I, II, III)**




(Minkowski, Yanagida, Gell-Mann-Ramond, Slansky)

$M = \nu_R$ , $T_H$, $T_f$ *mass*

**☆ Radiative induced mass**




(Zee, Ma, NH, Matsuda, Tanimoto, Kanemura, Aoki, ･････ )

$M = \xi$ *mass* × $(4\pi^2)$

## ☆ Dirac ν:

$$m_\nu \sim y_\nu \langle \Phi \rangle$$

$y_\nu \sim 10^{-12} \leftrightarrow y_t \sim 1$

natural?

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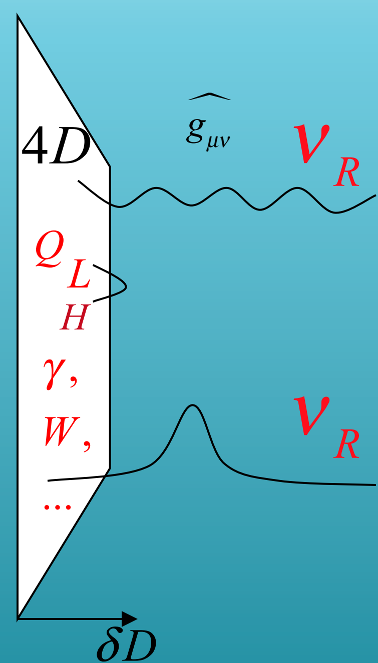
## BSM (BeNe, underlying theory)

**☆ Large Extra Dimension**




volume suppression

$$y_\nu \sim \frac{1}{(M_* R)^{\delta/2}}$$

distant suppression

$$y_\nu \propto e^{-(y-y_0)^2}$$

They are 『tiny $y_\nu$ 』 and/or 『large $M$ 』,since ⟨H⟩~100GeV & $m_\nu$~0.1 eV.

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Today, let us consider another possibility, i.e.,

Small VEV is the origin of small ν mass !

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Today, let us consider another possibility, i.e.,

Small VEV is the origin of small ν mass !

Introduce new Higgs doublet, $\Phi_\nu$

$\langle\Phi_\nu\rangle \lll \langle\Phi_{SM}\rangle$ & have only ν-Yukawa int.

"neutrinophilic Higgs doublet model"

Majorana ν : E. Ma (2001, 2006), E. Ma and M. Raidal (2001), NH and K. Tsumura (2010), NH and O. Seto (2010).
Dirac ν : F. Wang, W. Wang and J. M. Yang (2006), S. Gabriel and S. Nandi (2007), G. Marshall, M. McCaskey, M. Sher (2010), S. M. Davidson and H. E. Logan (2009, 2010),

# contents

§1 Introduction

→ §2 neutrinophilic Higgs doublet model

§3 Why $\mathrm{TeV}^2 \sim m_\nu \times M_{GUT}$?

§4 Phenomenology of SUSY $\nu$ Higgs GUT

§5 Summary

# §2 neutrinophilic Higgs doublet model (νHDM)

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☆ $Z_2$ sym. (which distinguishes $\Phi_\nu$ from $\Phi$ )

| fields | $Z_2$-charge |
| --- | --- |
| SM fields (SM Higgs: $\Phi$ ) | $+$ |
| $\nu_R$: $N$ | $-$ |
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☆Yukawa interactions:

$$L_{Yukawa} = y_u Q\Phi U + y_d Q\Phi D + y_e L\Phi E + y_\nu L\Phi_\nu N$$ Dirac case

($+M\overline{N^c}N$ Majorana case )

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▶ wanted vacuum is

$\langle \Phi \rangle \sim 100$ GeV $>>> \langle \Phi_\nu \rangle \sim 0.1$ eV$/y_\nu$ (0.1 MeV$/y_\nu$ (Majorana))

# §2 neutrinophilic Higgs doublet model (νHDM)

## ☆Higgs potential:

$$V = -m_{\Phi}^2 |\Phi|^2 + m_{\Phi_\nu}^2 |\Phi_\nu|^2 + m_3^2(\Phi^\dagger\Phi_\nu + \Phi_\nu^\dagger\Phi) + \frac{\lambda_1}{2}|\Phi|^4 + \frac{\lambda_2}{2}|\Phi_\nu|^4$$

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$$|m_3^2| \ll m_{\Phi}^2, m_{\Phi_\nu}^2$$

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## ☆Higgs potential:

soft $Z_2$ breaking mass parameter

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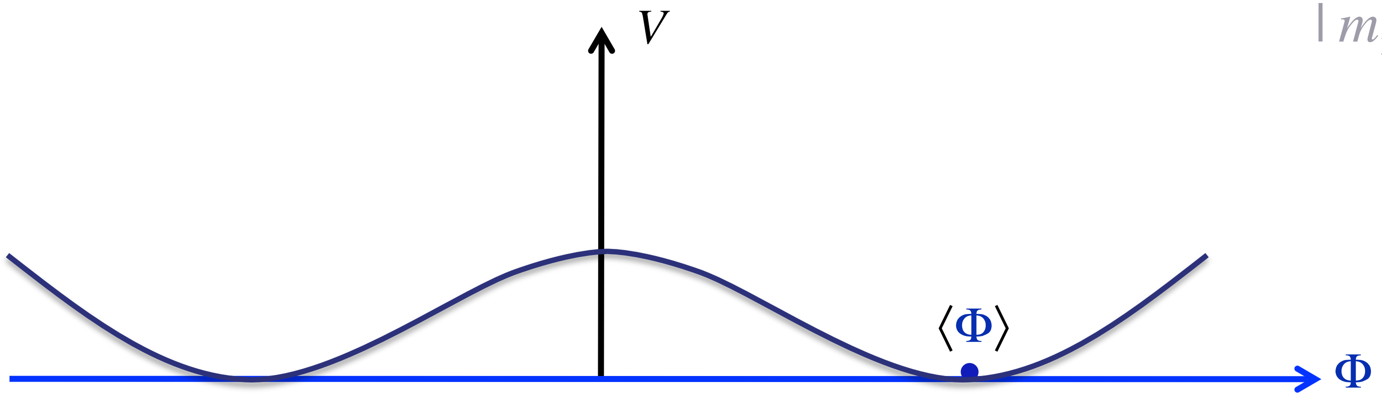


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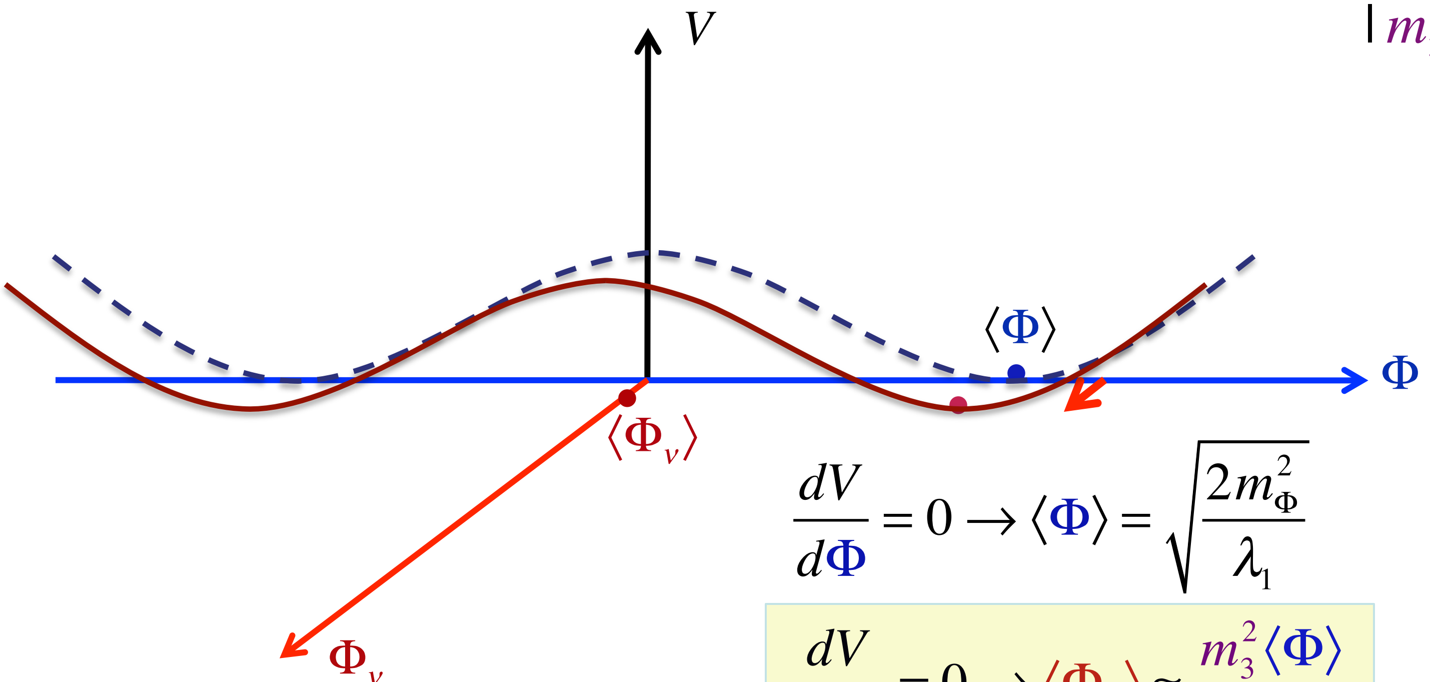


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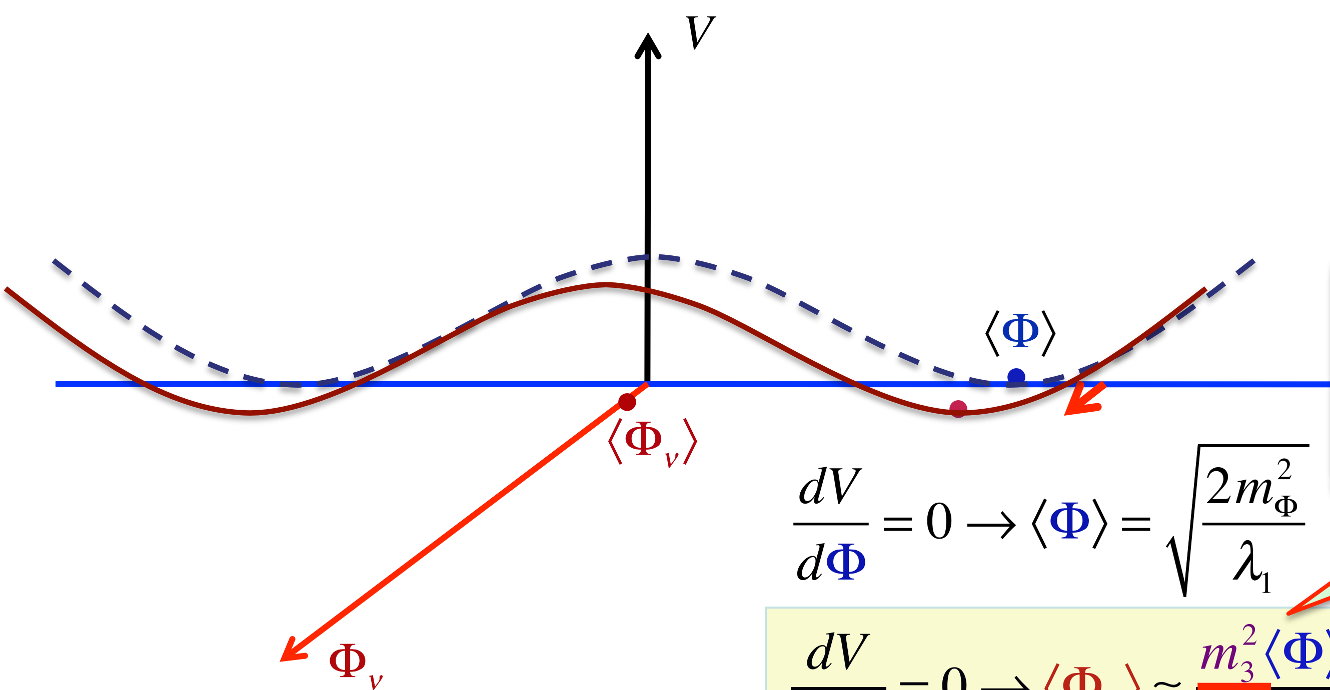


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①: tiny $m_3^2$

②: large $m_{\Phi\nu}^2$

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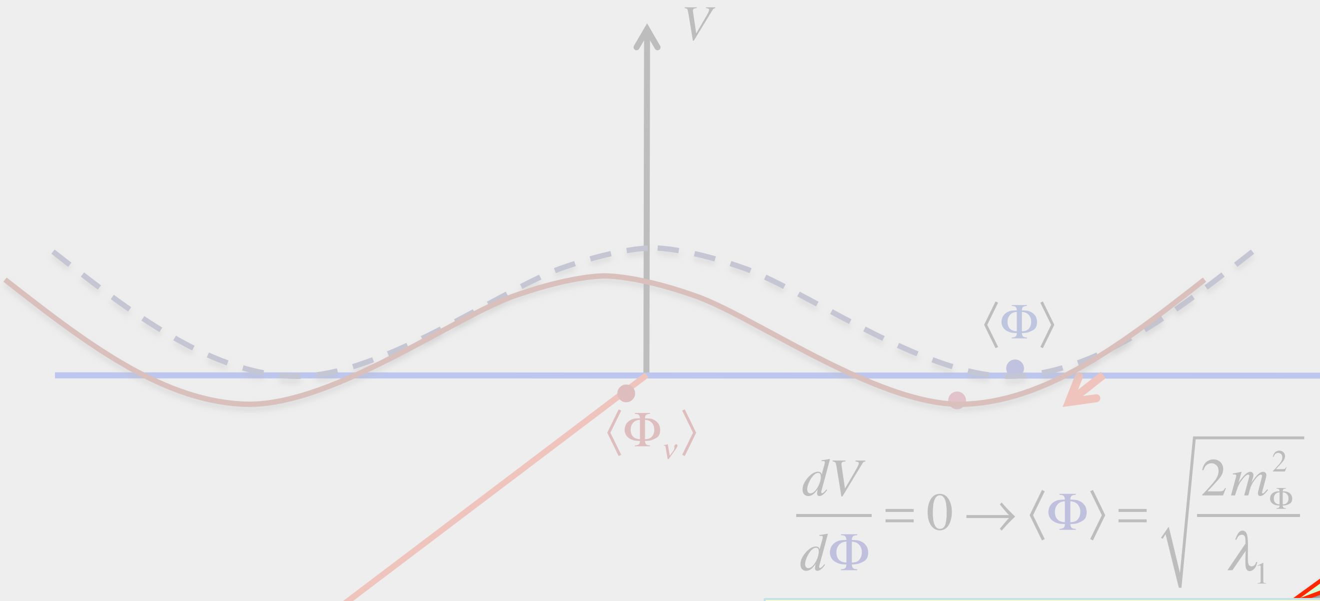


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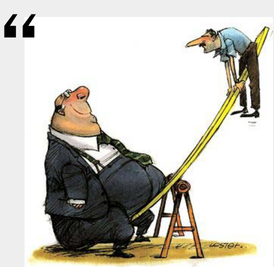
eV

""

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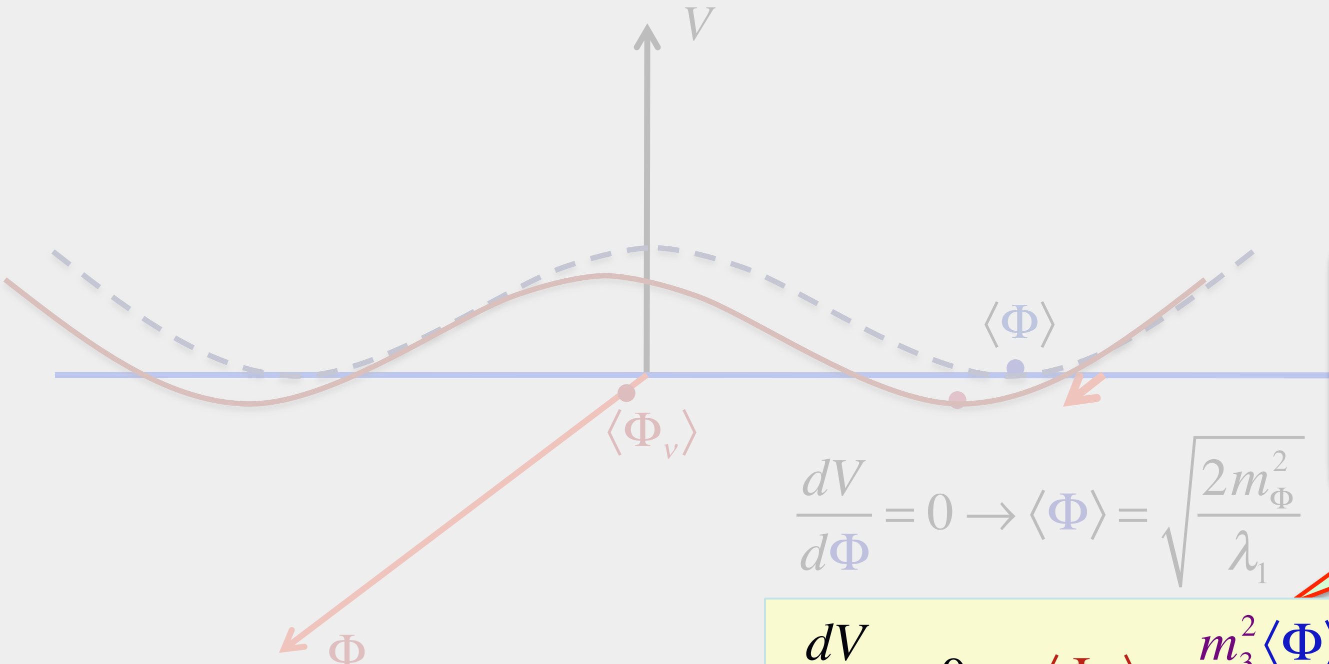


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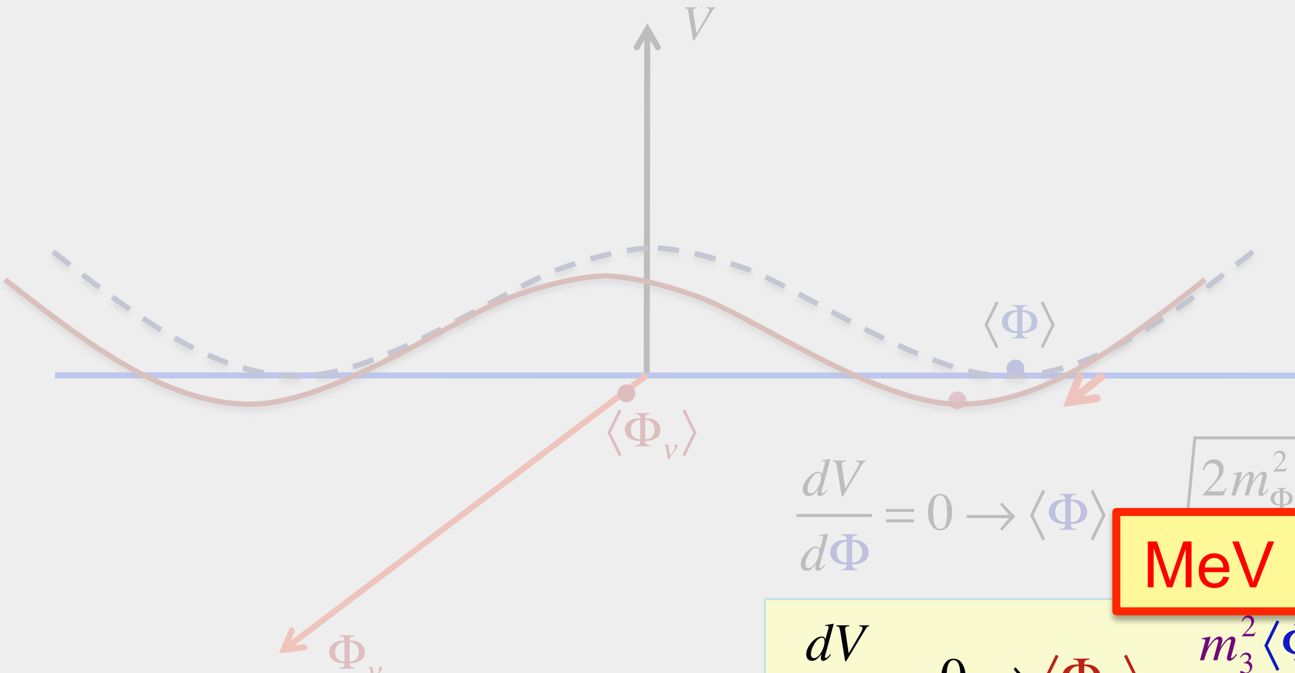


$\frac{dV}{d\Phi} = 0 \rightarrow \langle\Phi\rangle$ $\sqrt{2m_\Phi^2 \ldots}$

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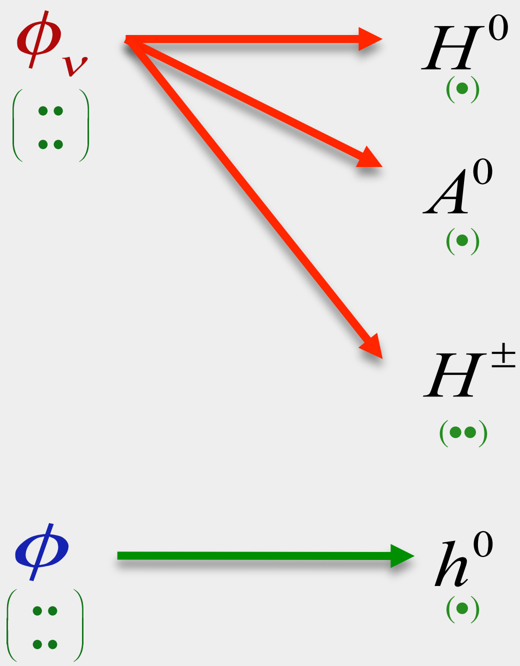
MeV

eV

TeV

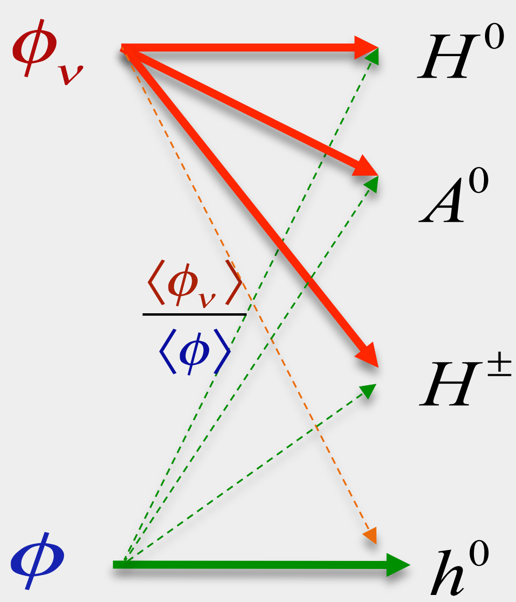
“  ”

## ☆Higgs mass spectra:



## ☆Higgs mass spectra:

Mixings ∝ rations of VEVs




$$m_H^2 \simeq m_{\Phi_\nu}^2 + \frac{\lambda_3 + \lambda_4 + \lambda_5}{2} \langle \phi \rangle^2$$

$$m_A^2 \simeq m_{\Phi_\nu}^2 + \frac{\lambda_3 + \lambda_4 - \lambda_5}{2} \langle \phi \rangle^2$$

$$m_{H^\pm}^2 \simeq m_{\Phi_\nu}^2 + \frac{\lambda_3}{2} \langle \phi \rangle^2$$

} $\sim m_{\Phi\,\nu}{}^2$

decoupling → NOT contribute STU

($m_{\Phi\,\nu}{}^2$ is independent from EW sym. breaking!)

$$m_{h^0}^2 \simeq 2\lambda_1 \langle \phi \rangle^2$$

} ~SM-like Higgs ($10^2$GeV)

Non-decoupling → contribute STU

$\Phi_\nu$ ⇒ heavy although tiny VEV!!

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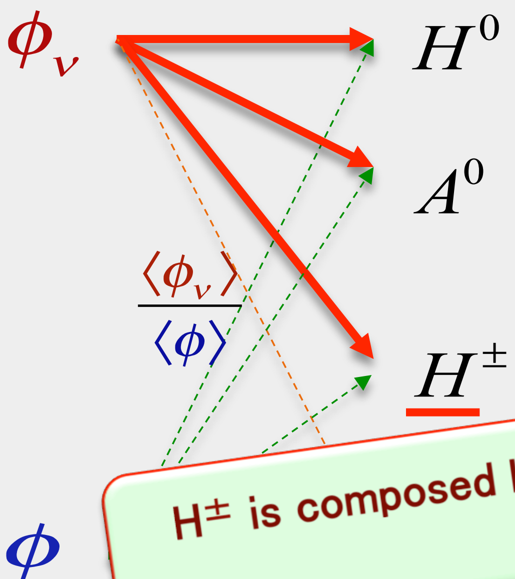


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$m_{H^\pm}^2 \simeq m^2 \ \ \lambda$ ...

... to STU

(... independent from EW sym. breaking!)

$H^\pm$ is composed by $\Phi_\nu \Rightarrow$ Yukawa is only coupled to $\nu_R$ ($L \sim y_\nu L\Phi_\nu N$)

→ LHC/ILC phenomenology

$\phi$

$$m_{h^0}^2 \simeq 2\lambda_1\langle\phi\rangle^2$$

} ~SM-like Higgs ($10^2$GeV)

Non-decoupling → contribute STU

$\Phi_\nu \Rightarrow$ heavy although tiny VEV!!

Small VEV is the origin of small ν mass !

→ $y_\nu$ needs not small any more.

→ (1): rich LHC phenomenology

NH, K.Tsumura, JHEP 1106, 068 (2011).

(2): TeV scale thermal leptogenesis is possible

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011),
Phys. Rev. D84, 103524 (2011).

EVs

$\langle\phi\rangle$

$H^\pm$

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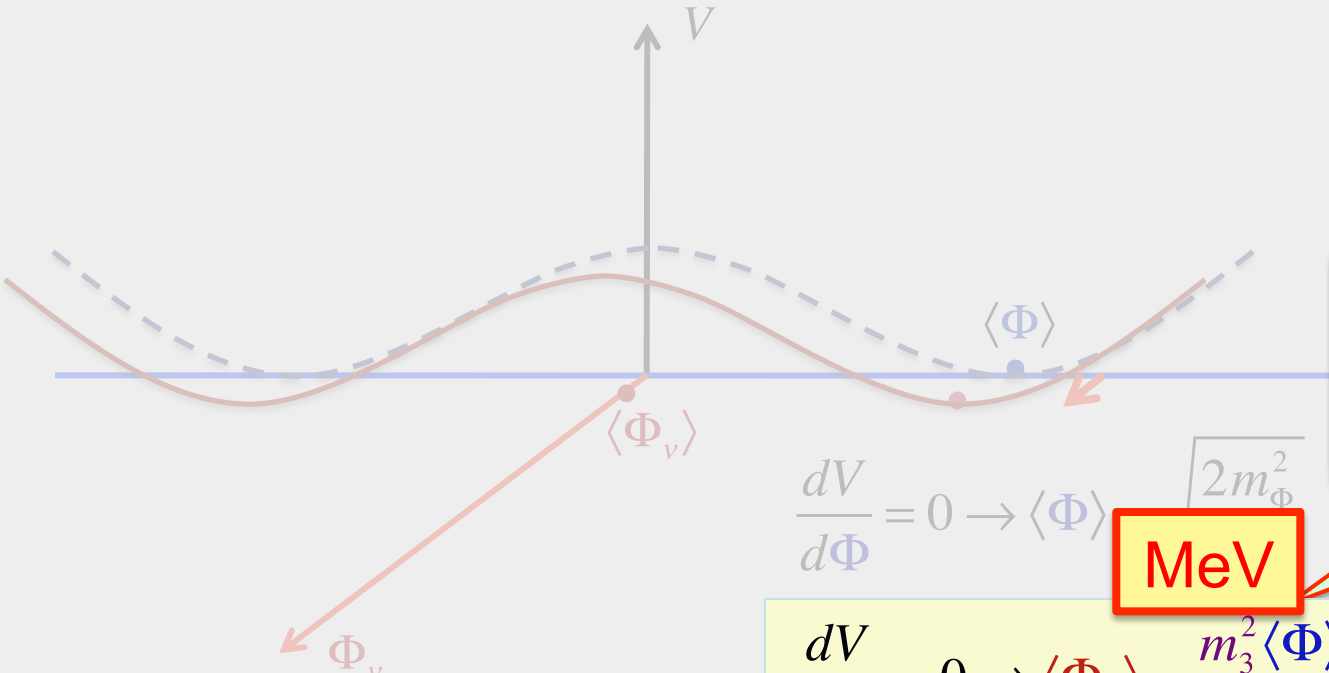


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MeV

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*Criticism*

*Smallness of ν mass is just replaced by smallness of $m_3$,*
*&*
*smallness of ν mass ($m_3$) is not explained yet…*
*Why & what's MeV scale??*

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②: large $m_{\Phi\nu}^2$

$\Rightarrow \langle\Phi\rangle \gg \langle\Phi_\nu\rangle$

$\sqrt{2m_\Phi^2}$

$d\Phi$

$\Phi_\nu$

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MeV

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TeV

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eV, MeV, TeV

""

## in SUSY version (4HDM),

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$$m_{\Phi_\nu}^2 \longrightarrow \mu_\nu^2$$

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MeV

eV

TeV

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TeV ($\mu_{mix}$)

eV ($\langle \Phi_\nu \rangle$)

GUT ($\mu_\nu$)

in SUSY version (4HDM),

$m_3{}^2 \longrightarrow \mu_{mix} \cdot \mu_\nu$

$m_{\Phi_\nu}{}^2 \longrightarrow \mu_\nu{}^2$

TeV

$$\frac{dV}{d\Phi_\nu} = 0 \rightarrow \langle \Phi_\nu \rangle \simeq \frac{\mu_{mix} \langle \Phi \rangle}{\mu_\nu}$$

eV

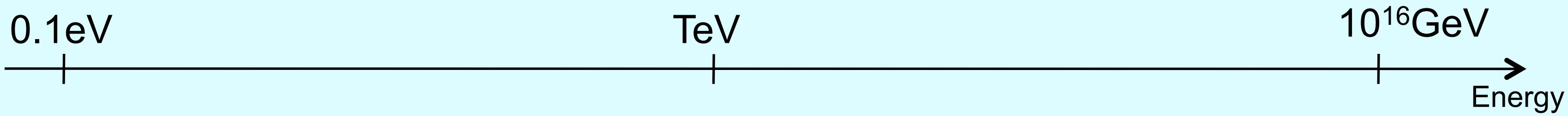
GUT

$m_\nu \sim \text{TeV}^2 / M_{GUT}$ !

Dynamical realization

# §3 Why $TeV^2 \sim m_\nu \times M_{GUT}$?

N.H., Europhys. Lett.96, (2011) 21001.




## Why $\text{TeV}^2 \sim m_\nu \times M_{GUT}$?

0.1eV — TeV — $10^{16}$GeV → Energy

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$$m_\nu \sim \mathrm{TeV}^2 / M_{GUT} \quad \Leftrightarrow \quad \langle H_\nu \rangle \sim \frac{\mu_{mix} \langle H_{u,d} \rangle}{\mu_\nu}$$

($\mu_{mix}$: TeV; $\mu_\nu$: $M_{GUT}$)

⇕

$$W_h = \mu H_u H_d + M_{GUT} H_\nu H_{\nu'} + \mu_{mix} H_u H_{\nu'} + \mu'_{mix} H_\nu H_d$$

$(\mu_{mix}, \mu'_{mix} : TeV\ \ scale)$

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$(\mu_{mix}, \mu'_{mix} : TeV \ \ scale)$

can be naturally embedded to SUSY GUT!

$$W_h^{GUT} = M_0 tr\Sigma^2 + \kappa tr\Sigma^3 + \kappa' \bar{5}\ \Sigma\ 5 - M_{GUT} \bar{5}\ 5 + \kappa'' \overline{5_{\nu'}}\ \Sigma\ 5_\nu - \widehat{M}_{GUT} \overline{5_{\nu'}}\ 5_\nu$$

$$\begin{cases} 5 = (T,\ H_u),\ \bar{5} = (\bar{T},\ H_d) \\ 5_\nu = (T_\nu,\ H_\nu),\ \bar{5}_\nu = (\bar{T}_\nu,\ H_{\nu'}) \end{cases}$$

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TeV → $\mu_{mix}$

$M_{GUT}$ → $\mu_\nu$

$$W_h = \mu H_u H_d + M_{GUT} H_\nu H_{\nu'} + \mu_{mix} H_u H_{\nu'} + \mu'_{mix} H_\nu H_d$$

$(\mu_{mix}, \mu'_{mix} : TeV\ scale)$

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$$K \supset \frac{S^\dagger}{M_{Pl}} [5\ \bar{5}_{\nu'} + 5_\nu \bar{5}_d]$$

$S$: $Z_2$ odd singlet with F-term → $\mu_{mix}, \mu'_{mix}$~TeV

**(origin of SUSY & $Z_2$ breakings) from non-canonical Kahler (Giudice-Masiero)**

0.1eV — TeV — $10^{16}$GeV → Energy

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**(origin of SUSY & $Z_2$ breakings) from non-canoni**

**fine & natural**

# §4 Phenomenology of SUSY $\nu$ Higgs GUT

NH, K. Kaneta and Y. Shimizu,
Phys. Rev. D 86, 015019 (2012).

## ☆ one problem in minimal SUSY SU(5) GUT

- for precise GCU, (threshold correction)

⇨ $m_{T,\bar{T}} \sim 5 \times 10^{14}$ GeV

- for enough proton stability,

⇨ $m_{T,\bar{T}} > 2 \times 10^{16}$ GeV

incompatible

**colored triplet Higgs**:

$$5 = (T,\ H_u),\ \bar{5} = (\bar{T},\ H_d)$$

# ♡ SUSY $\nu$ Higgs SU(5) GUT ♡

$$W_{Yukawa} = f_{ij}^{u} 10_{fi} 10_{fj} 5 + f_{ij}^{d} 10_{fi} \bar{5}_{fj} \bar{5} + f_{ij}^{\nu} 1_{fi} \bar{5}_{fj} 5_{\nu}$$

$$5_{\nu} = (T_{\nu},\ H_{\nu})$$

$[\bar{5} = (\bar{T}_{\nu},\ H_{\nu'})]$

$$= f_i^{u} Q_i \bar{U}_i H_u + (V_{CKM}^{*})_{ij} f_i^{d} Q_i \bar{D}_j H_d + f_i^{d} \bar{E}_i L_i H_d + f_i^{\nu} (V_D)_{ij} \bar{N}_i L_j H_{\nu}$$

$$+ f_j^{u} (V_{CKM}^{*})_{ij} \bar{E}_i \bar{U}_j T + f_i^{u} Q_i Q_i T$$

$$+ (V_{CKM}^{*})_{ij} f_j^{d} \bar{U}_i \bar{D}_j \bar{T} + (V_{CKM}^{*})_{ij} f_j^{d} Q_i L_j \bar{T} + f_i^{\nu} (V_D)_{ij} \bar{N}_i \bar{D}_j T_{\nu}$$

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$$[\bar{5} = (\bar{T}_\nu,\ H_{\nu'})]$$

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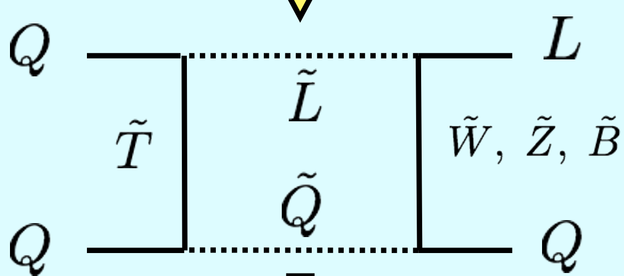
$$+ (V^*_{CKM})_{ij} f^d_j \bar{U}_i \bar{D}_j \bar{T} + (V^*_{CKM})_{ij} f^d_j Q_i L_j \bar{T} + f^\nu_i (V_D)_{ij} \bar{N}_i \bar{D}_j T_\nu$$




**Proton Stability**

$m_{T,\bar{T}} > 2 \times 10^{16}$ GeV

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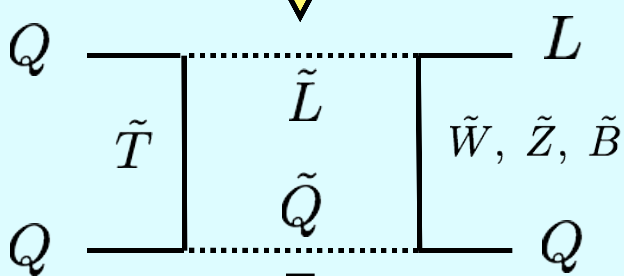


nothing to do with p-decay

while $T_{\nu}, \bar{T}_{\nu}$ contribute GCU

**Proton Stability**

$m_{T,\bar{T}} > 2 \times 10^{16}$ GeV

**precise GCU**

$m_{T\nu,\bar{T}\nu} \sim 5 \times 10^{14}$ GeV

## ☆ one problem in minimal SUSY SU(5) GUT

- for precise GCU, (threshold correction)

  ⇨ $m_{T,\bar{T}} \sim 5 \times 10^{14}$ GeV

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incompatible

**colored triplet Higgs:**

$$5 = (T,\ H_u),\ \bar{5} = (\bar{T},\ H_d)$$

## ☆ ~~one problem in minimal~~ SUSY ν Higgs SU(5) GUT

- for precise GCU, (threshold correction)

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**colored triplet Higgs:**

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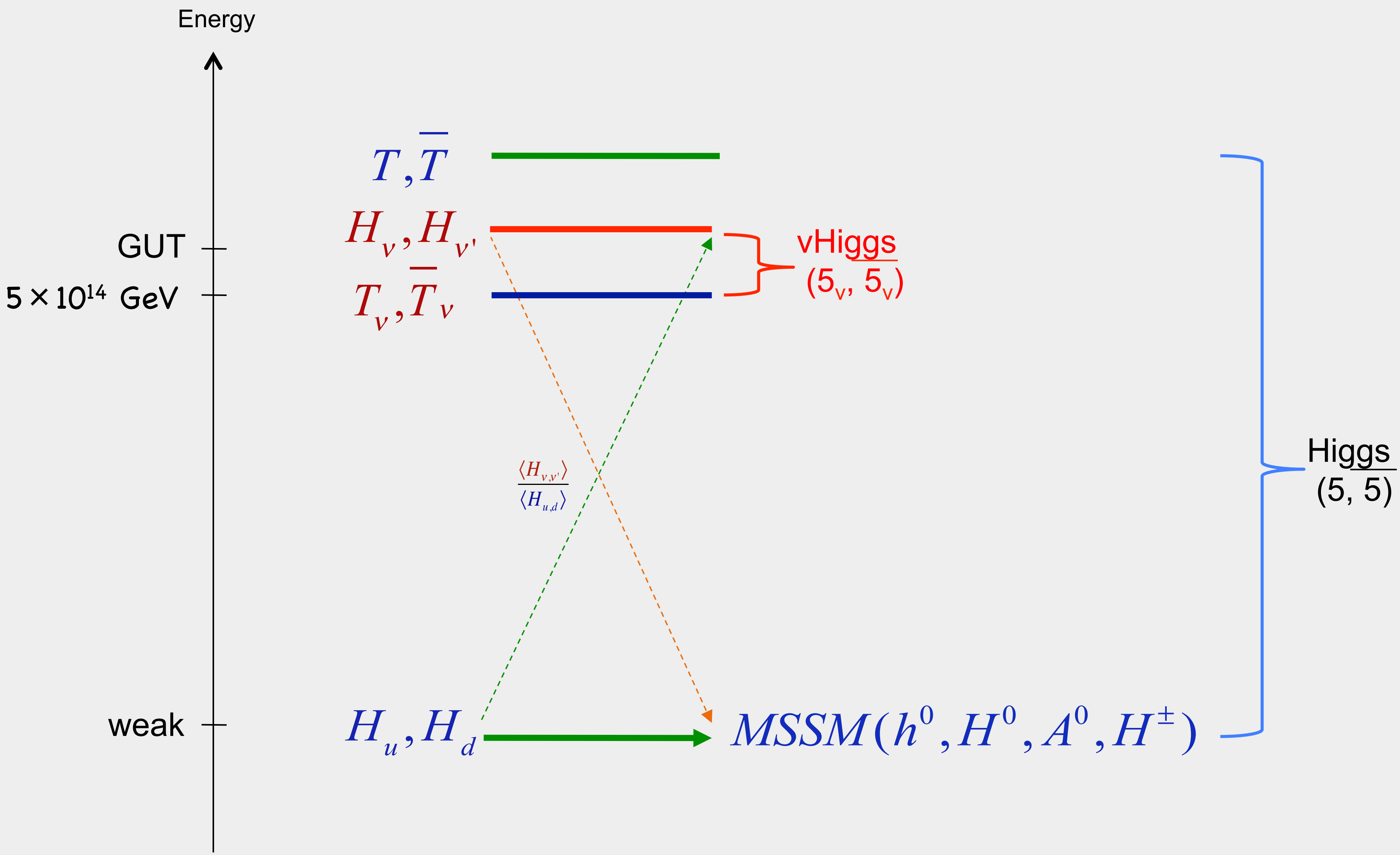
# ☆Higgs mass spectra:



- flavor violations in SUSY $\nu$ Higgs SU(5) GUT

$$W_{Yukawa} = f_i^u Q_i \overline{U}_i H_u + (V_{CKM}^*)_{ij} f_i^d Q_i \overline{D}_j H_d + f_i^d \overline{E}_i L_i H_d + f_i^\nu (V_D)_{ij} \overline{N}_i L_j H_\nu$$

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$$+ (V_{CKM}^*)_{ij} f_j^d \overline{U}_i \overline{D}_j \overline{T} + (V_{CKM}^*)_{ij} f_j^d Q_i L_j \overline{T} + f_i^\nu (V_D)_{ij} \overline{N}_i \overline{D}_j T_\nu$$

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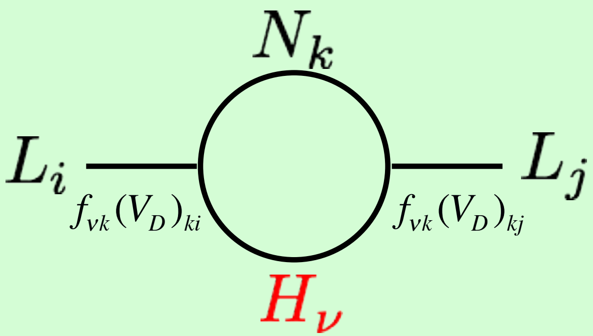
**flavor mixing through RGE:**

slepton doublet sector




$$(\delta m_L^2)_{ij} \simeq -\frac{f_{\nu k}^2}{8\pi^2} (V_D^*)_{ki} (V_D)_{kj} (3m_0^2 + a_0^2) \log \frac{M_P}{M_{H_\nu}}$$

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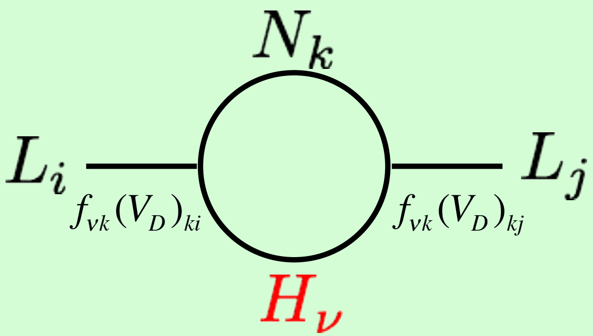


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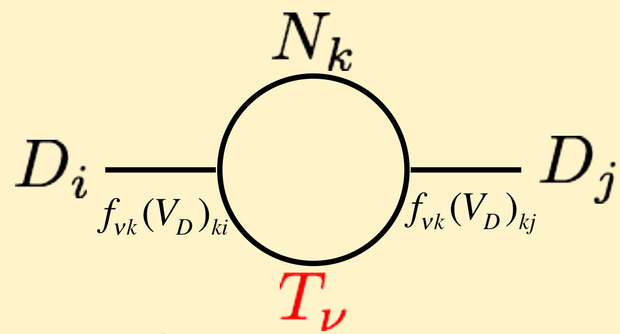
down-type squark sector

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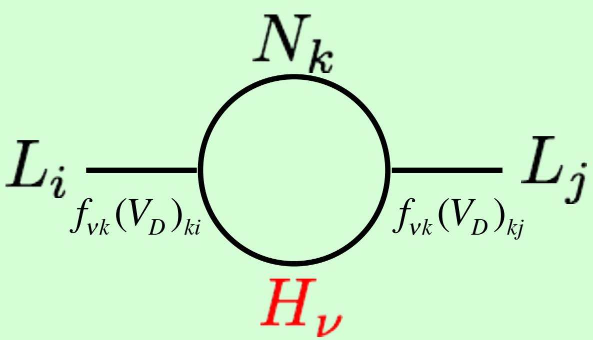


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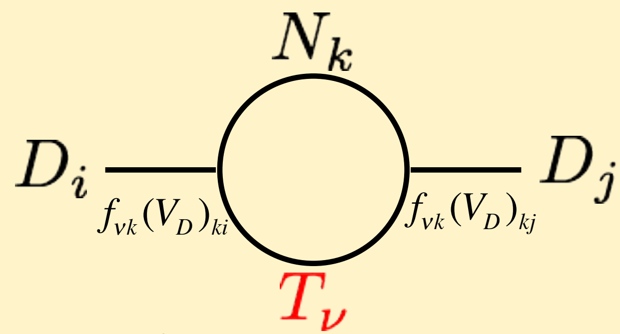


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**directly related through MNS**
(excellent predictivility)

$m_{T_\nu, \overline{T}_\nu} \sim 5 \times 10^{14}$ GeV

$m_{H_\nu, H_\nu'} \geqq 2 \times 10^{16}$ GeV in comparison,

☆ SUSY neutrinophilic Higgs GUT (Dirac ν)

$$W_{Yukawa} = f_{ij}^{u} 10_{fi} 10_{fj} 5 + f_{ij}^{d} 10_{fi} \bar{5}_{fj} \bar{5} + f_{ij}^{\nu} 1_{fi} \bar{5}_{fj} 5_{\nu}$$

☆ SUSY SU(5) GUT with $N_R$ (Majorana ν)

$$W_{Yukawa} = f_{ij}^{u} 10_{fi} 10_{fj} 5 + f_{ij}^{d} 10_{fi} \bar{5}_{fj} \bar{5} + f_{ij}^{\nu} 1_{fi} \bar{5}_{fj} 5 + M_{ij} 1_{fi} 1_{fj}$$

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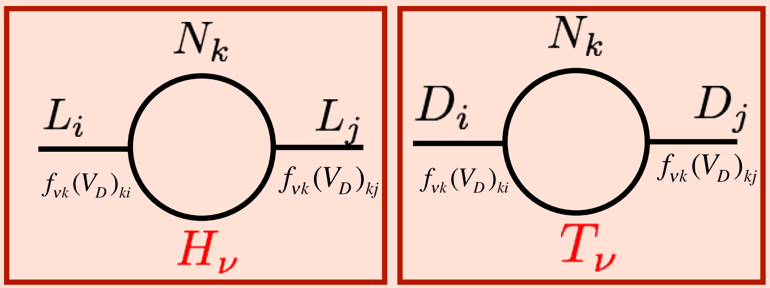


$$(\delta m_L^2)_{ij} \simeq -\frac{f_{\nu_k}^2}{8\pi^2}(V_D^*)_{ki}(V_D)_{kj}(3m_0^2 + a_0^2)\log\frac{M_P}{M_{H_\nu}}$$

$$(\delta m_D^2)_{ij} \simeq -\frac{f_{\nu_k}^2}{8\pi^2}(V_D^*)_{ki}(V_D)_{kj}(3m_0^2 + a_0^2)\log\frac{M_P}{M_{T_\nu}}$$

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## ☆ SUSY SU(5) GUT with $N_R$ (Majorana ν)

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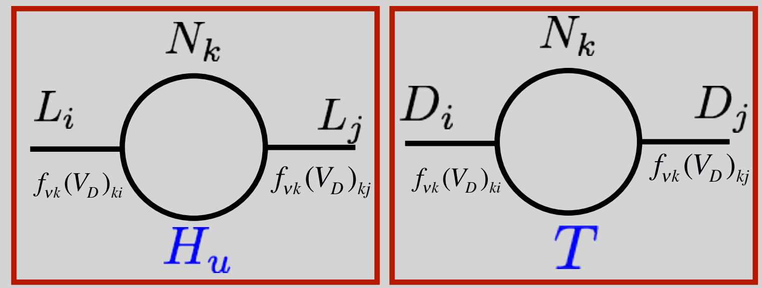



$$(\delta m_L^2)_{ij} \simeq -\frac{f_{\nu_k} f_{\nu_m}}{8\pi^2}(V_D^*)_{ki}(V_M^*)_{lk}(V_M)_{lm}(V_D)_{mj}(3m_0^2 + a_0^2)\log\frac{M_P}{M_N}$$

unknown matrix

$$(\delta m_D^2)_{ij} \simeq -\frac{f_{\nu_k} f_{\nu_m}}{8\pi^2}(V_D^*)_{ki}(V_M^*)_{lk}(V_M)_{lm}(V_D)_{mj}(3m_0^2 + a_0^2)\log\frac{M_P}{M_T}$$

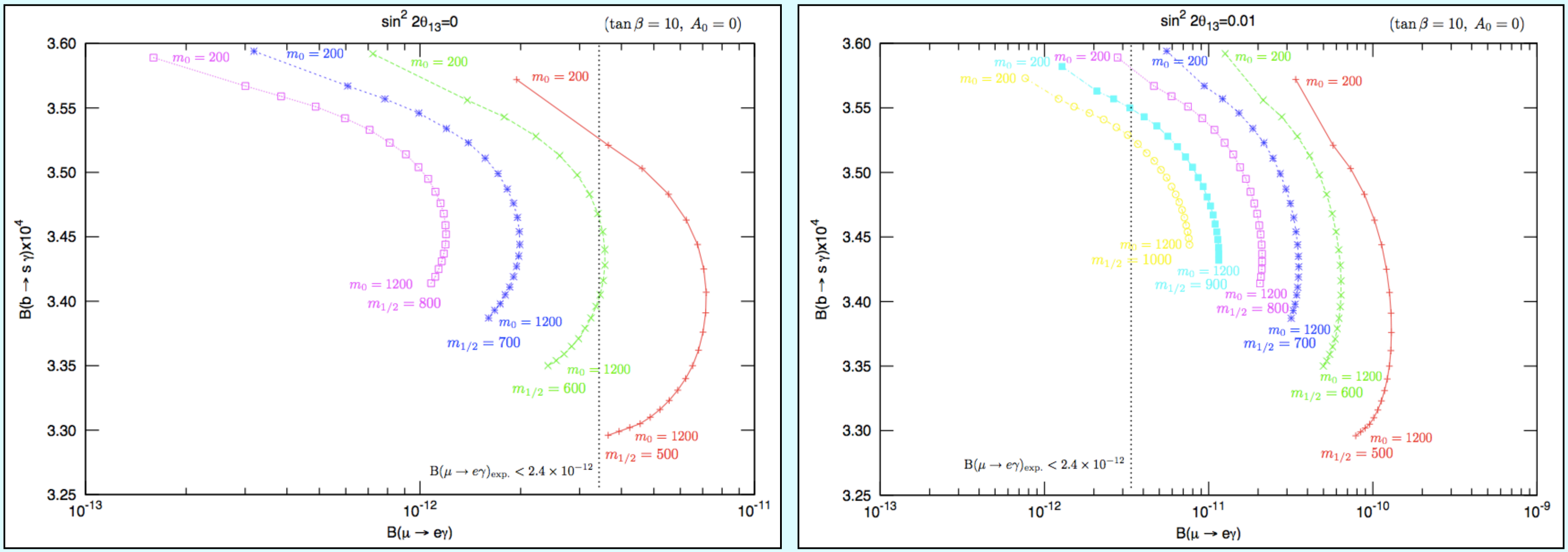
$(M_T > M_{\rm GUT})$

# ▸ flavor violations in SUSY $\nu$ Higgs SU(5) GUT

$m_{1/2}$ (GeV)

- 500
- 600
- 700
- 800

$$\heartsuit\ \mathrm{Br}(b \to s\gamma) - \mathrm{Br}(\mu \to e\gamma)$$




- b→sγ & μ→eγ are correlated one to one!
- strongly constrained by $\theta_{13}$

# ▸ flavor violations in SUSY $\nu$ Higgs SU(5) GUT

$m_{1/2}$ (GeV)

- 500
- 600
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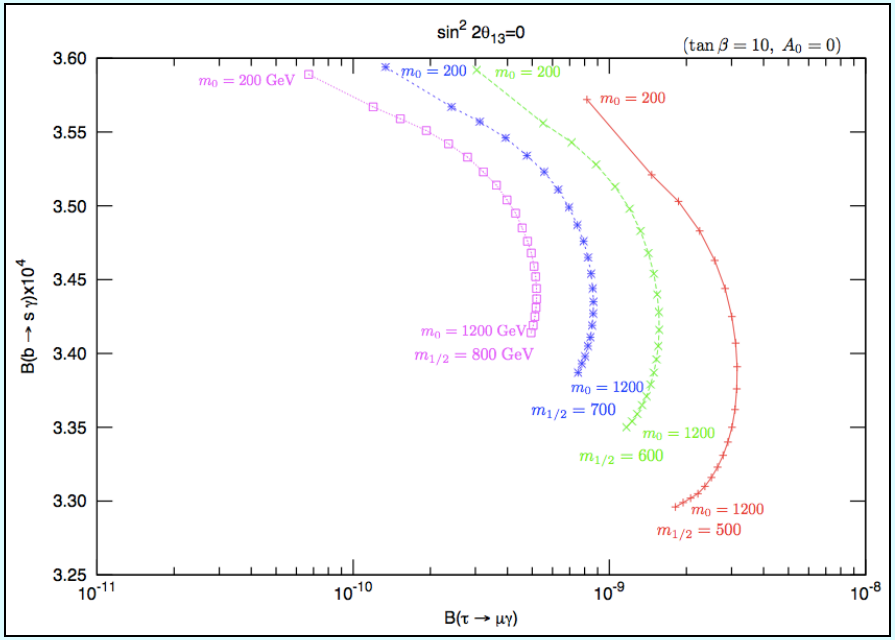
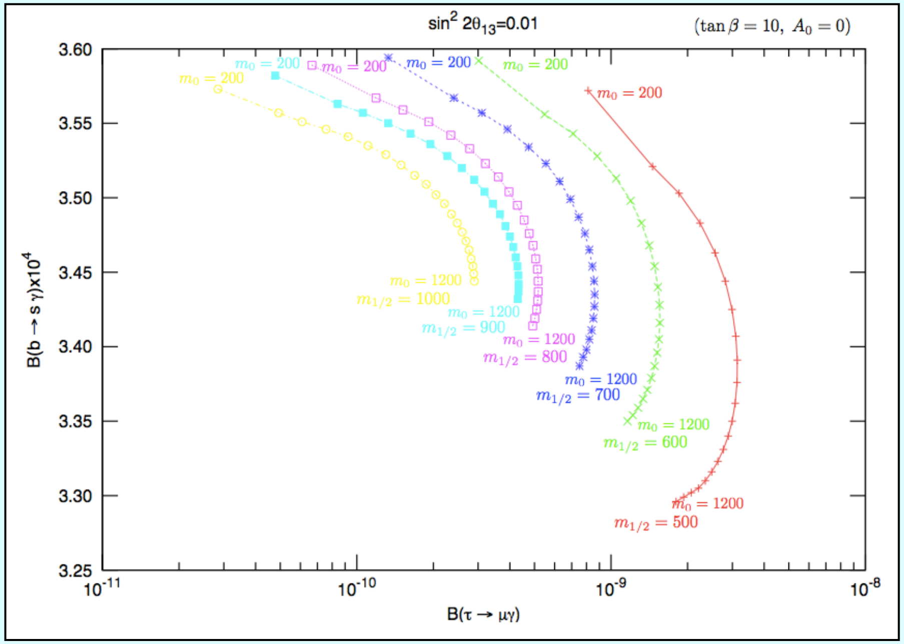
- 800

$$\heartsuit \ \mathrm{Br}(b \to s\gamma) - \mathrm{Br}(\tau \to \mu\gamma)$$




- below experimantal constraint Br(τ→μγ) < $4.4\times10^{-8}$

# 7. summary

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☆ GUT embedding naturally explains,

why $\mathrm{TeV}^2 \sim m_\nu \times M_{GUT}$!

☆ MSSM + $T_\nu, \bar{T}_\nu$ ($10^{14}$ GeV) + $H_\nu H_{\nu'}$ (≧GUT) + $T, \bar{T}$ (> GUT)

→ precise GCU + proton-stability

# 7. summary

Idea : small $\nu$ mass originates from small vev of $\nu$ Higgs

($H_\nu$ only have $y_\nu$, (and $y_\nu$ is non-small anymore.))

☆ GUT embedding naturally explains,

why $TeV^2 \sim m_\nu \times M_{GUT}$!

☆ MSSM + $T_\nu, \bar{T}_\nu$ ($10^{14}$ GeV) + $H_\nu H_{\nu'}$ (≧GUT) + $T, \bar{T}$ (> GUT)

→ precise GCU + proton-stability

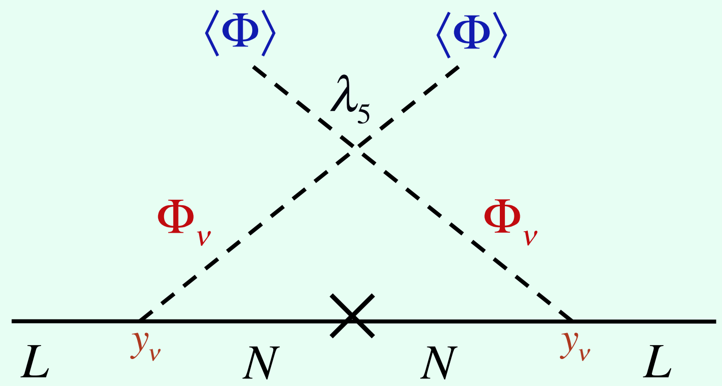
☆ FVs in lepton and quark directly related through MNS

→ excellent predictivility

## $m_3^2$ =0 case:

☆ exact $Z_2$ sym.→ $\nu_R$ is DM & $\langle\Phi_\nu\rangle$=0

☆ ν mass induced radiatively



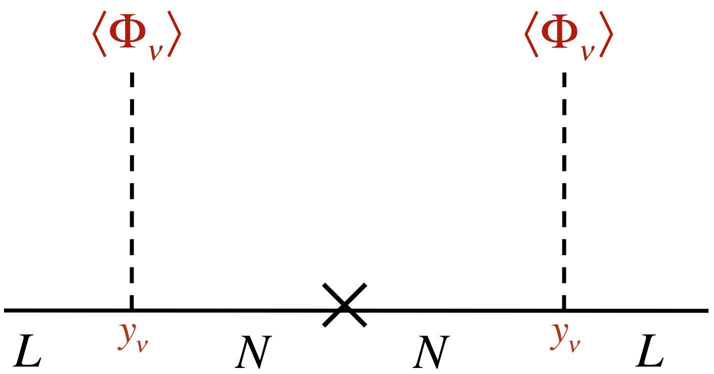

E. Ma, PRD 73, 077301 (2006).

☆ $m_3^2$ =0 induces $\langle\Phi_\nu\rangle$=0, so Z2 is not broken.
☆ no global U(1) due to $\lambda_5 \neq 0$, so no NG boson.

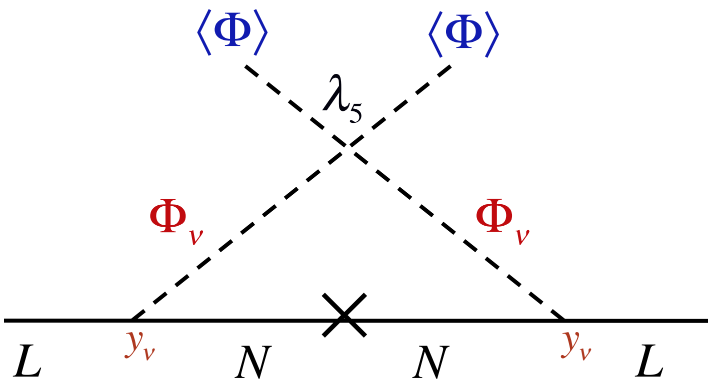
- Majorana case with $\langle \Phi_\nu \rangle \neq 0$ ($m_3^2 \neq 0$)

there are two sources of ν mass as,

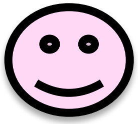
☆ ν mass from seesaw




☆ ν mass induced radiatively




$$m_\nu^{tree} : m_\nu^{loop} \sim \langle \Phi_\nu \rangle^2 : \lambda_5 \langle \Phi \rangle^2 / (4\pi)^2$$



# Stability of VEV hierarchy

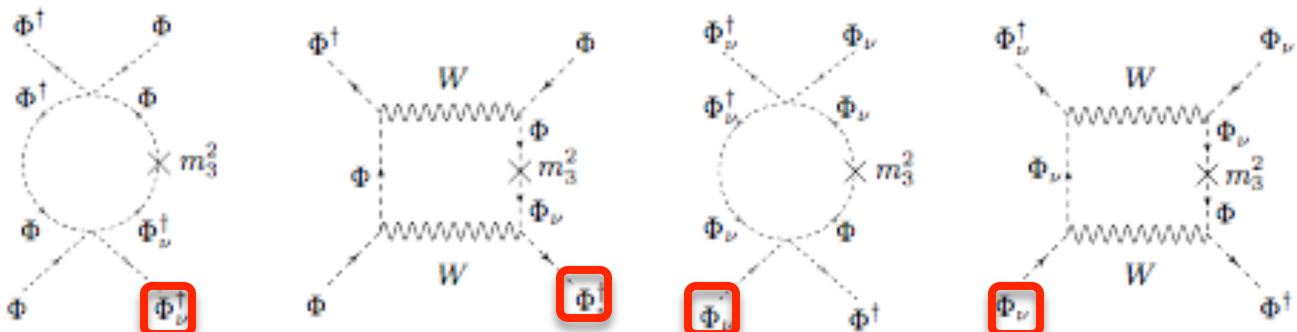
NH, T.Horita, Phys. Lett. B705, 98 (2011).

- $\langle\Phi_\nu\rangle \ll \langle\Phi\rangle$ is global minimum?

  → yes, under condition of $(\lambda_3+\lambda_4+\lambda_5)^2 > \lambda_1\lambda_2$ with $\lambda_2 m_\Phi{}^4 > \lambda_1 m_{\Phi\nu}{}^4$

- $\langle\Phi_\nu\rangle \ll \langle\Phi\rangle$ is preserved against radiative corrections?

  → yes, νHDM satisfies $\frac{\alpha}{16\pi^2}\langle\Phi\rangle^3 / m_3^2 \le \frac{3}{4\pi^2}\log\frac{\langle\Phi\rangle}{\langle\Phi_\nu\rangle}$




(most dangerous diagrams with 4-external lines in Coleman-Weinberg 1-loop effective potential)

$$V^{1-loop} \sim \frac{\alpha}{16\pi^2}\langle\Phi_\nu\rangle\langle\Phi\rangle^3 \to \frac{dV^{1-loop}}{d\langle\Phi_\nu\rangle} \sim \frac{\alpha}{16\pi^2}\langle\Phi\rangle^3 \quad \Rightarrow V \sim \left(m_3^2 + \frac{\alpha}{16\pi^2}\langle\Phi\rangle^3\right)\langle\Phi_\nu\rangle + \cdots$$

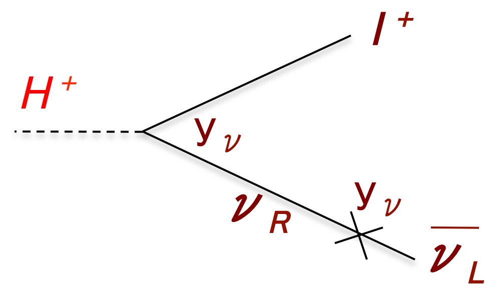
All 6-, 8-, 10-, ・・・external lines diagrams are summed, and the above condition is obtained.

☆$Z_2$ is softly broken by $m_3^2$ → $m_3^2 \ll m_\Phi{}^2, m_{\Phi\nu}{}^2$ is preserved against from quantum correction.

# LHC, ILC phenomenology

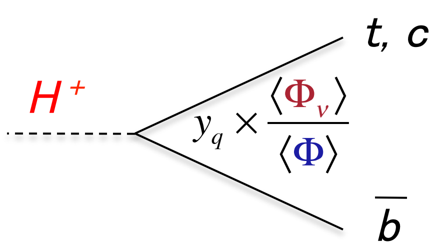
NH, K.Tsumura, JHEP 1106, 068 (2011).

$m_{H\pm} < m_{\nu R}$

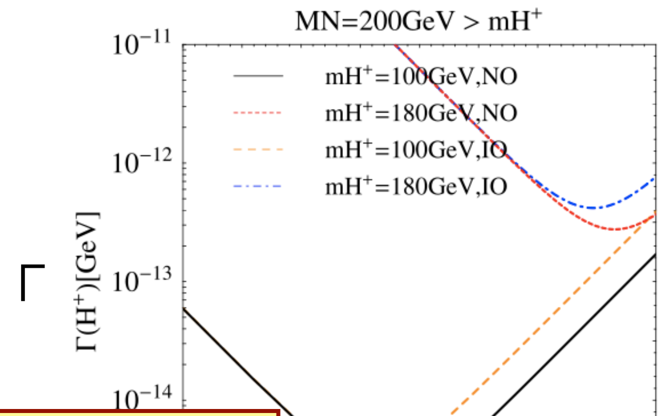



$$\Gamma(H^\pm \to l^\pm \nu_L) \sim G_F m_{H^\pm} m_\nu^2 \frac{\langle \Phi \rangle^2}{\langle \Phi_\nu \rangle^2}$$

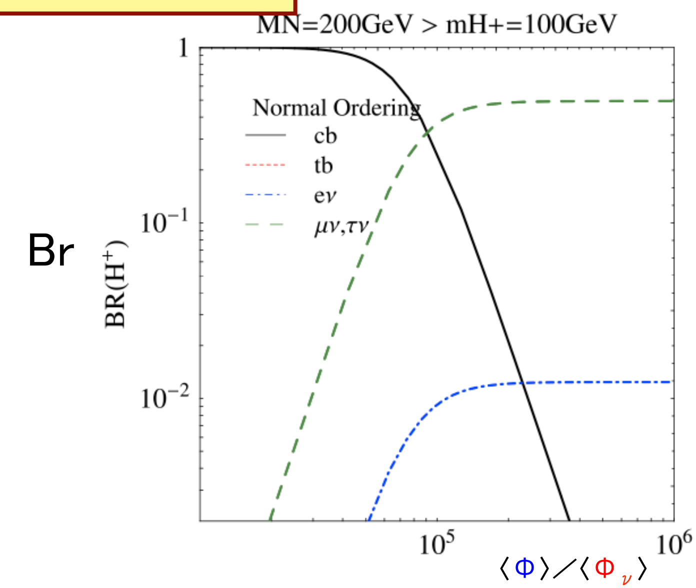
**or**




$$\Gamma(H^\pm \to q\overline{q}) \sim m_{H^\pm} y_q^2 \frac{\langle \Phi_\nu \rangle^2}{\langle \Phi \rangle^2}$$



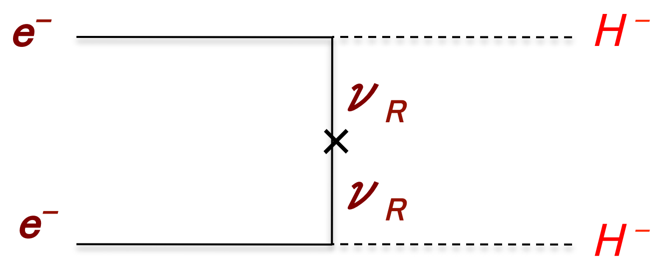

long lived $H^\pm$ !
(10cm in detector)
Conventional 2HDM can't induce
(due to no tiny couplings)

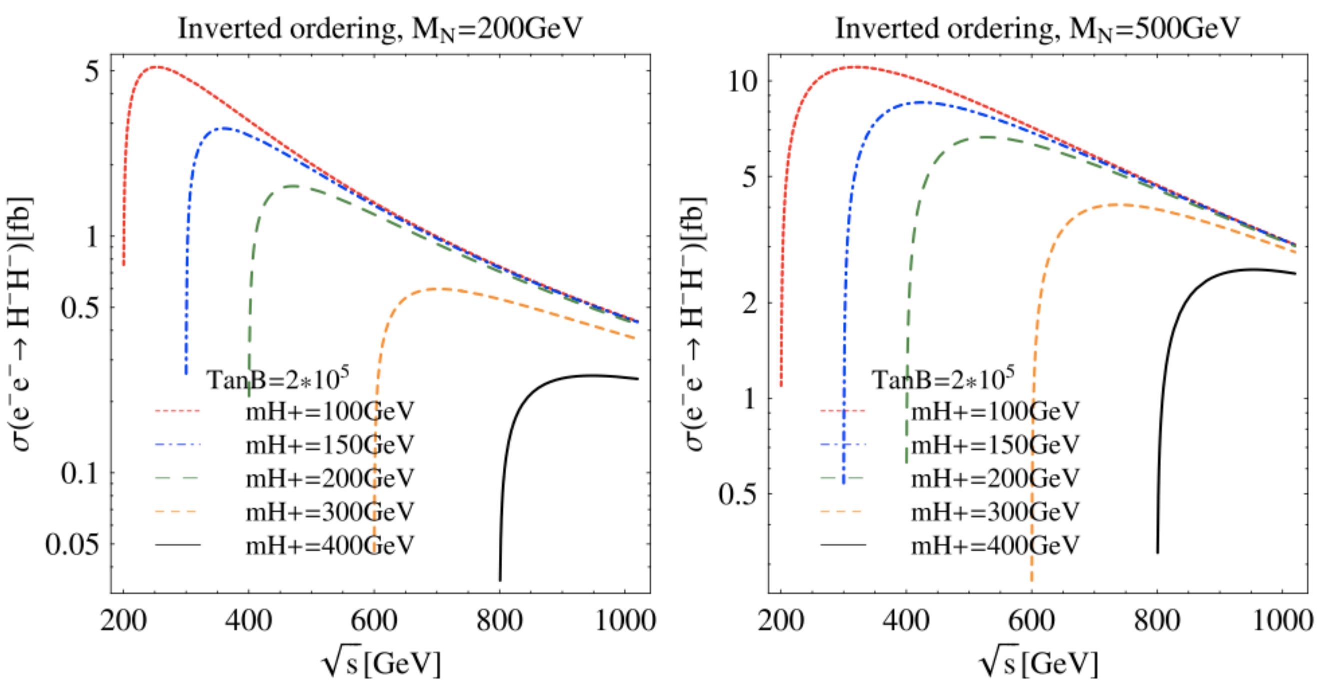


# LHC, ILC phenomenology

NH, K.Tsumura, JHEP 1106, 068 (2011).

☆ILC: $e^-e^-$ collider:




Total cross sections of $e^-e^- \to H^-H^-$ in $\nu$THDM with $\nu_R$, whose mass is $M_{\nu R}$ = 200 GeV and 500 GeV.

# Low energy thermal leptogenesis

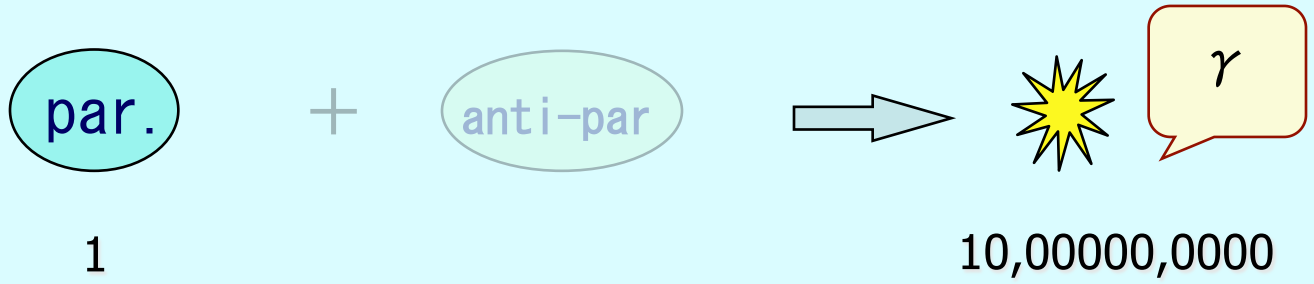
NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

par. + anti-par

100,0000,0001 10,00000,0000

# Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).



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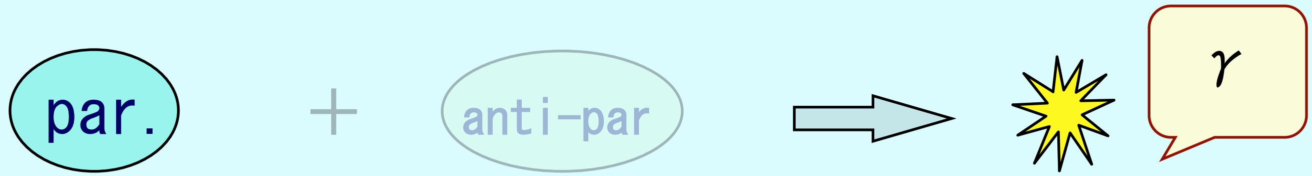
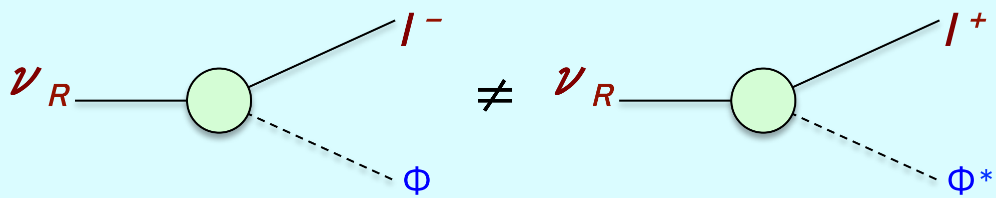



1 10,00000,0000

$n_b/s \fallingdotseq 10^{-10}$

## ☆ leptogenesis

$$\Gamma(\nu_R \rightarrow l + \Phi) \neq \Gamma(\nu_R \rightarrow \bar{l} + \Phi^*)$$ ← CP violation

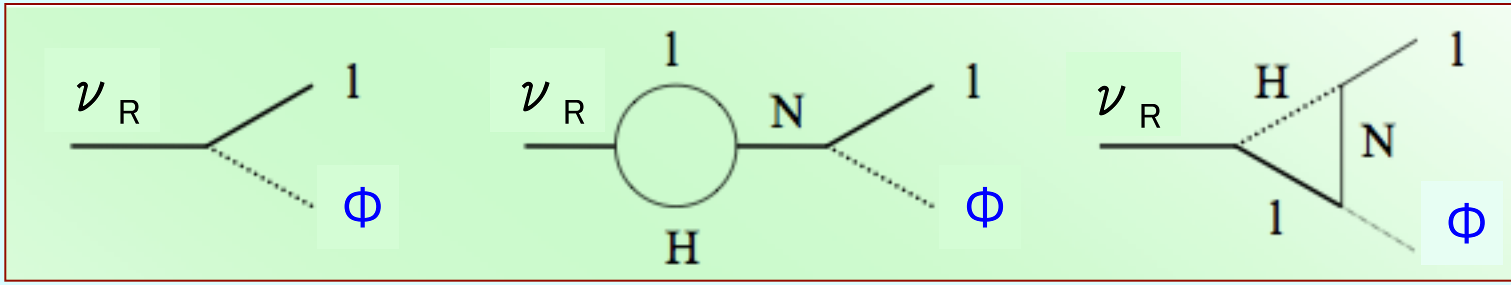



#L →(Sphaleron process)→ #B

# Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

leptogenesis: $\Gamma(\nu_R \to l + \Phi) \neq \Gamma(\overline{\nu}_R \to l + \Phi^*)$ ← CP violation




Conventional See-Saw (type-I)

$$\varepsilon \equiv \frac{\Gamma(\nu_{R1} \to \Phi + \overline{l}_j) - \Gamma(\nu_{R1} \to \Phi^* + l_j)}{\Gamma(\nu_{R1} \to \Phi + \overline{l}_j) + \Gamma(\nu_{R1} \to \Phi^* + l_j)}$$

$$\simeq -\frac{3}{8\pi}\frac{1}{(y_\nu y_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}(y_\nu y_\nu^\dagger)_{1i}^2\frac{M_1}{M_i},\ (M_i \gg M_1)$$

$$\simeq \frac{3}{8\pi}\frac{M_1 m_{\nu 3}}{\langle\Phi\rangle^2}\sin\delta \simeq 10^{-6}\left(\frac{M_1}{10^{10}GeV}\right)\left(\frac{m_{\nu 3}}{0.05eV}\right)\sin\delta$$

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

$\varepsilon \sim 10^{-7}$ for suitable $n_b/s$

thermal: $T_R > M_1$, $\nu_{R1}$ is produced in thermal

$M_1 > 10^9$ GeV : Davidson-Ibarra bound

S. Davidson and A. Ibarra, PLB 535, 25 (2002)

TeV-scale thermal leptogenesis is difficult !

# Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

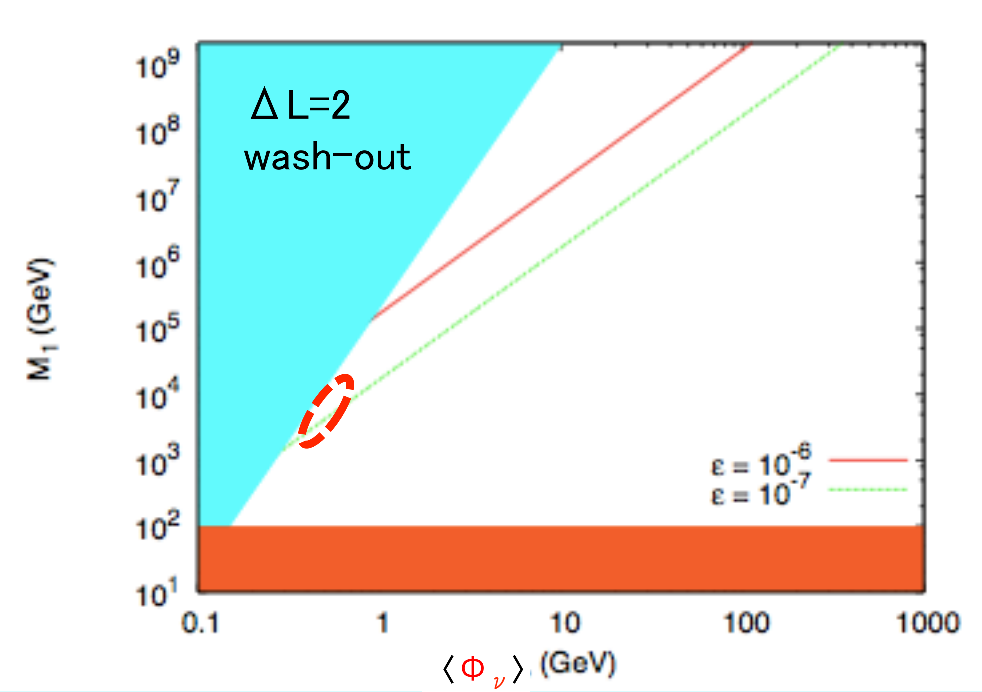
$\nu$ HDM: non-small $y_\nu$ with TeV-scale Majorana mass

$$\varepsilon \simeq -\frac{3}{8\pi}\frac{1}{(y_\nu y_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}(y_\nu y_\nu^\dagger)_{1i}^2\frac{M_1}{M_i} \simeq -\frac{3}{8\pi}\frac{M_1 m_{\nu 3}}{\langle\Phi_\nu\rangle^2}\sin\delta$$

$$\simeq -\frac{3}{16\pi}10^{-6}\left(\frac{0.1GeV}{\langle\Phi_\nu\rangle}\right)^2\left(\frac{M_1}{100GeV}\right)\left(\frac{m_\nu}{0.05eV}\right)\sin\delta$$

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

$M_1 \geqq$ 5 TeV is possible for thermal leptogenesis



☆ thermal leptogenesis: (= leptogenesis with thermally produced *N*)

inflation (inflaton decay) → reheating temperature

*N* is produced in thermal

(# of *N* is determined only by $T_R$)

↕

non−thermal leptogenesis

*N* is produced non−thermally, such as,

inflaton decay, inflaton=right−handed sneutrino (condensation), etc.

(# of *N* is determined by unknown physics
(coupling between inflaton & *N* etc.) )

# Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

Leptogenesis in SUSY $\nu$HDM: non-small $y_\nu$ with TeV-scale Majorana mass

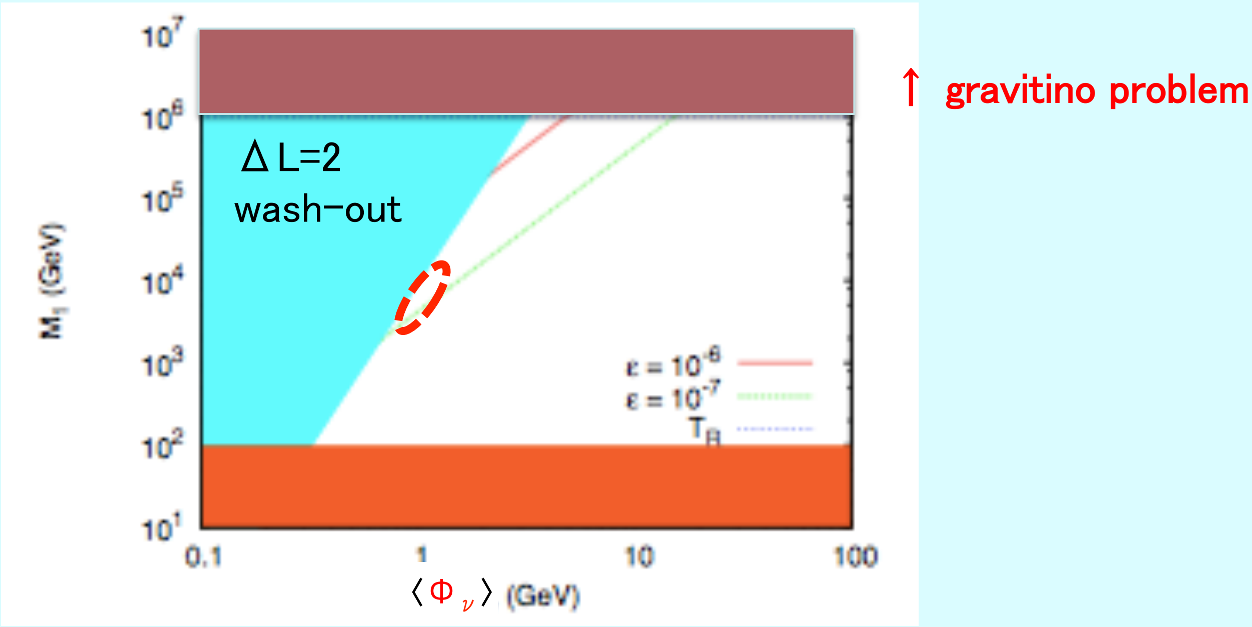
$$\varepsilon \equiv \varepsilon(\nu_R \to lH) + \varepsilon(\nu_R \to \tilde{l}\widetilde{H}) + \varepsilon(\widetilde{\nu_R} \to l\widetilde{H}) + \varepsilon(\widetilde{\nu_R} \to \tilde{l}H)$$

$$\simeq -\frac{3}{16\pi}10^{-5}\left(\frac{0.1GeV}{\langle\Phi_\nu\rangle}\right)^2\left(\frac{M_1}{10^3 GeV}\right)\left(\frac{m_\nu}{0.05eV}\right)\sin\delta$$

(NH, $m_1 \sim 0$, ($y_{i1} \ll y_{i2}, y_{i3}$))

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

$M_1 \geqq 5$ TeV is possible for thermal leptogenesis




SUSY $\nu$HDM is free from gravitino problem

- O(100) GeV gravitino with no-disturbing BBN needs $T_R < 10^6$ GeV.
- even this $T_R$, $N_1$ is thermally produced in our setup.

## ☆ gravitino problem

gravitino is produced in scattering in thermal bath
but NOT in thermal equilibrium (3/2's production is one way 一方通行)

(# of gravitino is determined only by $T_R$)

● gravitino NLSP case: (～100 GeV)

non-disturbing BBN (1s ～3 min) → $T_R < 10^6$ GeV

● gravitino LSP case: (<100 GeV)

NLSP's decay: non-disturbing BBN (1s ～3 min) → $T_R < 10^6 \sim 10^9$ GeV
not overclose condition → $T_R < 10^9$ GeV

cf). Gauge mediation: interaction of longitudinal of gravitino (～1/F)
is large (not Planck suppressed) → gravitino problem is sever