Relic abundance of right-handed neutrino and sneutrino dark matter in SUSY $SU(2)_H$ gauge theory with confinement

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Multi-Higgs Models , Lisbon, 2-5 Sep.

Contents

Introduction

The SM-like Higgs boson has been discovered at the LHC.

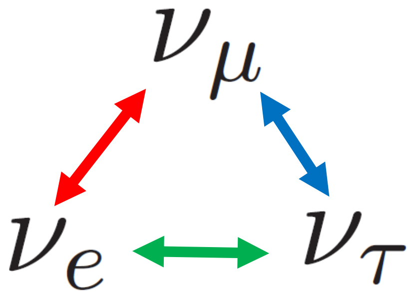
- The mass is 126 GeV.
- Spin/parity is 0^+ .
- Coupling constants are consistent with the SM.
- No other new particles are found.

The SM is very successful!

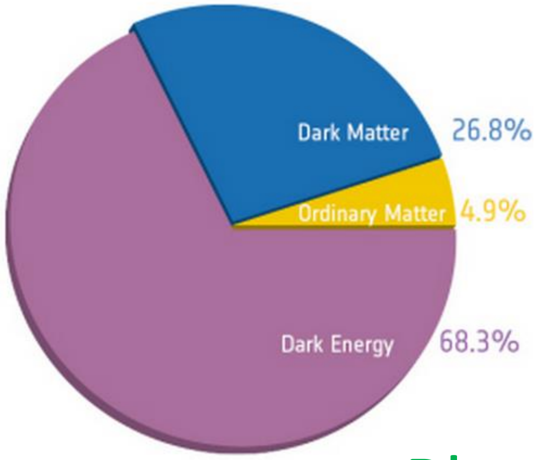
Introduction

However, many problems still remain.

- Neutrino mass

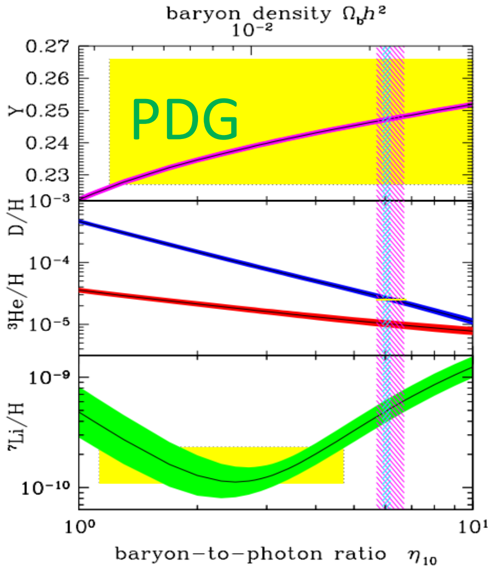


- Dark matter



Planck

- Baryon asymmetry



These problems can not be explained in the SM.

New physics beyond the SM must exist.

Introduction

- Neutrino mass

  - Ridiative seesaw scenario
  - Neutirino mass is generated by loop induced diagram.

- Dark matter

  - WIMP
  - A new symmetry gurantees DM stability (e.g. Z2-symmetry).

- Baryon asymmetry

  - Electroweak baryogenesis

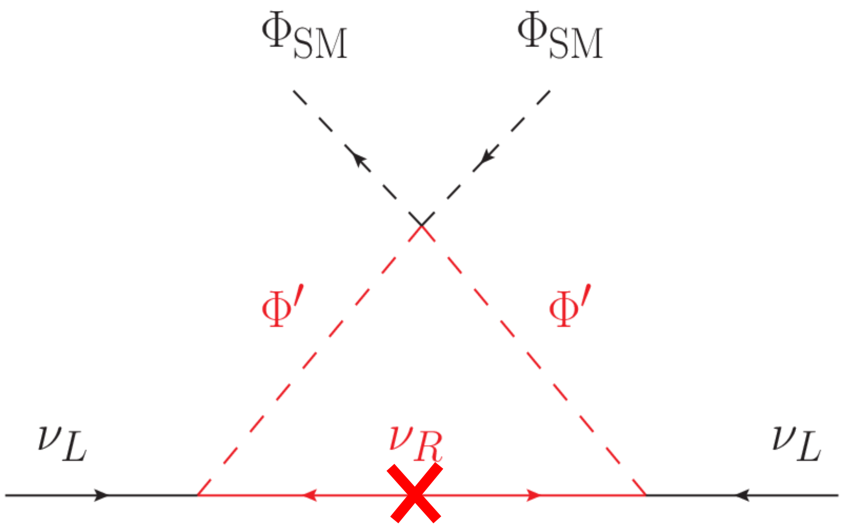
Radiative seesaw scenario

- Inert scalars and Z_2-odd right-handed neutrinos are introduced.
- Tiny neutrino masses are generated by loop-level diagram.
- The lightest Z_2-odd particle can be DM candidate.

Ma model **Ma (2006)**

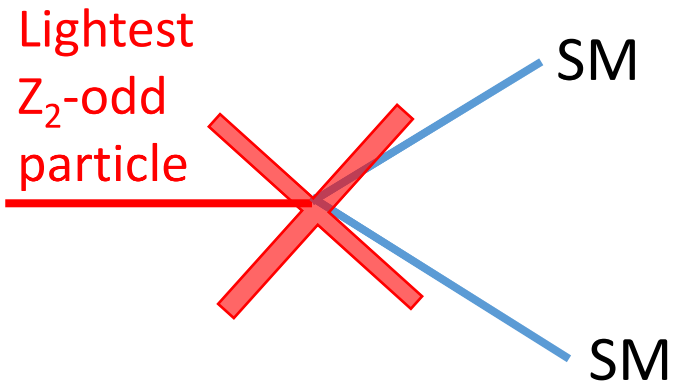
Φ' : Inert scalar doublet
ν_R : Z_2-odd right-handed neutrinos

- Neutrino mass diagram



- Dark matter

Because of unbroken Z_2 symmetry, lightest Z_2-odd particle is a dark matter candidate.



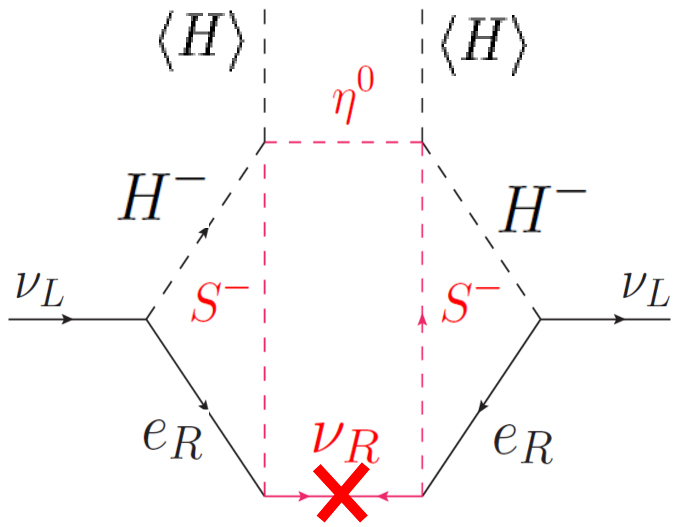
Radiative seesaw scenario

- Inert scalars and Z_2-odd right-handed neutrinos are introduced.
- Tiny neutrino masses are generated by loop-level diagram.
- The lightest Z_2-odd particle can be DM candidate.

AKS model **Aoki, Kanemura, Seto(2009)**

$$\Phi_{\rm SM} + \Phi_2 + S^{\pm} + \eta^0 + \nu_R$$

- Neutrino mass diagram



- Dark matter

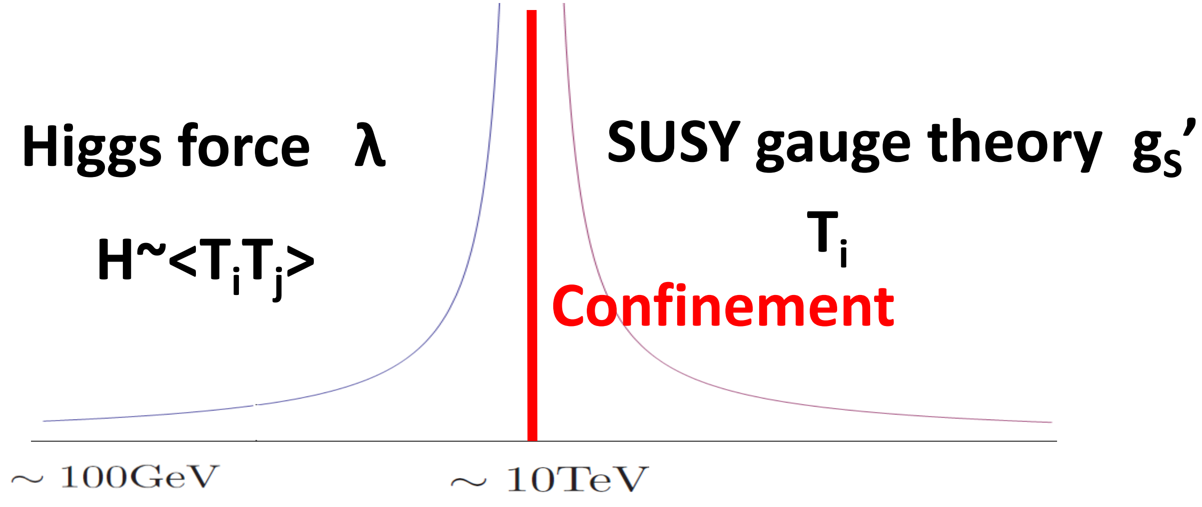
  Because of unbroken Z_2 symmetry, lightest Z_2-odd particle is a dark matter candidate.

- Electroweak baryogenesis

  ◆Extra boson loops enhance ϕ_C/T_C , so that $\phi_C/T_C \gtrsim 1$ can be satisfied.

What is a fundamental theory?

- Electroweak baryogensis requires strong coupling constant in the Higgs sector. This leads Landau pole at O(10)TeV.
- Origin of the Higgs force is SUSY gauge theory with confinement above Landau pole.
- Higgs sector at low energy scale is composite states which is formed by fundamental fields. $H_{ij} \sim T_i T_j$



SUSY $SU(2)_H$ gauge theory

Intriligator, Seiberg Nucl.Phys.Proc.Suppl.45BC:1-28,1996

SUSY QCD : $N_f = N_C + 1$ → Confinement

$N_f = 3,\ N_c = 2$

Kanemura, Shindou, Yamada, PRD86 055023

Harnik, Kribs, Larson, Murayama, PRD70 015002

UV picture

Fundamental fields

Field	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	**2**	0	+
T_3	**1**	+1/2	+
T_4	**1**	−1/2	+
T_5	**1**	+1/2	−
T_6	**1**	−1/2	−

T_i : $SU(2)_H$ doublet

$$H_{ij} \sim T_i T_j$$

IR picture

Composite fields

MSSM doublets

Exotic fields

Field	$SU(2)_L$	$U(1)_Y$	Z_2
H_u	2	+1/2	+
H_d	2	−1/2	+
Φ_u	2	+1/2	−
Φ_d	2	−1/2	−
Ω^+	1	+1	−
Ω^-	1	−1	−
$N,\ N_\Phi,\ N_\Omega$	1	0	+
$\zeta,\ \eta$	1	0	−

We introduce Z_2-symmetry and Z_2-odd RH-neutrino to realize radiative seesaw scenario.

In the Fat Higgs model, Hu, Hd and N are light. Other fields are decoupled by introducing additional fields.

Multi-Component DM System

- The Z_2-symmetry and R-parity guarantee DM stability. (Z_2,Rp)
  - (+,-) Neutralino
  - (-,+) Z_2-odd Higgs or RH-neutrino
  - (-,-) Z_2-odd Higgsino or RH-sneutrino

- In benchmark scenario, the lightest particles in Z_2-odd sector are RH-neutrino and RH-sneutrino.

- For simplicity, we assume that the lightest neutralino mass is heavier than RH-neutrino and RH-sneutrino.

Higgs sector

Field	$SU(2)_L$	$U(1)_Y$	Z_2
H_u	2	$+1/2$	$+$
H_d	2	$-1/2$	$+$
Φ_u	2	$+1/2$	$-$
Φ_d	2	$-1/2$	$-$
Ω^+	1	$+1$	$-$
Ω^-	1	-1	$-$
$N, \ N_\Phi, \ N_\Omega$	1	0	$+$
$\zeta, \ \eta$	1	0	$-$

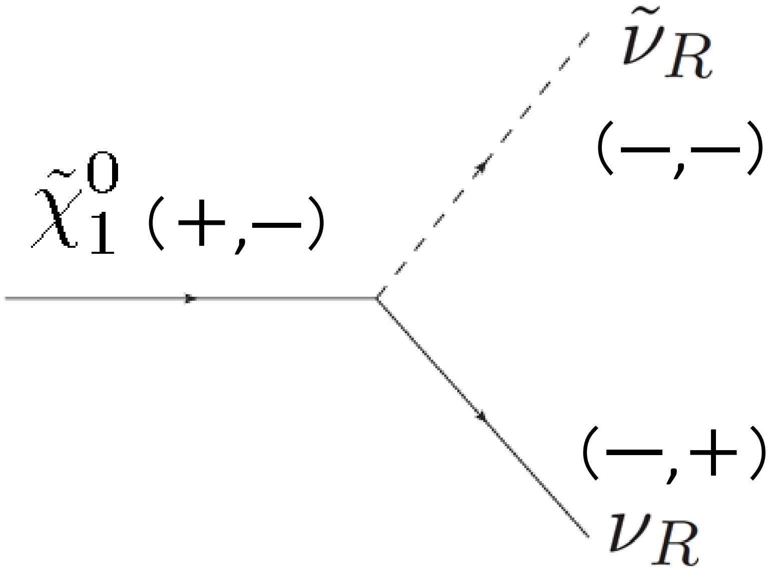
RH-neutrino ν_R

Multi-Component DM System

- The lightest neutralino mass is $m_{\chi^0} > m_{\tilde{\nu}_R} + m_{\nu_R}$.

$$W_{\rm eff}^N = \frac{\kappa}{2} N \nu_R^c \nu_R^c + y_N^i \nu_R^c L_i \Phi_u + h_N^i \nu_R E_i^c \Omega^- + \frac{M}{2} \nu_R^c \nu_R^c$$

N : Z_2-even neutral singlet



The lightest neutralino decays into RH-neutrino and RH-sneutrino.

RH-neutrino and RH-sneutrino are DM candidates.

Relic abundance of RH-neutrino and sneutrino

- In order to reproduce DM relic abundance $\Omega_{\rm DM}h^2 = \sum_i \Omega_{\rm DM_i}h^2 \simeq 0.12$,

  RH-neutrino and sneutrino masses are about $m_h/2$~63 GeV
  (Higgs portal DM).

- In this mass region, VV-channel doesn't open. The dominant process is

$$\nu_R\nu_R,\ \tilde{\nu}_R\tilde{\nu}_R \to \mathrm{SM\ SM}$$

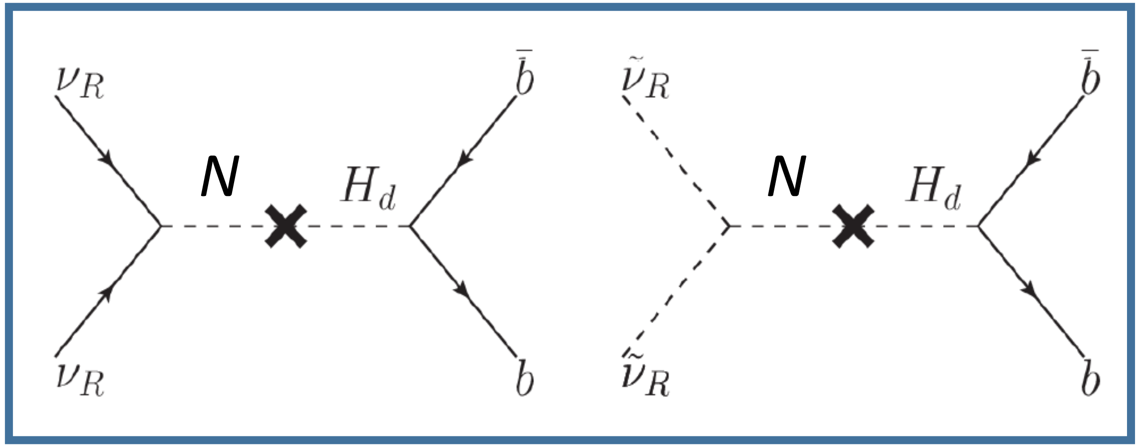
- We also take into account the conversion process.

$$\nu_R\nu_R \leftrightarrow \tilde{\nu}_R\tilde{\nu}_R$$

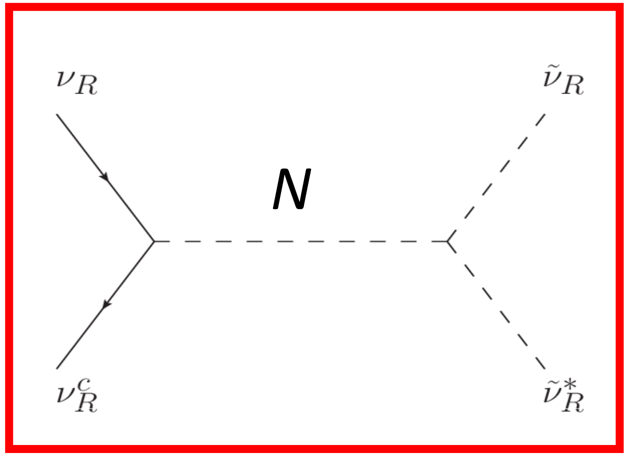
Relic abundance of RH-neutrino and sneutrino

$$\frac{dY}{dx} = 0.264 g_*^{1/2}\left(\frac{\mu_R M_P}{x^2}\right)\times\left\{-\langle\sigma_\nu v\rangle\left(Y^2 - Y_{\rm eq}^2\right) - \langle\sigma_{\nu\tilde{\nu}} v\rangle\left(Y^2 - \tilde{Y}^2\frac{Y_{\rm eq}^2}{\tilde{Y}_{\rm eq}^2}\right) + \langle\sigma_{\tilde{\nu}\nu} v\rangle\left(\tilde{Y}^2 - Y^2\frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right)\right\}$$

$$\frac{d\tilde{Y}}{dx} = 0.264 g_*^{1/2}\left(\frac{\mu_R M_P}{x^2}\right)\times\left\{-\langle\sigma_{\tilde{\nu}} v\rangle\left(\tilde{Y}^2 - \tilde{Y}_{\rm eq}^2\right) - \langle\sigma_{\tilde{\nu}\nu} v\rangle\left(\tilde{Y}^2 - Y^2\frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) + \langle\sigma_{\nu\tilde{\nu}} v\rangle\left(\tilde{Y}^2 - Y^2\frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right)\right\}$$



Annihilation



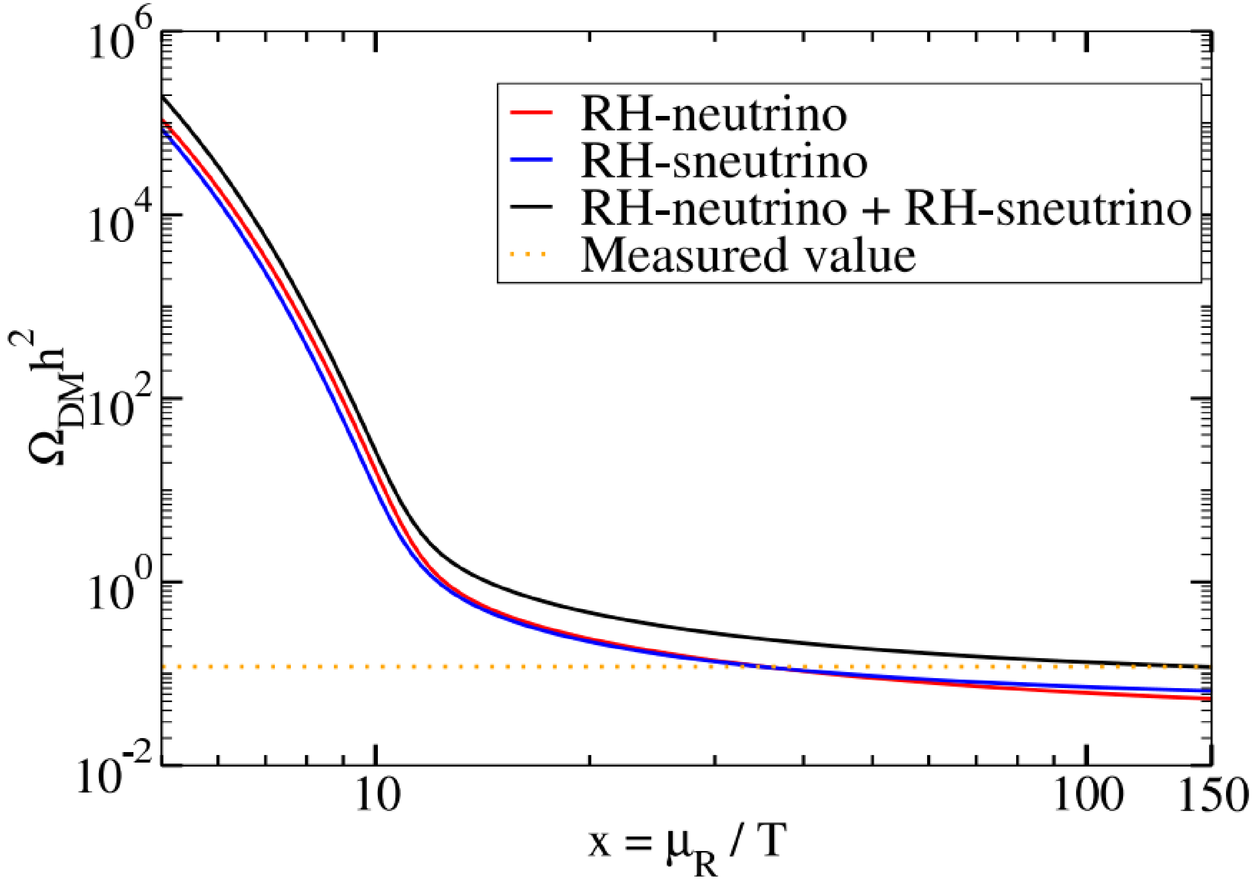
Conversion

RH-neutrino and sneutrino mainly couple to Z2-even scalar singlet *N*.
In order to enhance annihilation cross section, the mixing between S and Hd is very large.

Relic abundance of RH-neutrino and sneutrino

$$\frac{dY}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right) \times \left\{ -\langle\sigma_\nu v\rangle \left(Y^2 - Y_{\rm eq}^2\right) - \langle\sigma_{\nu\tilde{\nu}} v\rangle \left(Y^2 - \tilde{Y}^2 \frac{Y_{\rm eq}^2}{\tilde{Y}_{\rm eq}^2}\right) + \langle\sigma_{\tilde{\nu}\nu} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) \right\}$$

$$\frac{d\tilde{Y}}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right) \times \left\{ -\langle\sigma_{\tilde{\nu}} v\rangle \left(\tilde{Y}^2 - \tilde{Y}_{\rm eq}^2\right) - \langle\sigma_{\tilde{\nu}\nu} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) + \langle\sigma_{\nu\tilde{\nu}} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) \right\}$$



$$x = \frac{\mu_R}{T}$$

$$\mu_R^{-1} = m_{\nu_R}^{-1} + m_{\tilde{\nu}_R}^{-1}$$

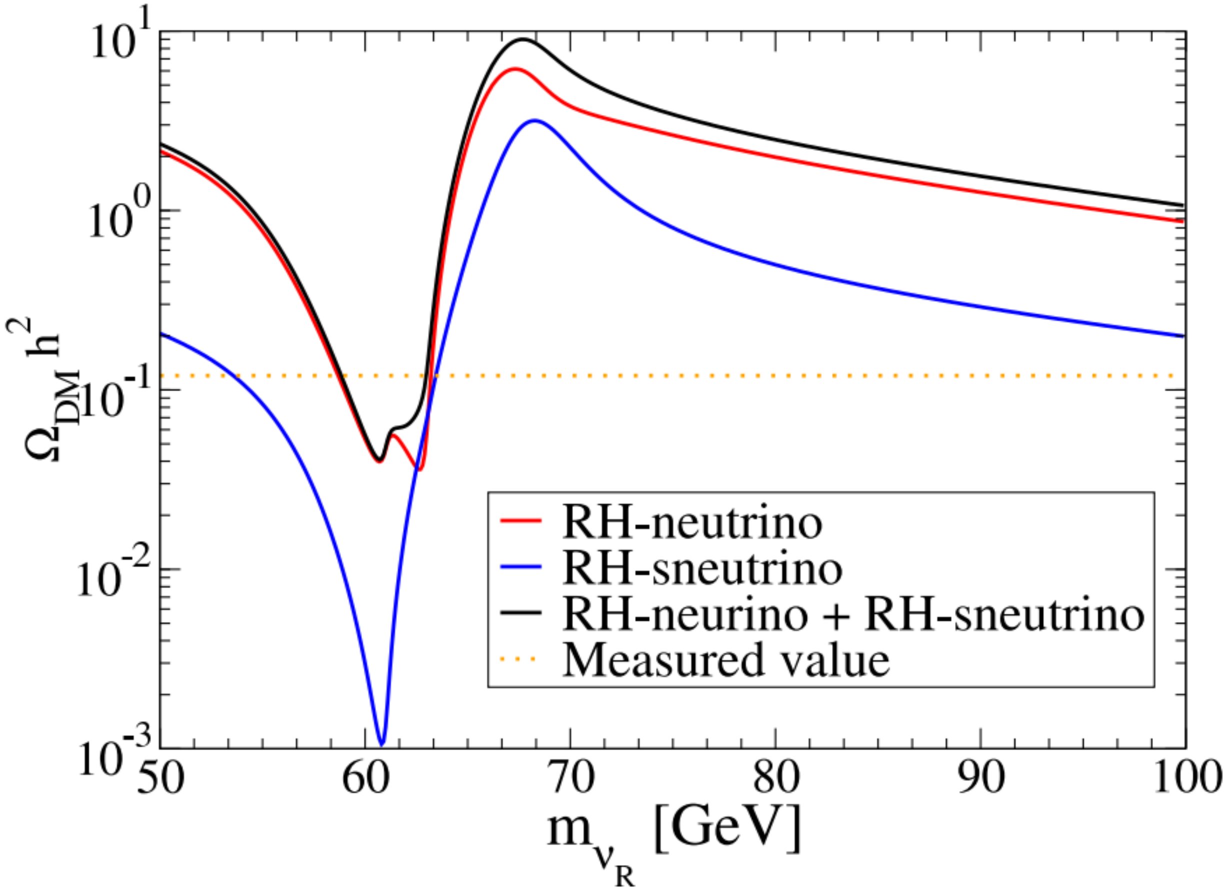
$$m_{\nu_R} = 63\mathrm{GeV}$$

$$m_{\tilde{\nu}_R} = 65\mathrm{GeV}$$

Relic abundance of RH-neutrino and sneutrino

$$\frac{dY}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right) \times \left\{ -\langle\sigma_\nu v\rangle \left(Y^2 - Y_{\rm eq}^2\right) - \langle\sigma_{\nu\tilde{\nu}} v\rangle \left(Y^2 - \tilde{Y}^2 \frac{Y_{\rm eq}^2}{\tilde{Y}_{\rm eq}^2}\right) + \langle\sigma_{\tilde{\nu}\nu} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) \right\}$$

$$\frac{d\tilde{Y}}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right) \times \left\{ -\langle\sigma_{\tilde{\nu}} v\rangle \left(\tilde{Y}^2 - \tilde{Y}_{\rm eq}^2\right) - \langle\sigma_{\tilde{\nu}\nu} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) + \langle\sigma_{\nu\tilde{\nu}} v\rangle \left(\tilde{Y}^2 - Y^2 \frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) \right\}$$



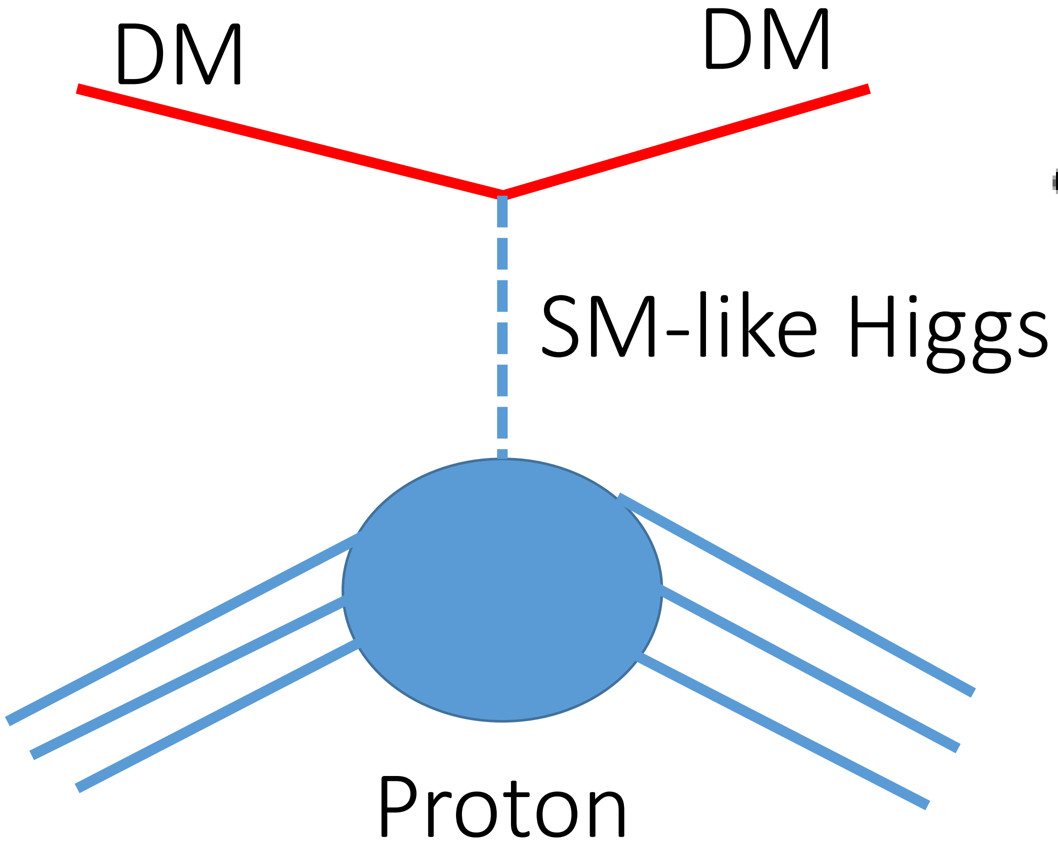
$$x = \frac{\mu_R}{T}$$

$$\mu_R^{-1} = m_{\nu_R}^{-1} + m_{\tilde{\nu}_R}^{-1}$$

$$m_{\tilde{\nu}_R} = m_{\nu_R} + 2\text{GeV}$$

Direct Detection

- RH-neutrino and sneutrino are gauge singlet.
- These do not have gauge interaction .
- Constrains from direct detection can be avoid.



$$\sigma_{\rm DM}^{\rm SI} = 1.1 \times 10^{-46} {\rm cm}^2 < 10^{-45} {\rm cm}^2$$

- The futute experiment such as XENON 1T can find RH-neutrino and sneutino DM.

Summary

- We propose a UV complete model which can explain neutrino mass, dark matter and baryogensis with confinement.

UV

$SU(2)_H \times Z_2$ with $N_f=3$ + Z_2-odd ν_R

$T_1, T_2, T_3, T_4, T_5, T_6$

$H_{ij} \sim T_i T_j$

Confinement O(10) TeV

IR

$H_u, H_d, \Phi_u, \Phi_d, \cdots$

Extended Higgs sector

- RH-neutrino and sneutrino DM is a typical case of multi-component DM.
- Relic abudance and dirext detection constrains are satisfied.
- Future direct detection experiment can detect RH-neutrino and sneutrino.

Back up slides

Yukawa coupling

- Introduce four SU(2)L doublets (SU(2)H singlets),

$$W_f = M_f(\varphi_u\bar{\varphi}_u + \bar{\varphi}_d\varphi_d) + \bar{\varphi}_d(TT^4) + \bar{\varphi}_u(TT^3) + h_u^{ij}Q_iu_j\varphi_u + h_d^{ij}Q_id_j\varphi_d + h_e^{ij}L_ie_j\varphi_d$$

$\varphi_u,\ \bar{\varphi}_d\ (2, +\frac{1}{2}),$

$\varphi_d,\ \bar{\varphi}_u\ (2, -\frac{1}{2})$

Integrated out $\varphi_u,\ \bar{\varphi}_d\ ,\ \varphi_d,\ \bar{\varphi}_u$

$$W_f = \frac{4\pi}{M_f}\left[h_u^{ij}Q_iu_j(TT^3) + h_d^{ij}Q_id_j(TT^4) + h_e^{ij}L_ie_j(TT^4)\right]$$

Below Landau pole, $(TT^3) \to \Lambda_H H_u/4\pi,\ (TT^4) \to \Lambda_H H_d/4\pi$

$$W_f = h_u^{ij}Q_iu_jH_u + h_d^{ij}Q_id_jH_d + h_e^{ij}L_ie_jH_d$$

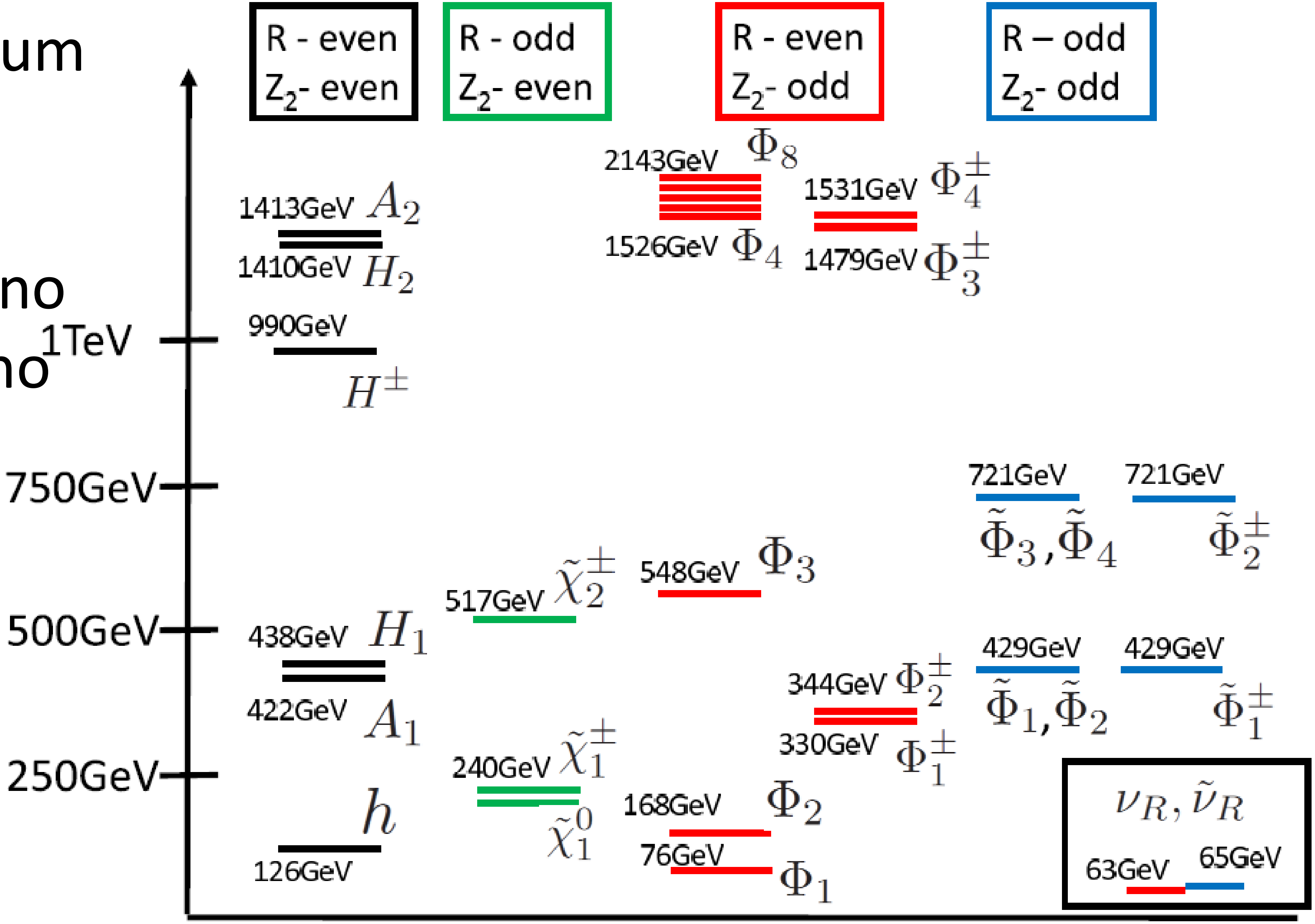
Z_2-even Higgs scalar mass matirices at tree level

$$M^2_{\rm even} = \begin{pmatrix} m_Z^2 s_\beta^2 + \left(\frac{A_N}{\sqrt{2}} v_N + \lambda^2 v_0^2\right)\cot\beta & * & * \\ \frac{1}{2}(\lambda^2 v^2 - m_Z^2 s_{2\beta}) - (\lambda^2 v_0^2 + \frac{A_N}{\sqrt{2}} v_N) & m_Z^2 c_\beta^2 + \left(\frac{A_N}{\sqrt{2}} v_N + \lambda^2 v_0^2\right)\tan\beta & * \\ \lambda^2 v v_N s_\beta - \frac{A_N}{\sqrt{2}} v c_\beta & \lambda^2 v v_N c_\beta - \frac{A_N}{\sqrt{2}} v s_\beta & \frac{A_N}{2\sqrt{2}} \frac{v^2}{v_S} s_\beta^2 - \sqrt{2} C\lambda \frac{v_0^2}{v_N} \end{pmatrix}$$

$$M^2_{\rm odd} = \begin{pmatrix} \left(\frac{A_N}{\sqrt{2}} v_N + \lambda^2 v_0^2\right)\cot\beta & * & * \\ \frac{A_N}{\sqrt{2}} v_N + \lambda^2 v_0^2 & \left(\frac{A_N}{\sqrt{2}} v_N + \lambda^2 v_0^2\right)\tan\beta & * \\ \frac{A_N}{\sqrt{2}} v c_\beta & \frac{A_N}{\sqrt{2}} v s_\beta & \frac{A_N}{\sqrt{2}} \frac{v^2}{v_N} s_\beta^2 - \sqrt{2} \frac{v_0^2}{v_N} \lambda C \end{pmatrix}$$

$$M^2_{\pm} = \frac{1}{\sin\beta\cos\beta}\left\{\frac{1}{2}(m_W^2 - \frac{1}{2}\lambda^2 v^2)\sin 2\beta + \left(\frac{A_N}{\sqrt{2}} v_N + \lambda^2 v_0^2\right)\right\}$$

Mass spectrum in the Higgs sector & RH-neutrino and sneutrino



Coannihilation process

$$W_{\text{eff}}^{N} = \frac{\kappa}{2} N \nu_R^c \nu_R^c + y_N^i \nu_R^c L_i \Phi_u + h_N^i \nu_R E_i^c \Omega^- + \frac{M}{2} \nu_R^c \nu_R^c$$