Two Loop Radiative Seesaw Model with B-L Symmetry

Takashi Toma (IPPP Durham University)

Based on arXiv: 1303.7356

In collaboration with Yuji Kajiyama and Hiroshi Okada

Baryon and Lepton Number Violation (BLV)

@Heidelberg Germany

8-11 Apr. 2013

Outline

- Introduction
  - Neutrino mass and Dark Matter
  - Radiative Seesaw Models
- A New Radiative Seesaw Model
  - Multi-component Dark Matters
  - Constraints to the model
  - Numerical calculation
- Summary

Standard Model

Unsatisfied points

- Zero neutrino masses $m_\nu \sim 0.1\ [\mathrm{eV}] \ll 100\ [\mathrm{GeV}]$
- No Dark Matter candidate $\leftarrow$ cosmological observations

- Seesaw mechanism
  - introduce right-handed neutrinos

Majorana mass term

$$\mathcal{L} = -\overline{\nu_L} m_D N_R - \frac{1}{2}\overline{N_R^c} M N_R + \mathrm{h.c.}$$

⇒ Block diagonalization (when $m_D \ll M$)

$$m_\nu^L \simeq -m_D M^{-1} m_D^T$$

But no DM candidate

- DM candidate in MSSM: neutralino
  neutrino mass?

$\longrightarrow$ improve simultaneously $\longrightarrow$ radiative seesaw models

Radiative Seesaw Models

- Ma model

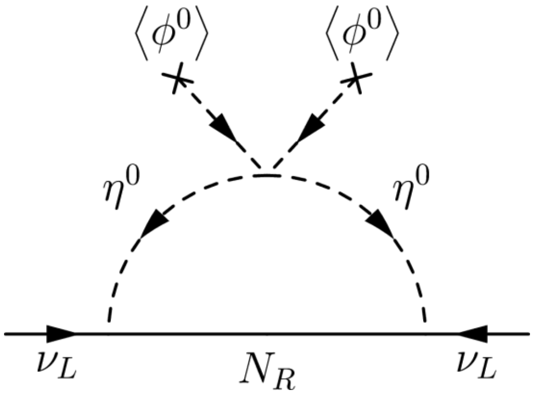
  neutrino mass (1-loop)

  Dark Matter

$$m_\nu \sim \frac{\text{couplings}}{(4\pi)^{2n}}$$

$$\begin{array}{cc} \nu_L & N_R \end{array}$$
$$\begin{pmatrix} 0 & 0 \\ 0 & M \end{pmatrix}$$

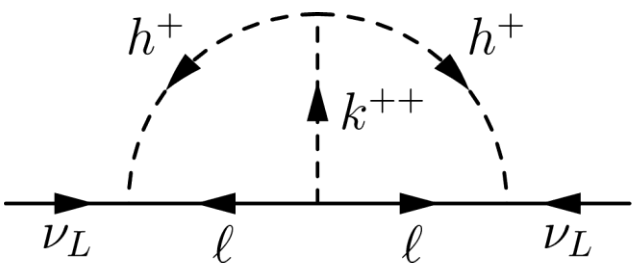
	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
N_i	$\mathbf{1}$	0	$-$
η	$\mathbf{2}$	$1/2$	$-$



- Zee-Babu model

  neutrino mass (2-loop)

  (one is massless)



	$SU(2)_L$	$U(1)_Y$
h^+	$\mathbf{1}$	1
k^{++}	$\mathbf{1}$	2

$$m_\nu \propto fyf$$

$$\mathcal{L} = f_{ij}\overline{\ell_i^c}P_L\ell_j h^+ + y_{ij}\overline{e_i^c}P_R e_j k^{++}$$

- f: 3x3 anti-symmetric
- Doubly charged scalar

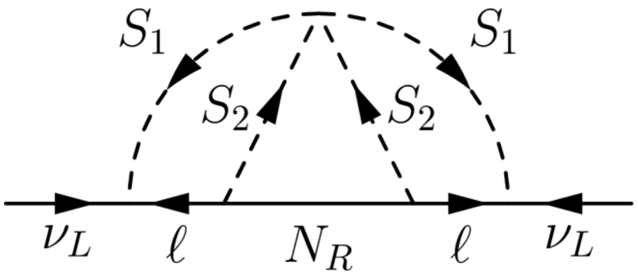
Radiative Seesaw Models

- Krauss-Nasri-Trodden model

  neutrino mass (3-loop)

  Dark Matter candidate (N_R)   (only one generation)

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
S_1^+	$\mathbf{1}$	1	$+$
S_2^+	$\mathbf{1}$	1	$+$
N_R	$\mathbf{1}$	0	$-$

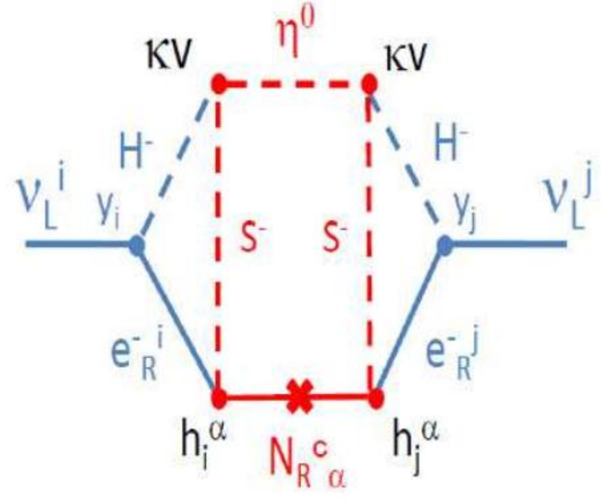


- Aoki-Kanemura-Seto model

  neutrino mass (3-loop)

  Dark Matter candidate

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Φ_2	$\mathbf{2}$	$1/2$	$+$
S^+	$\mathbf{1}$	1	$-$
η	$\mathbf{1}$	0	$-$
N_R	$\mathbf{1}$	0	$-$



A New Radiative Seesaw Model with B-L symmetry

Field contents

Fermion: $U(1)_{B-L}$ symmetry is imposed.

	Q	u^c	d^c	L	e^c
$(SU(2)_L, Y)$	$(\mathbf{2}, 1/6)$	$(\mathbf{1}, -2/3)$	$(\mathbf{1}, 1/3)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, 1)$
Q_{B-L}	$1/3$	$-1/3$	$-1/3$	-1	1
$\mathbb{Z}_2$	$+$	$+$	$+$	$+$	$+$

N^c	S	$\bar{S}$
$(\mathbf{1}, 0)$	$(\mathbf{1}, 0)$	$(\mathbf{1}, 0)$
1	$-1/2$	$1/2$
$-$	$-$	$+$

New particles

$N^c, S, \bar{S}$

η, Σ, χ

Boson:

	Φ	η	Σ	χ
$(SU(2)_L, Y)$	$(\mathbf{2}, 1/2)$	$(\mathbf{2}, 1/2)$	$(\mathbf{1}, 0)$	$(\mathbf{1}, 0)$
Q_{B-L}	0	0	1	$-1/2$
$\mathbb{Z}_2$	$+$	$-$	$+$	$+$

Lagrangian

$$\mathcal{L}_{\text{lepton}} = y_\ell \Phi^\dagger e^c L + y_\nu \eta^\dagger N^c L + y_N \chi N^c S + y_S \Sigma S S$$
$$+ y_{\bar{S}} \Sigma^\dagger \bar{S}\bar{S} + \text{h.c.} - \mathcal{V}(\Phi, \eta, \Sigma, \chi)$$

$\langle \eta \rangle = \langle \chi \rangle = 0$ → no Dirac mass term

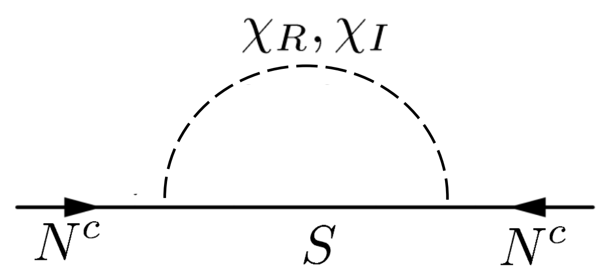
→ realized by constraining the scalar potential

$\langle \Sigma \rangle \neq 0 \;\Rightarrow\; U(1)_{B-L} \to \mathbb{Z}_6$

Right-handed neutrino masses are forbidden.

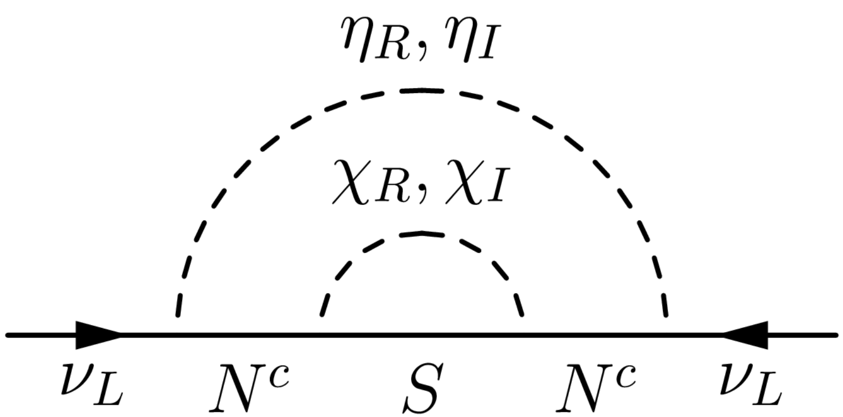
- get masses at one-loop.

$$(m_N)_{\alpha\beta} = \left(y_N y_N^T\right)_{\alpha\beta} \frac{m_S}{(4\pi)^2} I\left(\frac{m_{\chi_R}^2}{m_S^2}, \frac{m_{\chi_I}^2}{m_S^2}\right)$$



when $\delta m_\chi^2 \to 0 \;\Rightarrow\; N^c$ becomes massless

Neutrino mass generation



$$(m_\nu)_{\alpha\beta} = \left(y_\nu^T y_N^* y_N^\dagger y_\nu\right)_{\alpha\beta} \frac{m_S}{4\,(4\pi)^4} I\left(\frac{m_{\eta_R}^2}{m_S^2}, \frac{m_{\eta_I}^2}{m_S^2}, \frac{m_{\chi_R}^2}{m_S^2}, \frac{m_{\chi_I}^2}{m_S^2}\right)$$

$$\delta m_\eta^2 \to 0$$
$$\delta m_\chi^2 \to 0$$

⇨ massless since $\frac{\delta m_\eta^2}{\left(p^2 - m_{\eta_R}^2\right)\left(p^2 - m_{\eta_I}^2\right)}$

ex. when $m_S \sim 1\text{TeV}$, $I \sim \mathcal{O}(1)$

We need $y_\nu^2 y_N^2 \sim 10^{-8}$ for neutrino mass scale.
$m_\nu \sim 0.1\ \text{eV}$

Multi-component Dark Matter

DM candidates:

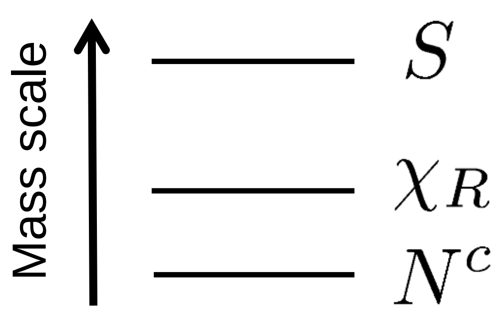
	N^c	S	$\bar{S}$	$\eta_{R(I)}$	$\chi_{R(I)}$
$\mathbb{Z}_2$	$-$	$-$	$+$	$-$	$+$
$\mathbb{Z}_6$	0	-3	3	0	-3

N^c mass is radiatively generated.

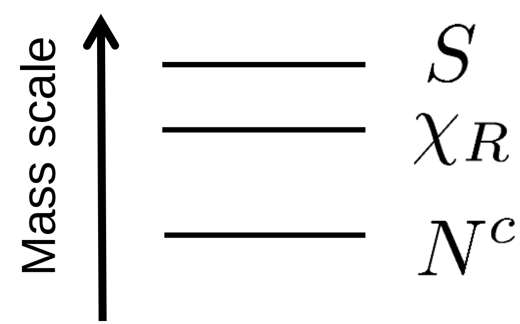
We have various combinations.
Two or three component DM.

~~$(N^c, \eta_{R(I)})$~~

Ex.1 $m_{N^c} + m_{\chi_R} < m_S$



Ex.2 $m_{N^c} + m_{\chi_R} > m_S$



Constraints to the model

- S,T parameters
  → vacuum polarization of gauge bosons

$$\delta S = 0.03 \pm 0.10 \quad \delta T = 0.05 \pm 0.12 \quad \text{at} \quad m_h = 126\text{GeV}$$

→ we get $(m_\eta - m_{\eta_R})(m_\eta - m_{\eta_I}) \lesssim 133^2\ \text{GeV}$

- Lepton Flavor Violation

$$\text{Br}(\mu \to e\gamma) = \frac{\alpha_{\text{em}} \left| \left(y_\nu^\dagger y_\nu\right)_{\mu e} \right|^2}{768\pi G_F^2 m_\eta^4} < 5.7 \times 10^{-13}$$

→ Flavor structure of Yukawa couplings

- Thermal relic density of DMs

- neutrino mass scale $m_\nu \sim 10^{-1}\ \text{eV}$

Annihilation channels

Simplest case: $(N^c, \bar{S})$ They do not exchange (at tree level).

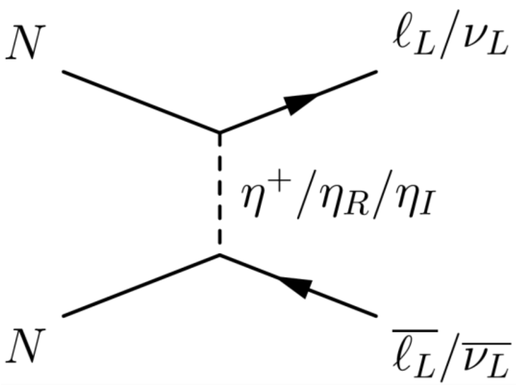
→ we can consider their abundances independently.

$$N^c N^c \leftrightarrow \bar{S}\bar{S}$$

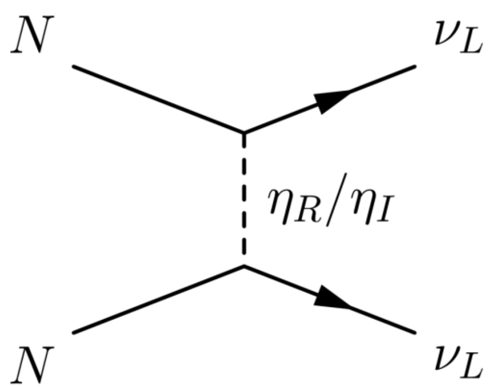
$$\Omega h^2 = \Omega_N h^2 + \Omega_{\bar{S}} h^2$$

$$\sigma v = a + b v^2$$

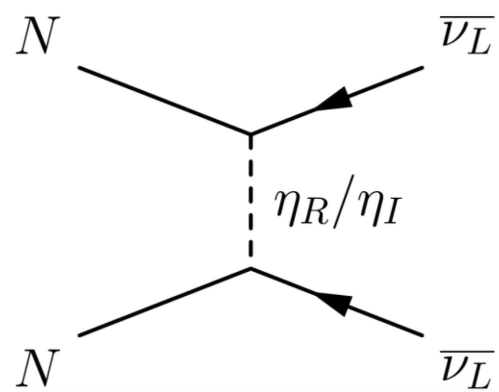
DM: lightest right-handed neutrino N^c



p-wave



s-wave



s-wave

vanish when $\delta m_\eta^2 \to 0$

Numerical calculation

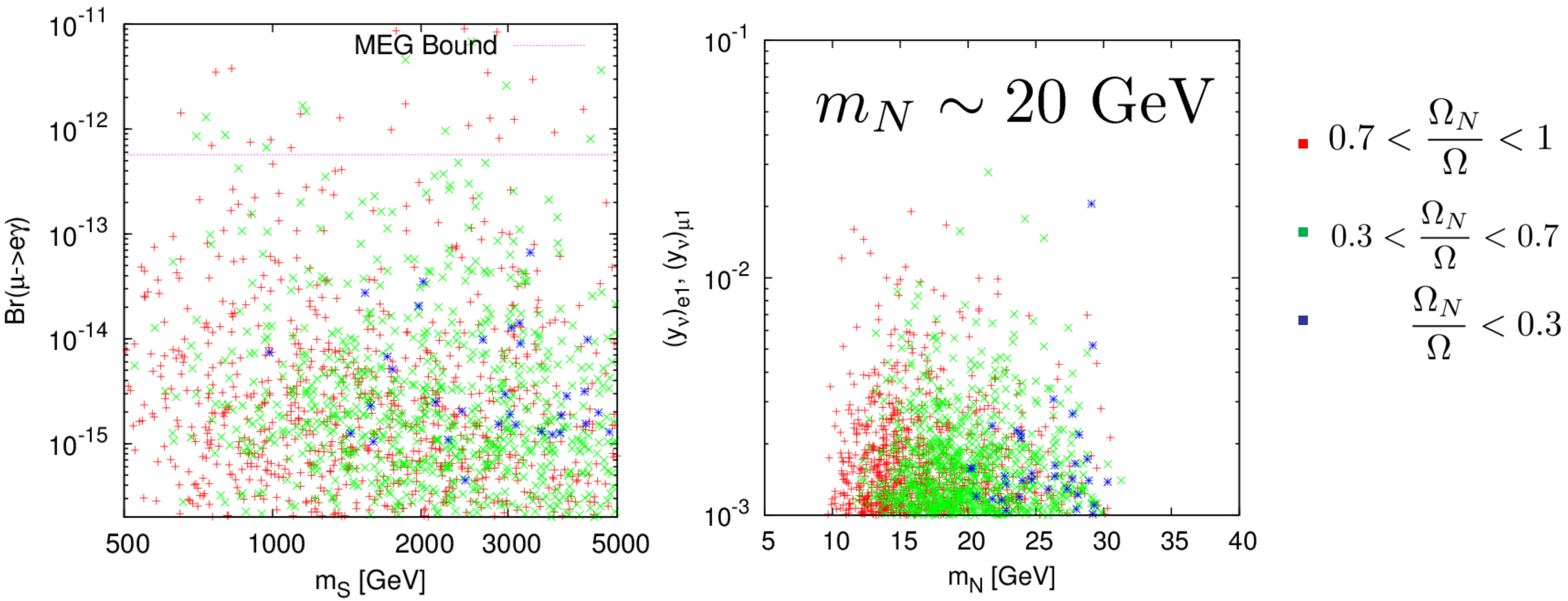
- constraints

S, T parameters　　Lepton Flavor Violation

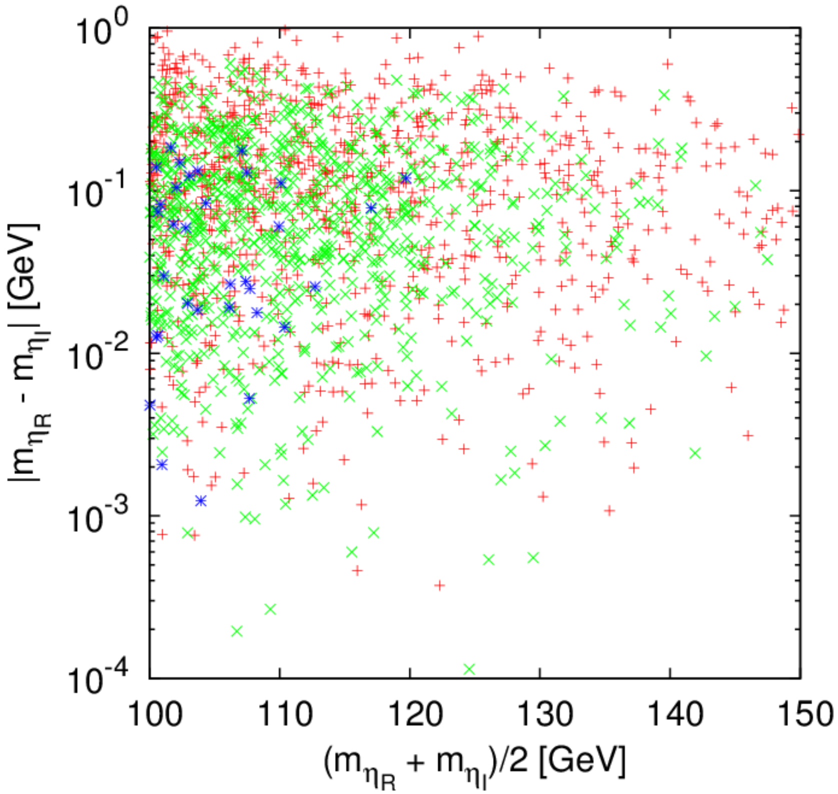
neutrino mass scale　　thermal relic density of DMs

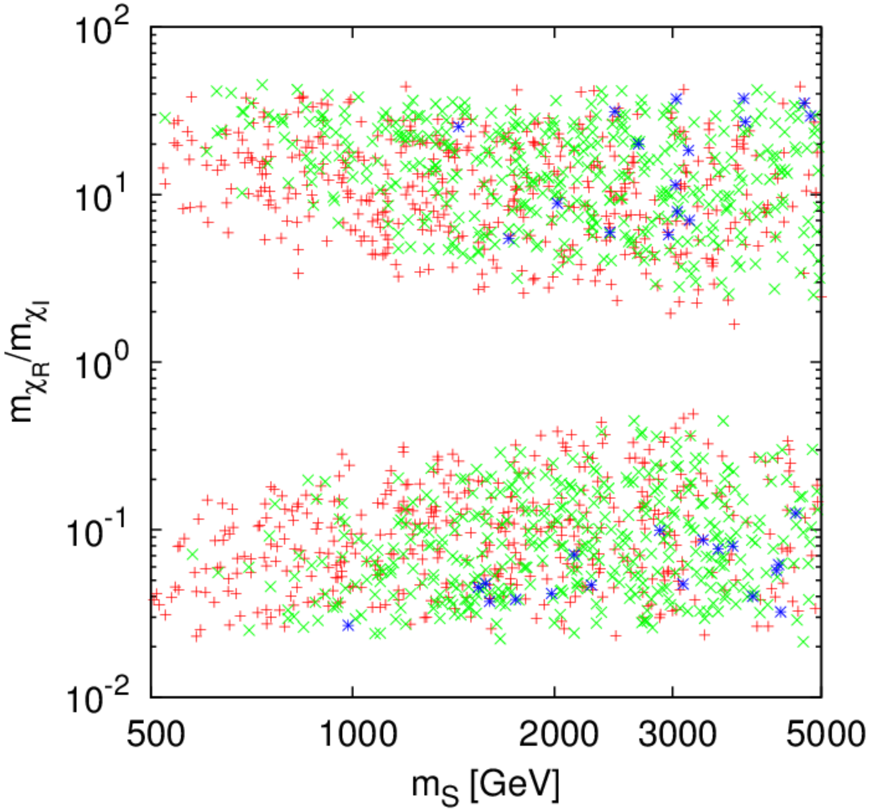
$$10^2 \text{ GeV} < m_S < 10^4 \text{ GeV} \qquad 10^{-3} < y_\nu < 1$$

$$10^2 \text{ GeV} < m_{\eta_R}, m_{\eta_I} < 10^4 \text{ GeV} \qquad 10^2 \text{ GeV} < m_{\chi_R}, m_{\chi_I} < 10^4 \text{ GeV}$$



Numerical calculation





$$\eta_R \sim \eta_I \sim 100 \text{ GeV}$$

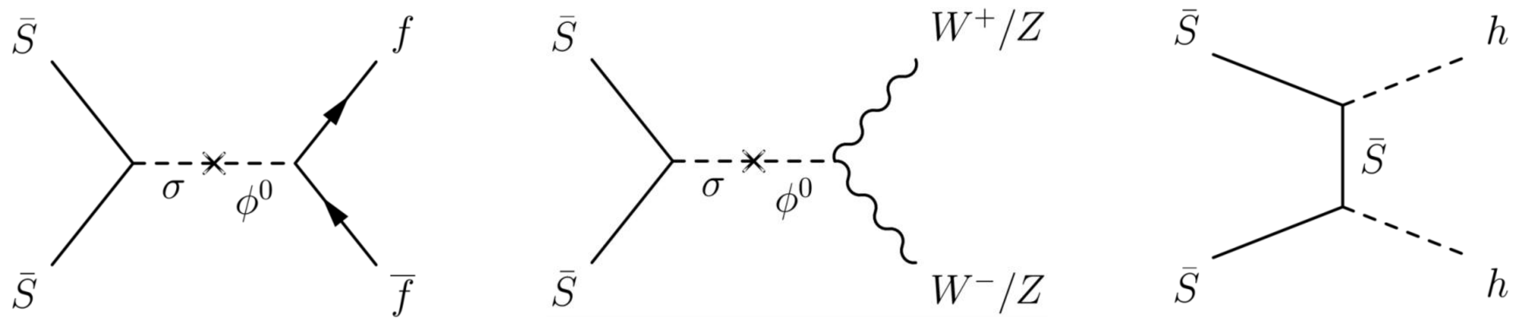
to get neutrino mass scale

$$\left| \log \left(\frac{m_{\chi R}}{m_{\chi I}} \right) \right| \sim 1$$

to $m_N \sim 20$ GeV

Annihilation channels

DM: SM singlet $\bar{S}$



All channels are p-wave.

$$\phi^0 = \cos\alpha h + \sin\alpha H$$

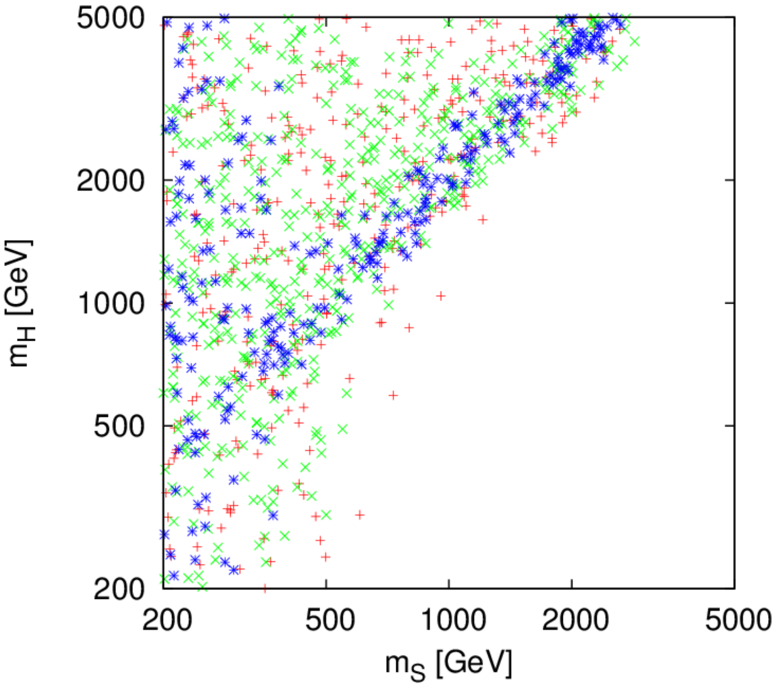
$$\sigma = -\sin\alpha h + \cos\alpha H$$

$$200 \text{ GeV} < m_{\bar{S}}, m_H < 5000 \text{ GeV}$$

$$10^{-3} < y_{\bar{S}} < 1 \quad 10^{-3} < \sin\alpha < 1$$

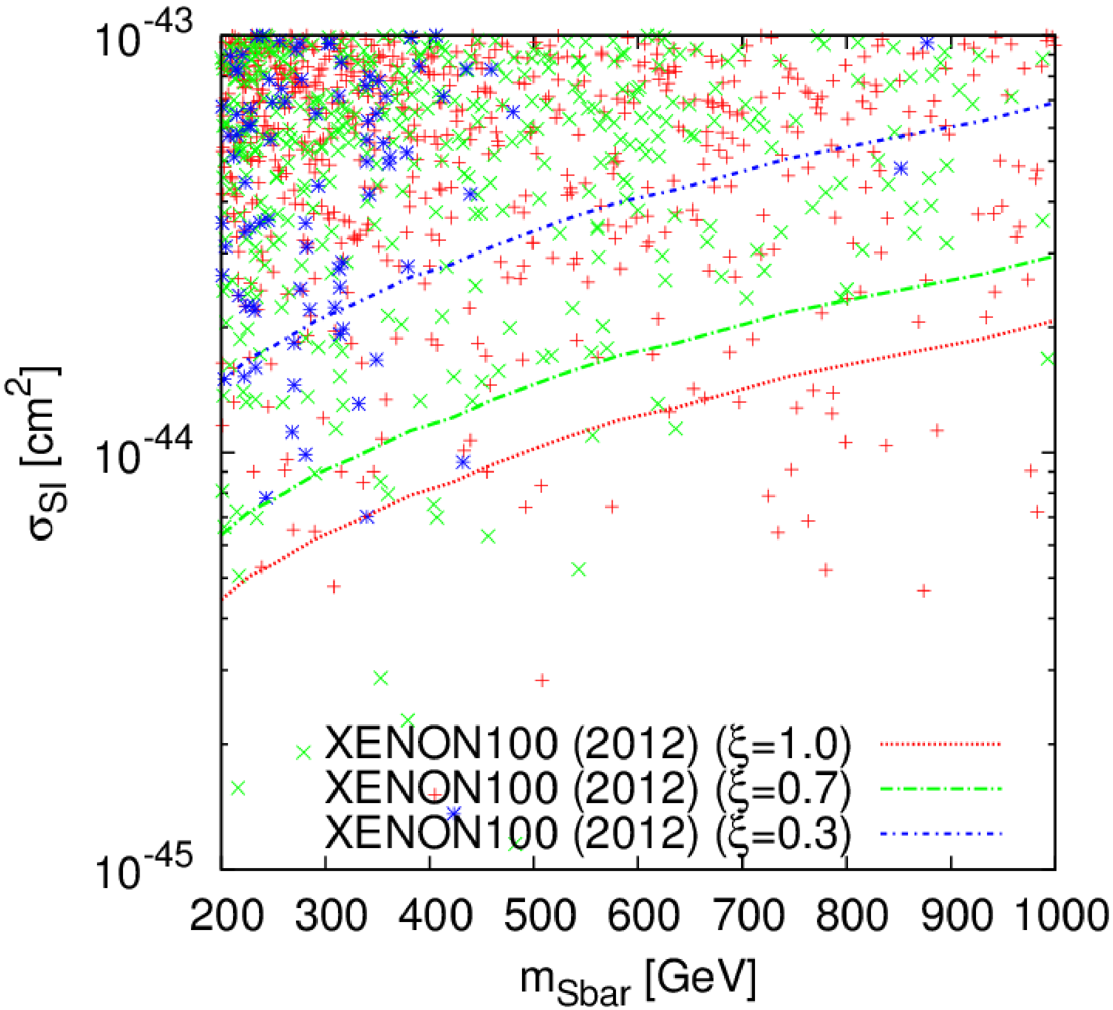
resonance

$$\bar{S}\bar{S} \to H \qquad 2m_{\bar{S}} \approx m_H$$



Direct detection of DM

Elastic scattering: $\bar{S}q \to \bar{S}q$ (Higgs exchange)



$$\sigma_{SI}^p = \frac{4\mu_{\bar{S}}^2}{\pi} \frac{y_{\bar{S}}^2 \sin^2\alpha \cos^2\alpha m_p^2}{2v^2} \times \left(\frac{1}{m_h^2} - \frac{1}{m_H^2}\right)^2 \left(\sum_q f_q^p\right)^2$$

Resonance is important

$$\bar{S}\bar{S} \to H \quad 2m_{\bar{S}} \approx m_H$$

We need $y_{\bar{S}} \ll 1$ but

$$\sigma v \sim 10^{-9}\ \mathrm{GeV}^{-2}$$

$$\xi = \frac{\Omega_{\bar{S}}}{\Omega}$$

Summary

- We constructed a new radiative seesaw model.
- Light neutrino masses are generated at two-loop level.
- Multi-component DMs are included.
  ($\mathbb{Z}_2 , \mathbb{Z}_6$ symmetries)
- We analyzed this model under some constraints.
  (S-T parameters, thermal relic density of DMs,
  Lepton Flavor Violation, neutrino mass scale)
- Resonance region is only allowed by both of relic density of DM $\bar{S}$ and direct detection experiment.

Thank you for your attention!