

# **Non-Abelian Dark Matter with Resonant Annihilation**

C. W. Chiang, T. N, J. Tandean, (arXiv : 1306.0882 )

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## 1. Introduction

**Some issues require the physics beyond the SM**

- **Astronomical evidence of dark matter**

- ❖ What is dark matter?
- ❖ How can DM be stable?

**Non-Abelian(  $SU(2)_X$  ) DM has interesting properties**

- ❖ Stability of DM is guaranteed by  $Z_2$  as its subgroup
- ❖ We can get resonant annihilation

→ **Interesting in estimating Relic density of DM**

We consider Pair annihilation mediated by new gauge boson

It is interesting if we get resonant annihilation naturally

## 2. Our model

### The structure of our model

❖ Gauge symmetry  $\rightarrow G_{SM} \times SU(2)_X \times U(1)_{B-L}$

❖ New particles [ $SU(2)_X(U(1)_{B-L})$ ]

\*Fermion      \*Scalar

$$\nu_R^i : 1(1) \quad \Phi_5 : 5(2) \quad S : 1(2)$$

\*Gauge boson

$$SU(2)_X : (X_\mu, X_\mu^*, C_\mu), \quad U(1)_{B-L} : E_\mu$$

❖ Stability of DM

$$SU(2)_X \xrightarrow{SSB} Z_2^X \quad T_3(SU(2)_X) \text{ even(odd) components is } Z_2 \text{ even(odd)}$$

The lightest  $Z_2$  odd particle can be a DM candidate

❖ Quantum number assignments

	$f_{SM}$	$\nu_R$	$H$	$S$	$\phi_2$	$\phi_1$	$\phi_0$	$\phi_{-1}$	$\phi_{-2}$	$X_\mu$	$X_\mu^\dagger$	$C_\mu^3$	$E_\mu$
$SU(2)_X(U(1)_{B-L})$	1( $B - L$ )	1(-1)	1(0)	1(2)	5(2)	5(2)	5(2)	5(2)	5(2)	3(0)	3(0)	3(0)	1(0)
$T_3(SU(2)_X)$	0	0	0	0	2	1	0	-1	-2	1	-1	0	0
$Z_2^X$	+	+	+	+	+	-	+	-	+	-	-	+	+

## 2. Our model

### The Lagrangian

★  $L_{New-scalar} = (D_\mu \Phi_5)^* (D^\mu \Phi_5) + (D_\mu S)^* (D^\mu S) - V$

$$D_\mu \Phi_5 = \partial_\mu \Phi_5 + ig_X C_\mu^k T_k^{(5)} \Phi_5 + ig_{B-L} E_\mu \Phi_5$$

$$D_\mu \Phi_5 = \partial_\mu S + i2g_{B-L} E_\mu S$$

$$\begin{aligned} V = & -\mu_\Phi^2 |\Phi_5|^2 + (\lambda_S |S|^2 - \mu_S^2) |S|^2 \\ & + (\lambda_H |H|^2 - \mu_H^2) |H|^2 + (quartic terms) \end{aligned}$$

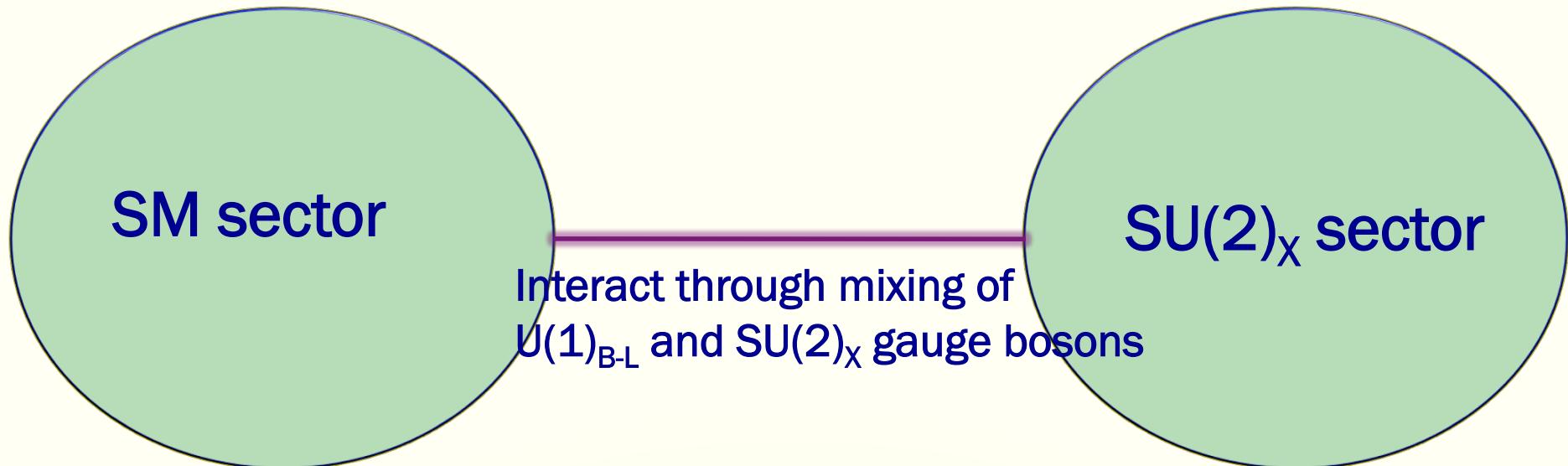
★  $L_\nu = i\lambda_{kl} \bar{\nu}_{kR} H^T \tau_2 L_{lL} - \frac{1}{2} \lambda'_{kl} \bar{\nu}_{kR} (\nu_{lR})^c S^* + H.c$

## 2. Our model

### Abstract of our scenario

- ❖ Singlet under  $SU(2)_X$
- ❖ Fermions have  $U(1)_{B-L}$  charge

- ❖ Singlet under  $G_{SM}$
- ❖  $\Phi_5$  have  $U(1)_{B-L}$  charge



- ❖ Symmetry breaking

$$SU(2)_X \xrightarrow{\langle \Phi_5 \rangle} Z_2^X$$

$$\langle \Phi_5 \rangle = (\nu_\Phi, 0, 0, 0, 0), (\Phi_5 = (\phi_2, \phi_1, \phi_0, \phi_{-1}, \phi_{-2}))$$

\*SSB of  $SU(2)_X$  through VEV of 5-plet scalar

$$U(1)_{B-L} \xrightarrow{\langle S \rangle}$$

$$\langle S \rangle = \nu_S$$

\*SSB of  $(1)_{B-L}$  through VEV of S

## 2. Our model

### New gauge bosons in the model

❖  $X, X^\dagger$

From  $SU(2)_X$  gauge fields (  $Z_2$  odd )

$$X_\mu = \frac{1}{\sqrt{2}}[C_\mu^1 - iC_\mu^2]$$

★ Candidate of dark matter

❖  $Z_L, Z_H$

From linear combination of  $U(1)_{B-L}$  and  $SU(2)_X$  gauge fields (  $Z_2$  even )

$$Z_L^\mu = \cos\theta C_3^\mu + \sin\theta E_\mu$$

$$Z_H^\mu = -\sin\theta C_3^\mu + \cos\theta E_\mu$$

$$\tan(2\theta) = \frac{2g_X g_{B-L} R_v}{g_X^2 R_v - g_{B-L}^2 (1 + R_v)}$$

$$R_v = (\langle \Phi_5 \rangle / \langle S \rangle)^2$$

★ Mediate interaction between DM and SM fermions

## 2. Our model

### Masses of new gauge bosons

❖ Masses of new gauge bosons ( $Z_{L(H)}$ ) is linear combination of C and E)

$$m_X^2 = g_X^2 v_\Phi^2$$

$$m_{Z_L}^2 \approx 4m_X^2(1 - R_\nu)$$

$$m_{Z_H}^2 \approx 4m_X^2 \frac{g_{B-L}^2}{g_X^2 R_\nu} (1 + R_\nu)$$

$$v_S \gg v_\Phi \quad R_\nu = \frac{v_\Phi^2}{v_S^2} \ll 1$$

$$\theta \approx R_\nu g_X / g_{B-L} \text{ Mixing angle of C and E}$$

## 2. Our model

### Masses of new gauge bosons

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$$\underline{m_{Z_H}^2 = 4m_X^2 \frac{g_{B-L}^2}{g_X^2 R_\nu}(1 + R_\nu)}$$

$$m_{Z_L} \approx 2m_X$$

$$\left. \begin{aligned} v_S &>> v_\Phi & R_\nu &= \frac{v_\Phi^2}{v_S^2} \ll 1 \\ \theta &\approx R_\nu g_X / g_{B-L} & \text{Mixing angle of C and E} \end{aligned} \right\}$$

This relation gives resonant pair annihilation of DM

It is due to SSB of  $SU(2)_X$  by 5-plet VEV

❖ Masses of neutrinos

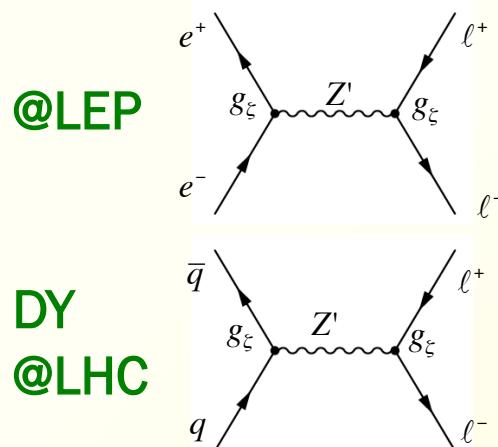
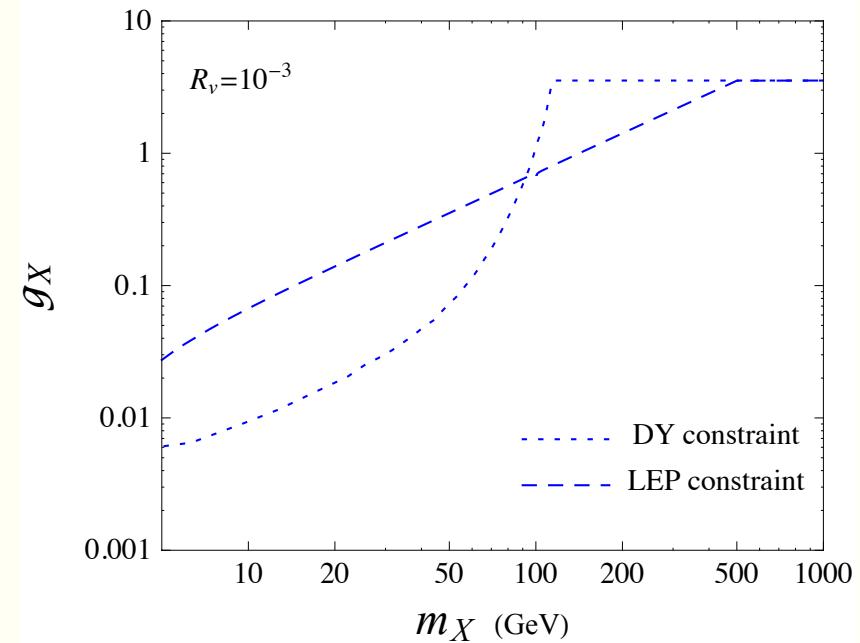
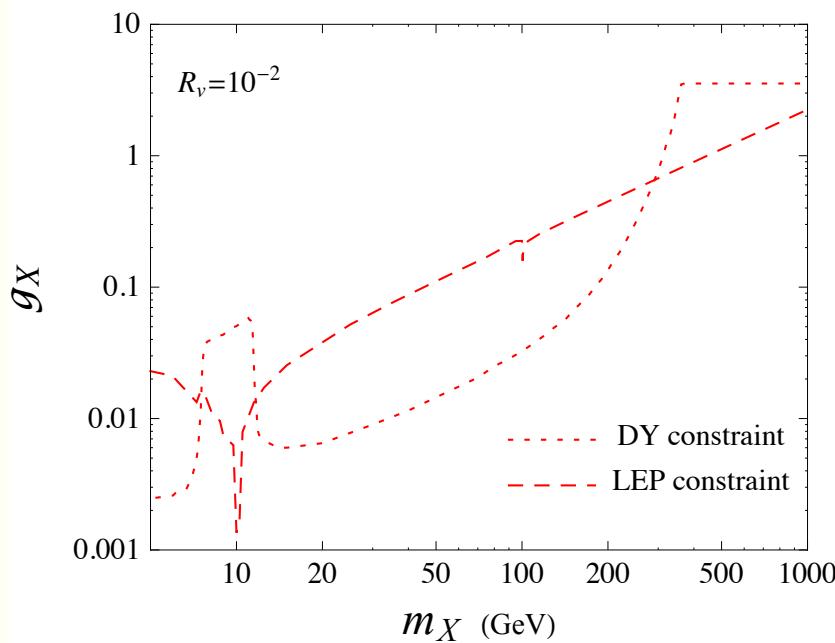
$$M_D = \lambda v_H / \sqrt{2}, \quad M_{\nu_R} = \lambda' v_S / \sqrt{2}$$

$$\left. \frac{m_X^2}{m_{Z_L}^2} \approx \frac{T_X(T_X + 1) - T_{3X}^2}{2T_{3X}^2} \right]$$

## 2. Our model

# Constraints on new gauge coupling

$U(1)_{B-L}$  gauge coupling is constrained by experimental data



@LEP

DY  
@LHC

- \*90% C.L. result is applied
- \*Used one-bin log likelihood analysis for DY
- \*For LEP-II data we used analysis given in

C.W. Chiang, N.D. Christensen,  
G.J. Ding, T. Han PRD 85 (2012)

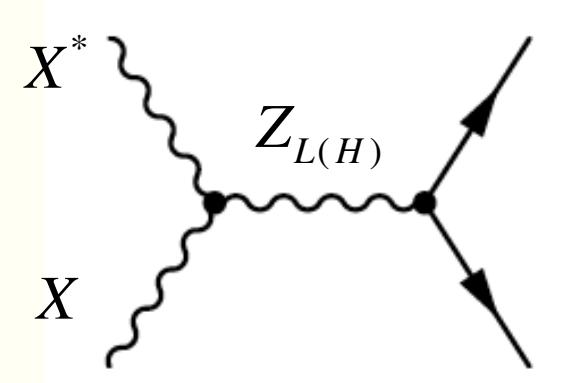
C.W. Chiang, Y.F. Lin, J. Tandean  
JHEP 1111 (2012)

### 3. Dark matter phenomenology

#### Estimation of relic density of X

$X X^*$  pair annihilate into SM particles as

→  $Z_L$  contribution is dominant  
due to resonant effect ( $m_{ZL} \sim 2m_X$ )



Thermal average of annihilation cross section ( $g_X = g_{B-L}$ )

$$\langle \sigma v_{rel} \rangle \approx \sum_f \left( \frac{Q_{B-L}^{(f)} g_X^2}{[K_2(x)]} R_v \right)^2 \frac{x}{846\pi m_X^5} \int_{4m_X^2}^{\infty} ds \frac{K_1\left(\frac{\sqrt{s}}{m_X} x\right)}{\sqrt{s}} \frac{(s+2m_f^2)(s-4m_X^2)^{\frac{3}{2}}}{(s-4m_X^2 + \Delta_M)^2 + 4m_X^2 \Gamma_{Z_L}^2} \sqrt{s-4m_f^2} \left( 3 + \frac{5s}{m_X^2} + \frac{s^2}{4m_X^4} \right)$$

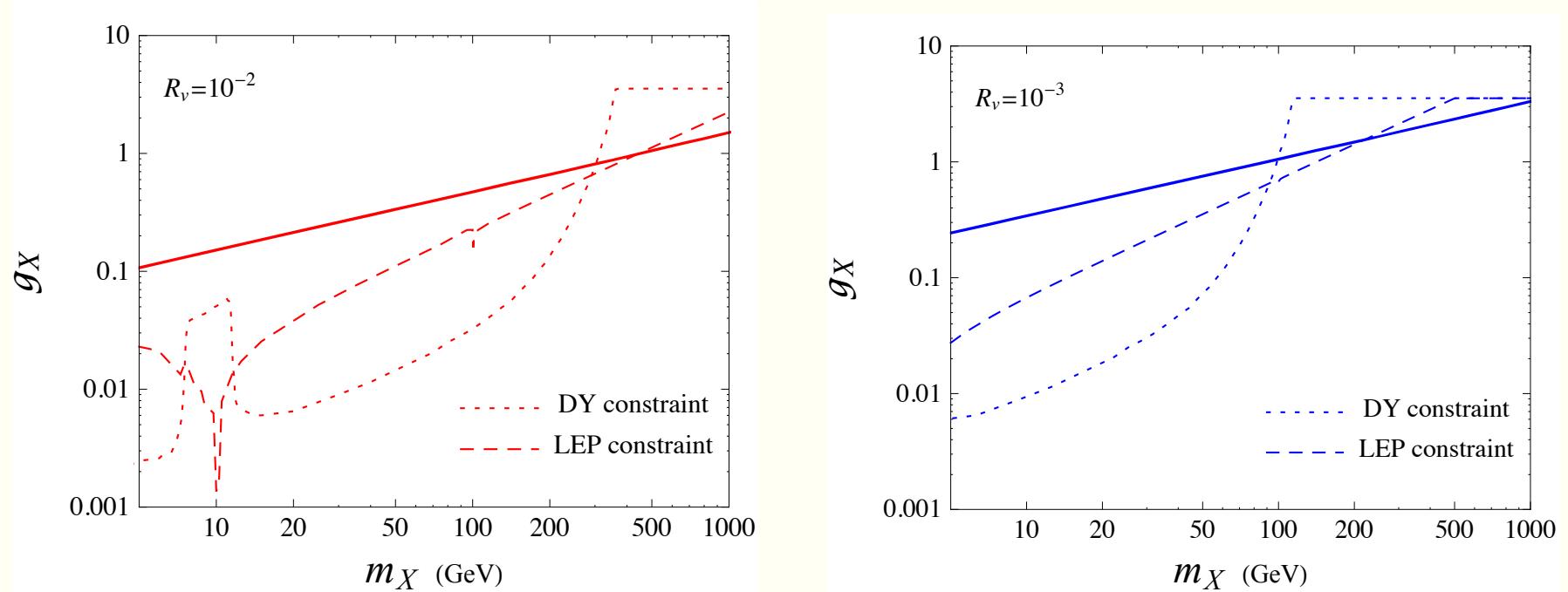
Relic density is estimated by approximated solution of Boltzmann eq.

Search for the parameter region satisfying observed relic density

Planck data (90% C.L.)  $0.1159 \leq \Omega_D h^2 \leq 0.1215$

### 3. Dark matter phenomenology

#### The parameter region giving observed relic density

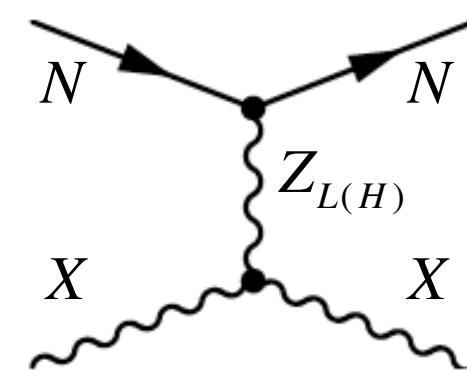


- ❖ The parameter region is more constrained by LEP II
- ❖  $m_X > 420(220)$  GeV region is allowed for  $Rv=10^{-2}(10^{-3})$
- ❖  $O(1)$  gauge coupling constant is required

### 3. Dark matter phenomenology

## DM-nucleon scattering cross section

Scattering Process:



$$\sigma \propto g_X^2 g_{B-L}^2 \cos^2 \theta \sin^2 \theta / m_{Z_{L(H)}}^4$$

$m_{Z_L} \ll m_{Z_H}$   $Z_L$  contribution dominates the scattering

Cross section:  $\sigma_{DN} \approx \frac{g_X^4 R_\nu^2 \mu_{XN}^2}{16\pi m_X^4} \quad \left( \mu_{XN} = \frac{m_X m_N}{m_X + m_N} \right) \quad \left\{ \begin{array}{l} g_X = g_{B-L} \\ m_{Z_L} \approx 4m_X \end{array} \right\}$

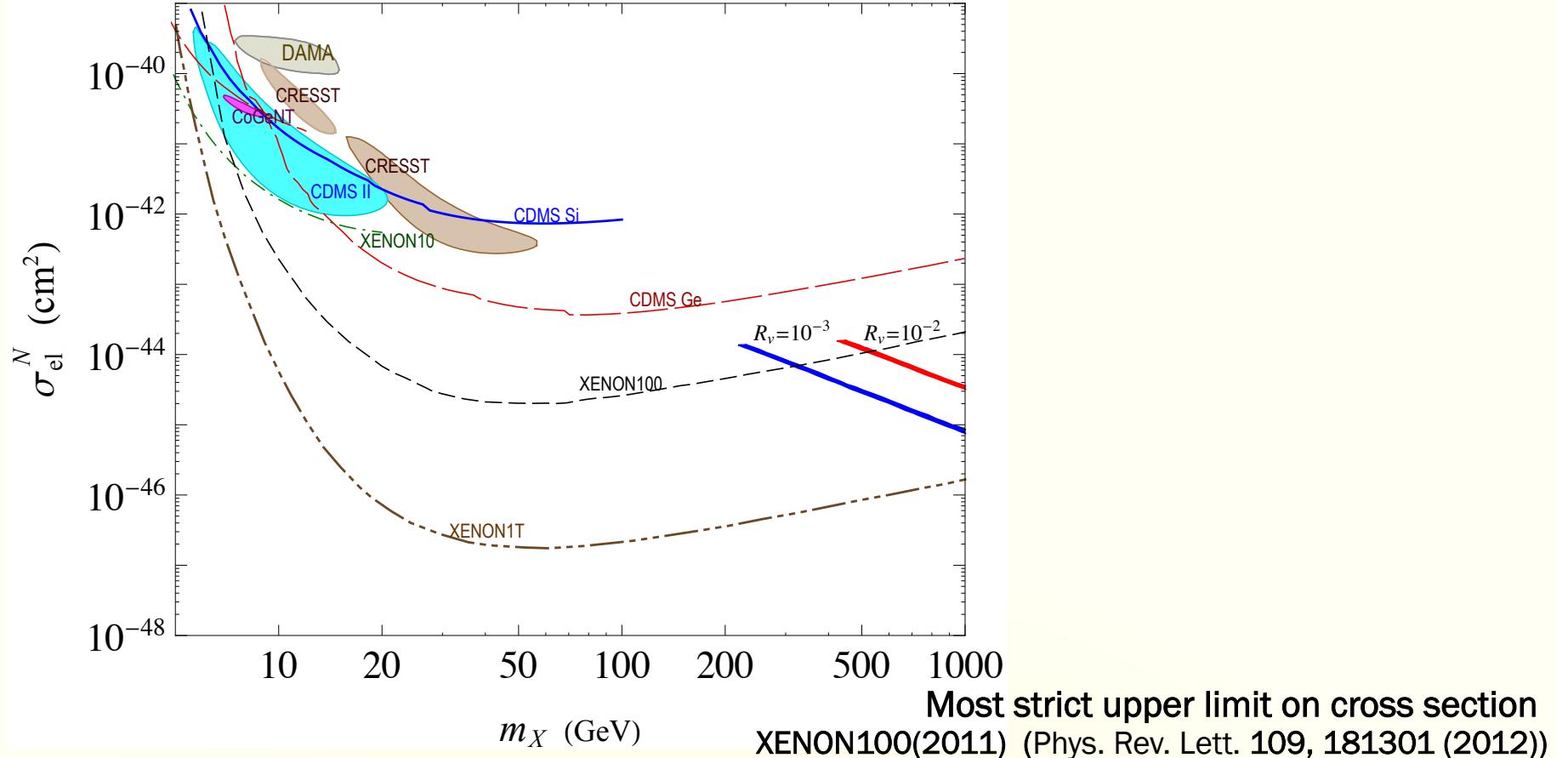
Applying the allowed parameter region

Compare the cross section with DM direct detection search

### 3. Dark matter phenomenology

## DM-nucleon scattering cross section

Comparison with the constraints from direct detection



Most of the allowed parameter region escape the constraints

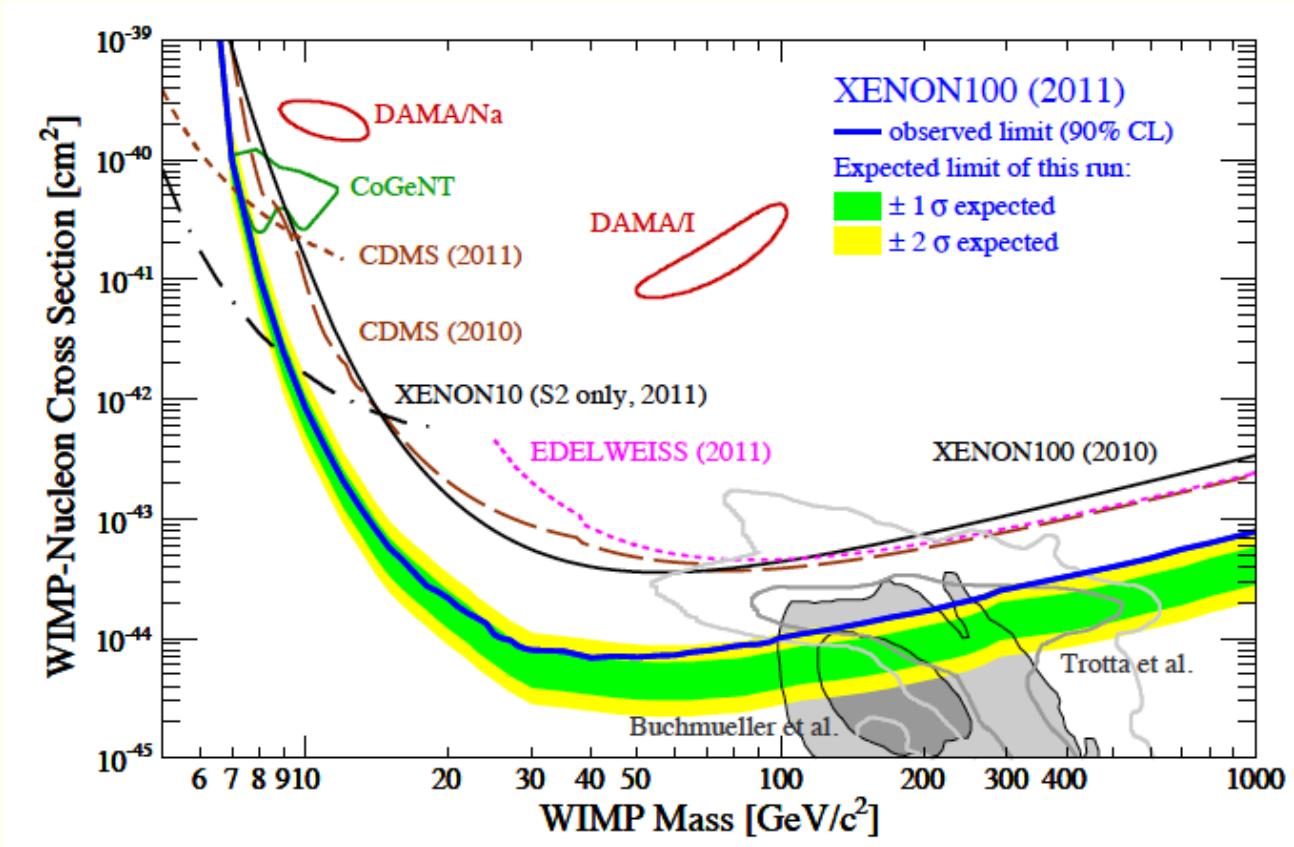
Future experiment like XENON1T will probe the region

# Summary

- ❖ We constructed a model for DM and neutrino mass generation
  - DM candidate is new massive gauge boson from extra  $SU(2)_X$
  - Stability of DM :  $Z_2$  symmetry as a subgroup of  $SU(2)_X$
  - $v_R$  is required by anomaly cancellation for  $U(1)_{B-L}$
  - Neutrino masses would be given by Type-I seesaw
  - The relation  $m_{Z_L} \sim 2m_X$  is obtained from SSB of  $SU(2)_X$  through VEV of 5-plet scalar field
- ❖ We discussed phenomenology regarding DM
  - The parameter giving observed DM relic density is extracted
  - DM-nucleon scattering cross section is estimated

# Direct detection search experiments

DM-Nucleon scattering cross section is constrained by the data



Most strict upper limit on cross section

XENON100(2011) (Phys. Rev. Lett. 109, 181301 (2012))

# Determination of relic density

- Estimated by Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v_{rel} \rangle \left( n^2 - n_{eq}^2 \right)$$

Thermal average of DM annihilation cross section × DM relative velocity

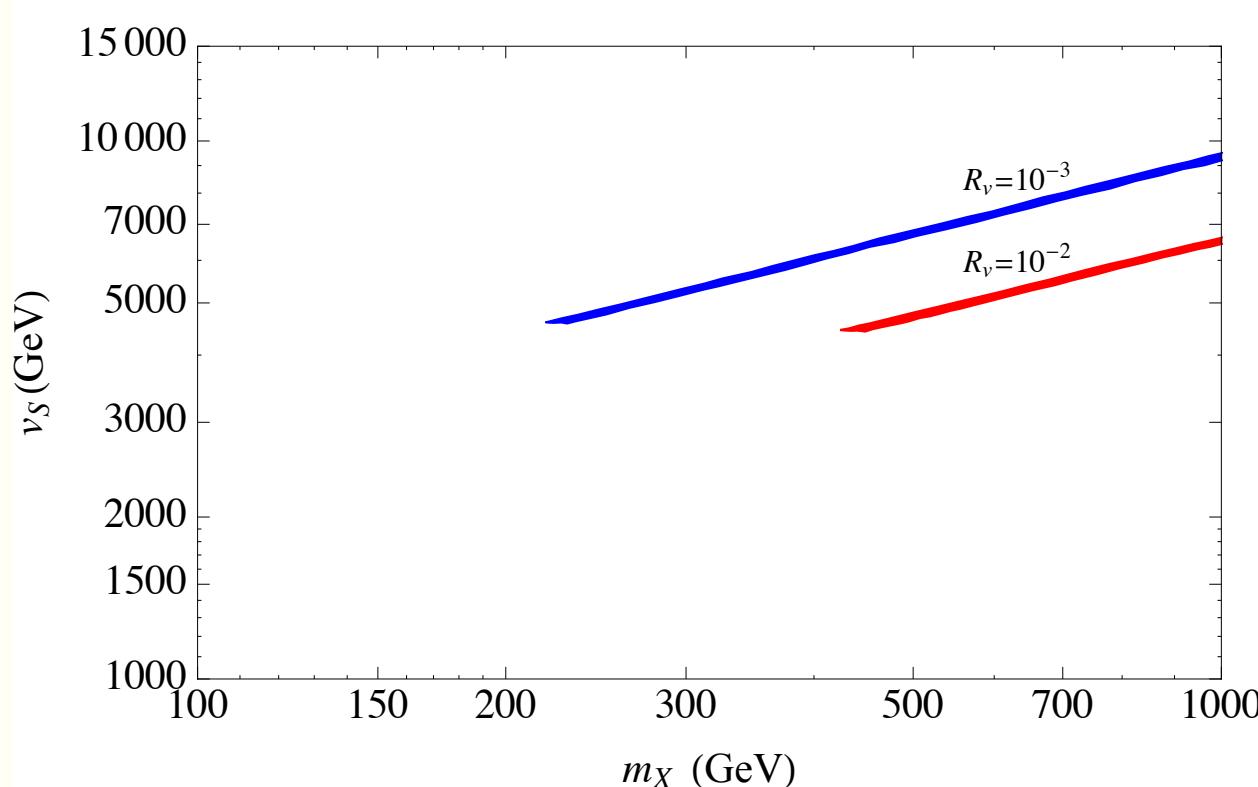
Annihilation cross section control the relic density

- Approximated solution of Boltzmann equation

$$\Omega_D h^2 \approx \frac{1.07 \times 10^9}{\sqrt{g^*} m_{pl} J \text{ GeV}} \quad J = \int_{x_f}^{\infty} dx \frac{\langle \sigma v_{rel} \rangle}{x^2} \quad (\text{x} = m/T)$$

$$x_f = \ln \left[ 0.038 g_{eff} m_D m_{pl} \langle \sigma v_{rel} \rangle (g^* x_f)^{-1/2} \right]$$

## Corresponding parameter region for $v_S$ - $m_X$ plane



VEV of S is about 5~10 TeV scale  
Mass of  $v_R$  is also same order  
Compatible with TeV scale seesaw