# Non-Abelian Dark Matter with Resonant Annihilation

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## 1. Introduction

### Dark Matter (DM) require the physics beyond the SM

- ❖DM candidate as new particle from BSM
- ❖What is a nature of 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** ➡ $G_{SM} \times SU(2)_X \times U(1)_{B-L}$

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

*Fermion: $\nu_R^i : 1(1)$

*Scalar: $\Phi_5 : 5(2)$  $S : 1(2)$

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

❖Stability of DM

$$SU(2)_X \xrightarrow{SSB} Z_2^X$$

$T_3(SU(2)_X)$ even(odd) components is $Z_2$ 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

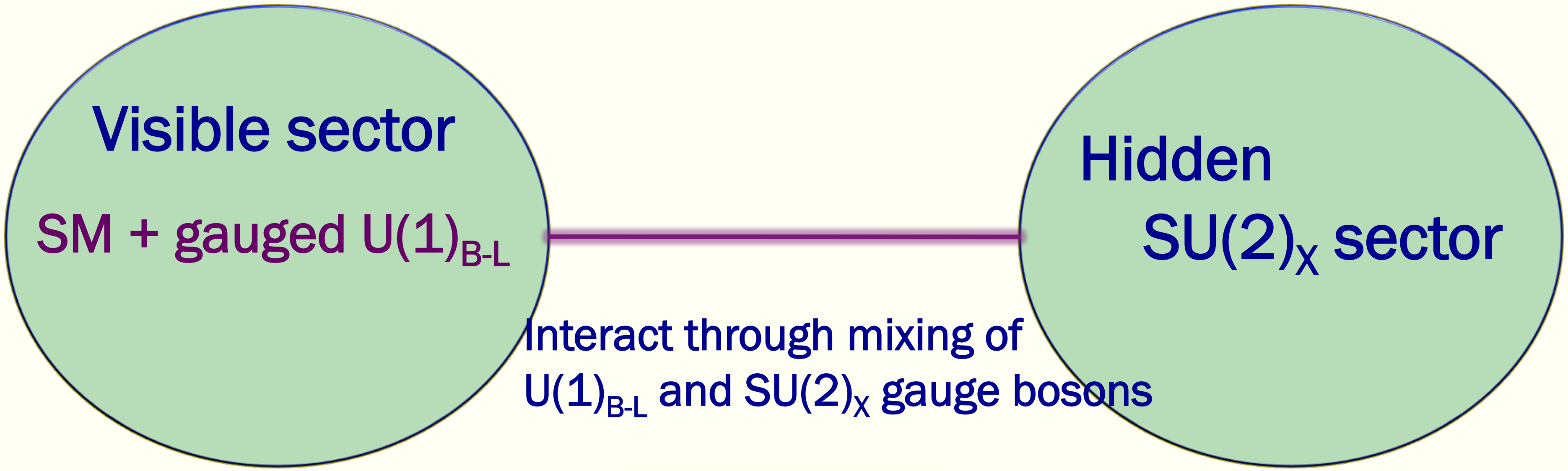
## Abstract of our scenario

❖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

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

$$SU(2)_X \xrightarrow{\langle \Phi_5 \rangle} Z_2^X$$ *SSB of $SU(2)_X$ through VEV of 5-plet scalar

$$\langle S \rangle = v_S$$

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

# New gauge bosons in the model

- X, X†

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)$_{B\text{-}L}$ and SU(2)$_X$ gauge fields ( $Z_2$ even )

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

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

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

$$R_v = (<\Phi_5> / <S>)^2$$

★ Mediate interaction between DM and SM fermions

# Masses of new gauge bosons

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

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

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

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

$$v_S >> v_\Phi \qquad R_v = \frac{v_\Phi^2}{v_S^2} << 1$$

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

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

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

This relation gives resonant pair annihilation of DM

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

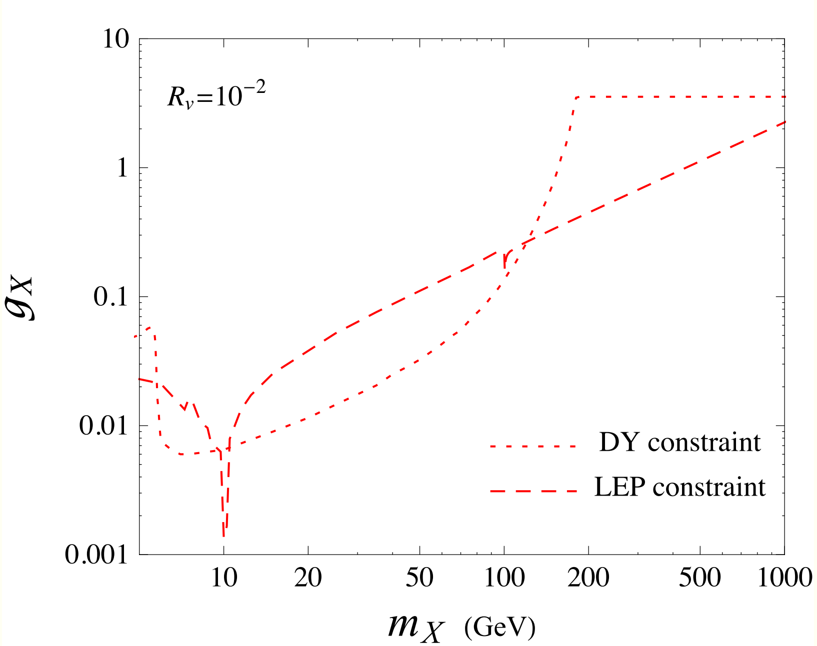
$$\frac{m_X^2}{m_{ZL}^2} \approx \frac{T_X(T_X+1) - T_{3X}^2}{2T_{3X}^2}$$

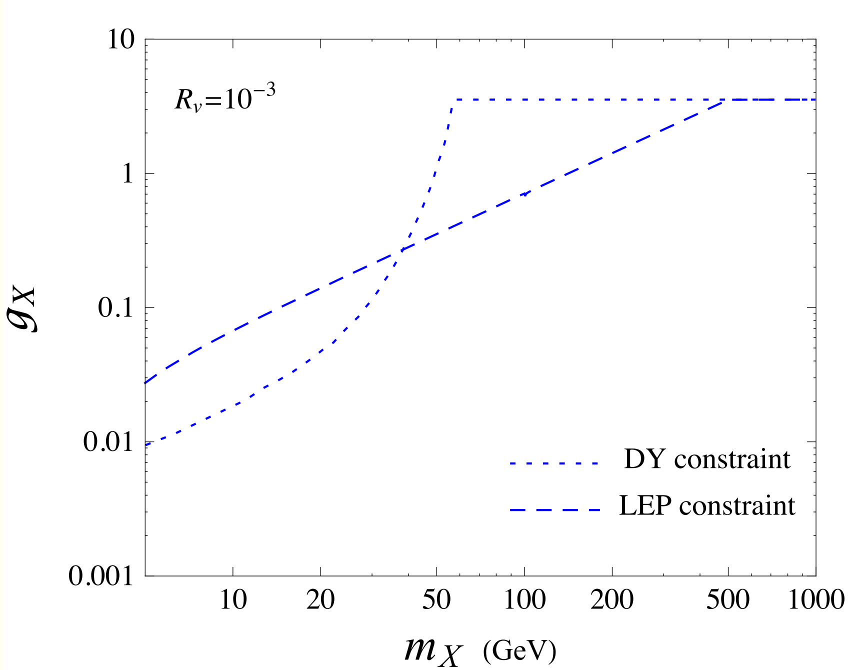
❖Masses of neutrinos

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

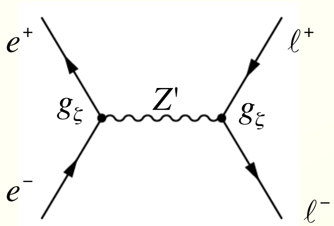
# Constraints on new gauge coupling

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

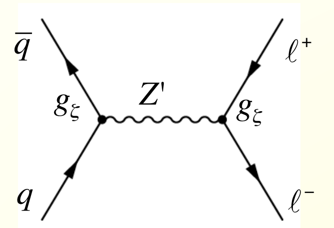



@LEP




DY @LHC




*90% C.L. result is applied

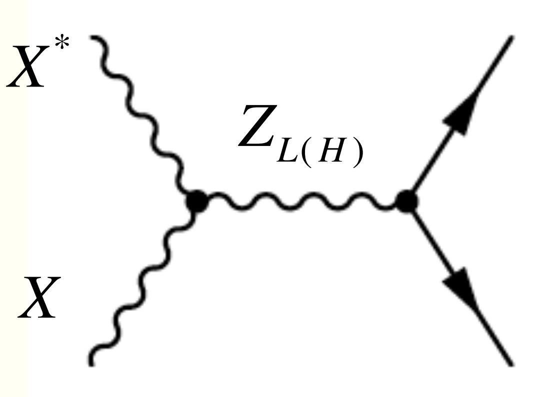
*Used one-bin log likelihood analysis for DY — C.W. Chiang, N.D. Christensen, G.J. Ding, T. Han PRD 85 (2012)

*For LEP-II data we used analysis given in — 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 ($m_{Z_L}$~$2m_X$)

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

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

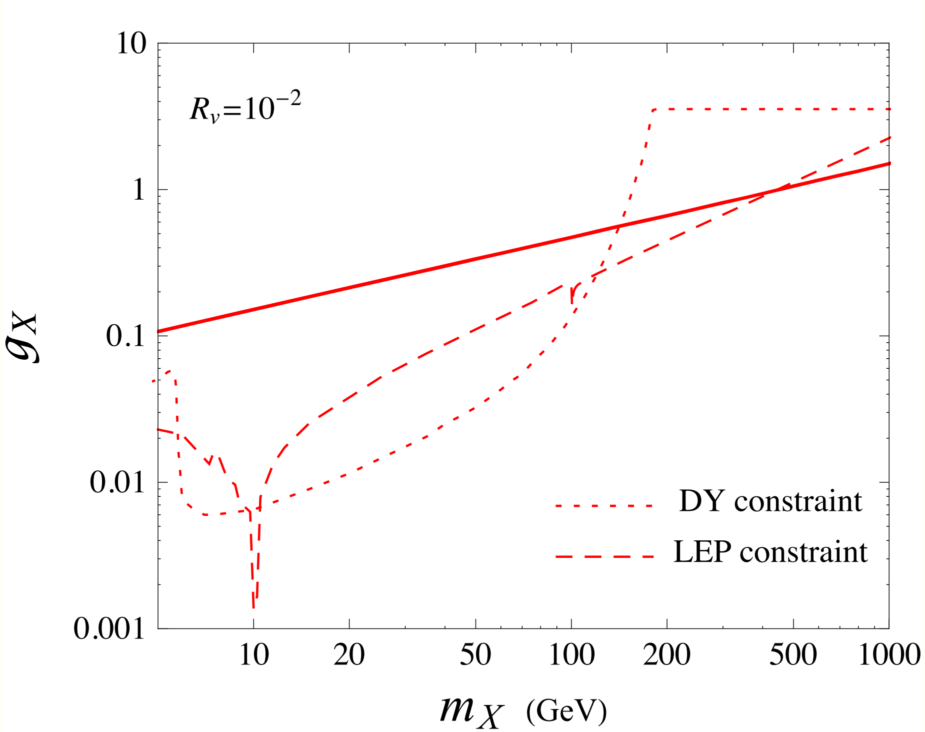
Relic density is estimated by approximated solution of Boltzmann eq.

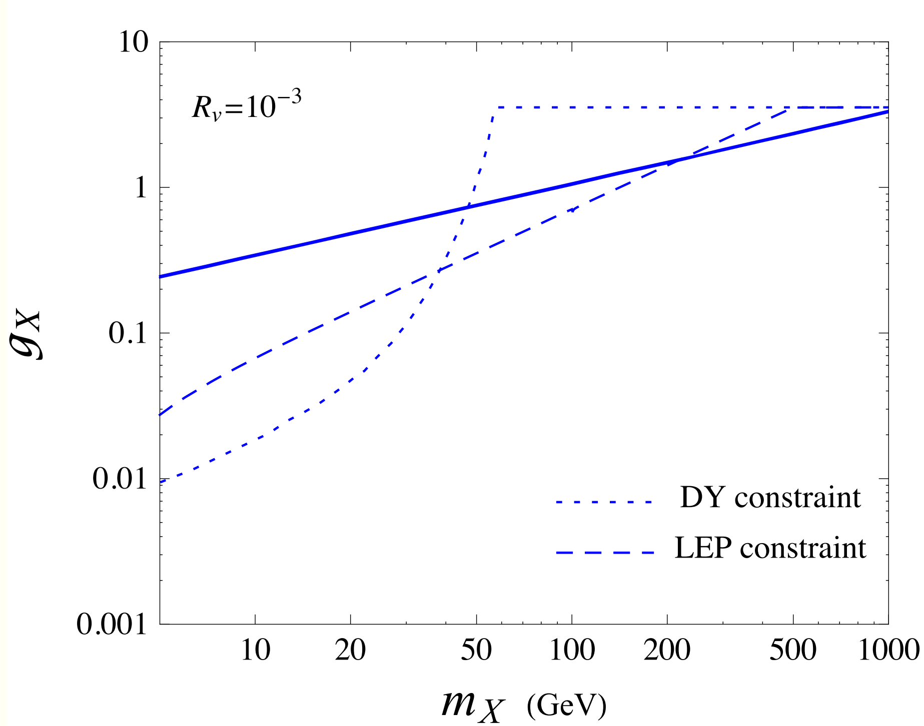
Search for the parameter region satisfying observed relic density

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

P.A.R. Ade et al [Planck Collaboration] (2013)

# The parameter region giving observed relic density

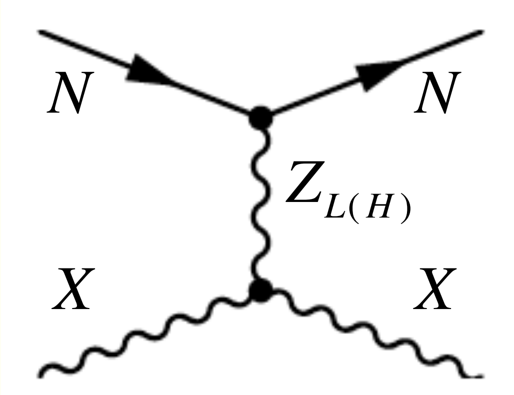



- ❖The parameter region is more constrained by LEP II
- ❖$m_X$ > 420(220) GeV region is allowed for Rv=$10^{-2}$($10^{-3}$)
- ❖O(1) gauge coupling constant is required

# DM-nucleon scattering cross section

**Scattering Process:**




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

$m_{Z_L} << m_{Z_H}$ ➡ $Z_L$ contribution dominates the scattering

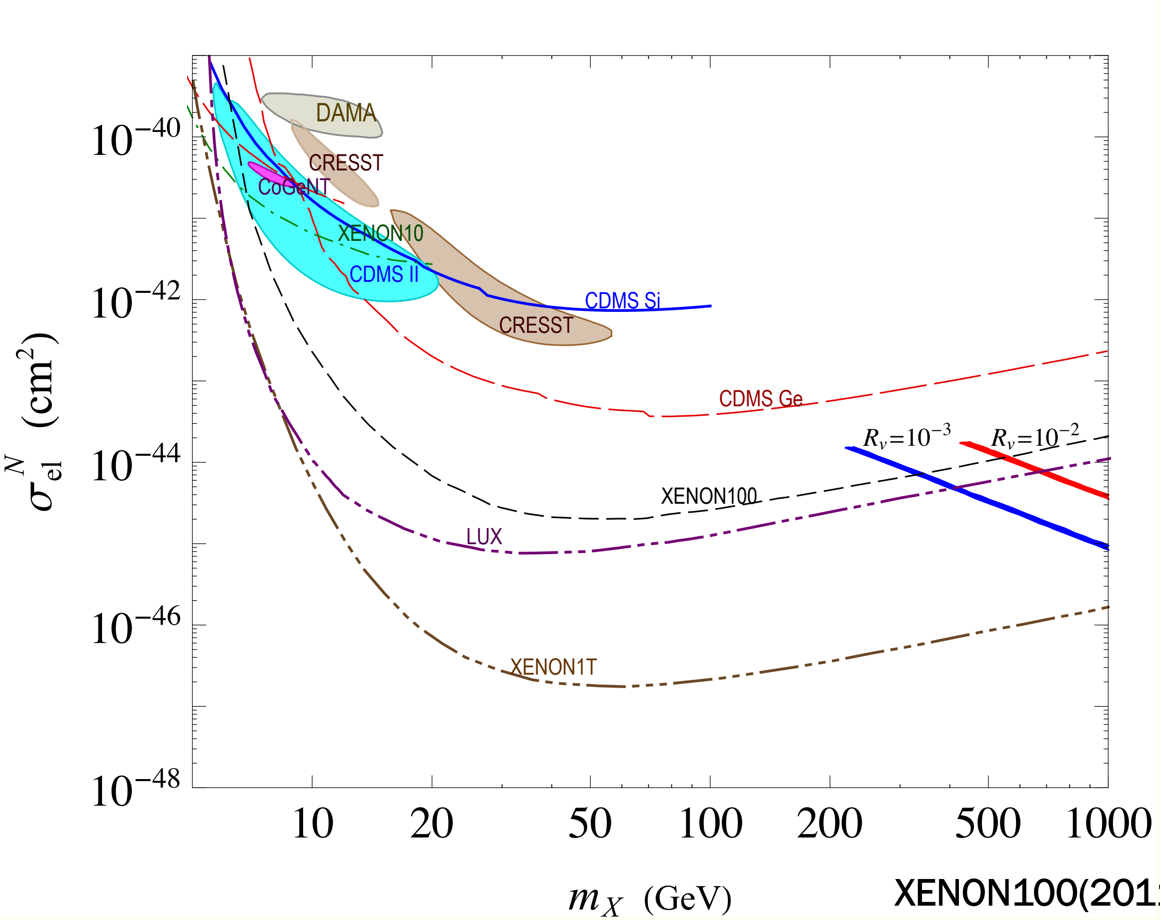
**Cross section:** $$\sigma_{DN} \approx \frac{g_X^4 R_\nu^2 \mu_{XN}^2}{16\pi m_X^4} \qquad \left( \mu_{XN} = \frac{m_X m_N}{m_X + m_N} \right) \qquad \left\{ \begin{array}{l} g_X = g_{B-L} \\ m_{Z_L} \approx 4 m_X \end{array} \right\}$$

Applying the allowed parameter region from relic density

Compare the cross section with DM direct detection search

# DM-nucleon scattering cross section

## Comparison with the constraints from direct detection




XENON100(2011) (Phys. Rev. Lett. **109, 181301 (2012)**)
LUX(2013) (arXiv:1310.8214 [astro-ph.CO] **(2013)**)

Most of the allowed parameter region escape the constraints

Future experiment like XENON1T will probe the region

# Summary

❖ We constructed a model for DM as new massive gauge boson

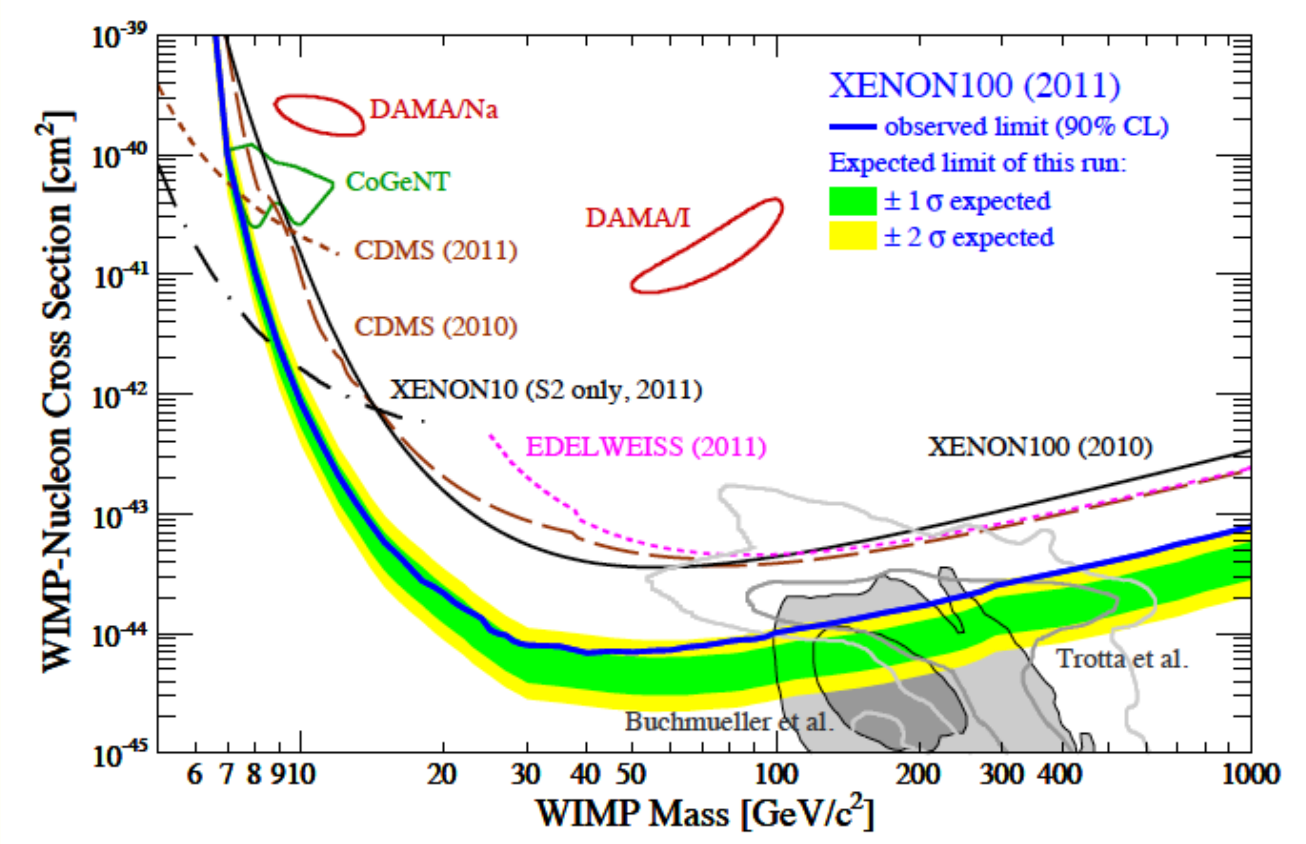
- ➢ DM candidate is new massive gauge boson from extra $SU(2)_X$
- ➢ Stability of DM : $Z_2$ symmetry as a subgroup of $SU(2)_X$
- ➢ $\nu_R$ is required by anomaly cancellation for $U(1)_{B-L}$
- ➢ Neutrino masses would be given by Type-I seesaw
- ➢ The relation $m_{ZL} \sim 2m_X$ is obtained from SSB 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))

## The Lagrangian

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

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

$$D_\mu \Phi_5 = \partial_\mu S + i 2 g_{B-L} E_\mu S$$

$$V = -\mu_\Phi^2 |\Phi_5|^2 + (\lambda_S |S|^2 - \mu_S^2) |S|^2 + (\lambda_H |H|^2 - \mu_H^2) |H|^2 + (quartic\ terms)$$

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

# Determination of relic density

● Estimated by Boltzmann equation

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

Thermal average of DM annihilation cross section × DM relative velocity

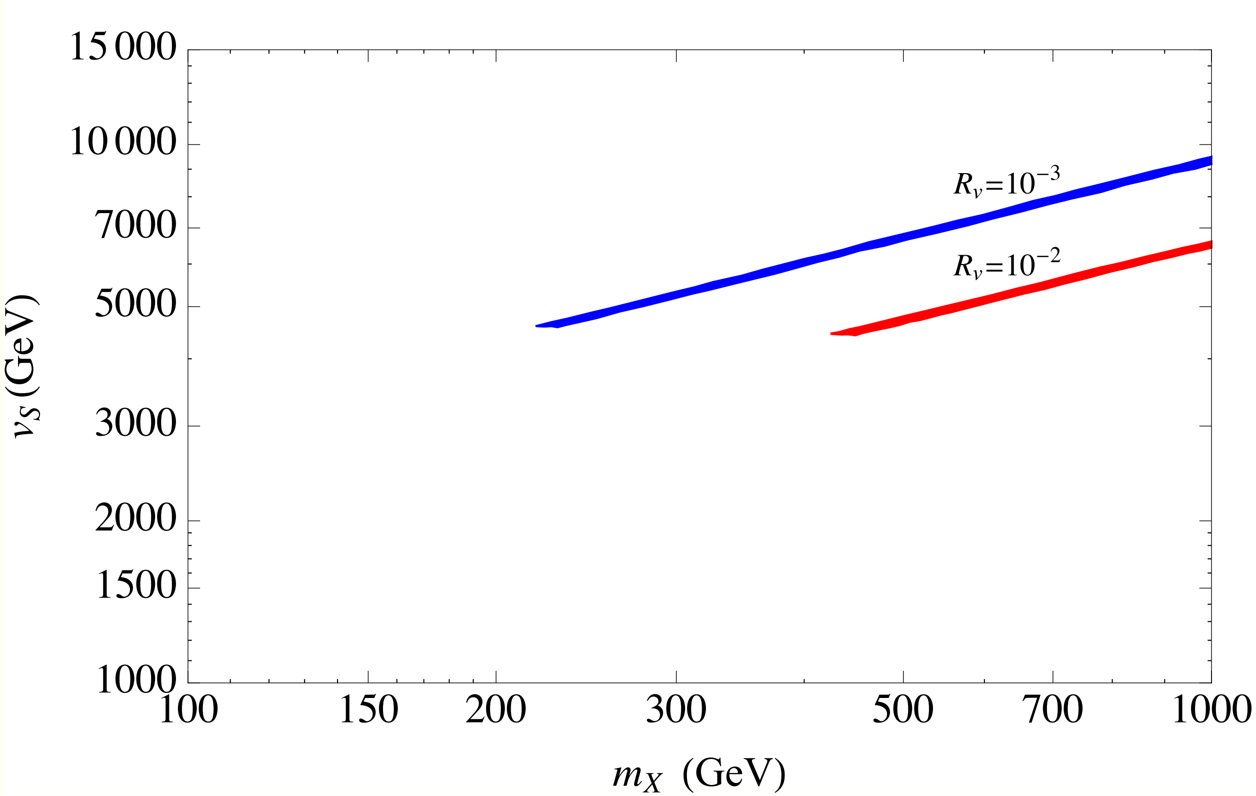
**Annihilation cross section control the relic density**

● Approximated solution of Boltzmann equation

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

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

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




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