Multicomponent dark matter in radiative seesaw model

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Collaboration with
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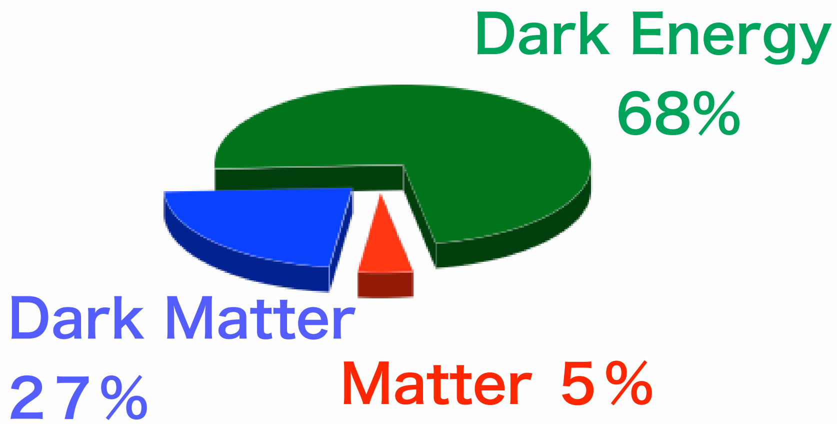
[arXiv:1406.xxxx [hep-ph]]

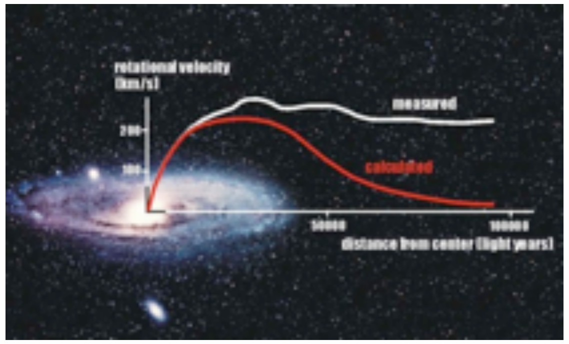
Contents

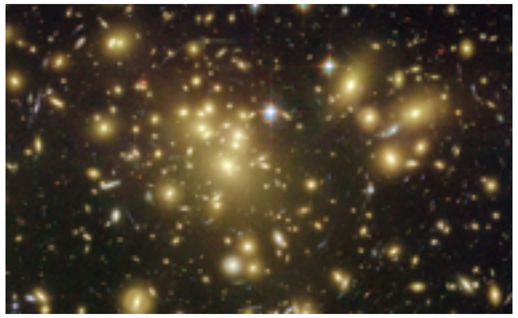
Introduction

Dark Matter

The existence of DM has been confirmed by astronomy, but the origin of DM is still unknown.




Galaxy rotation curves


Gravitational lens


Bullet Cluster

- Stability of the DM can be guaranteed by an unbroken symmetry.
- The simplest possibility is a Z_2 symmetry.
- If the DM stabilizing symmetry is larger than Z_2, a multicomponent DM system can be realized.

e.g.) Z_N ($N \geqq 4$)

a product of two or more Z_2's

:

Boehm, Fayet and Silk, PRD69 (2004); D'Eramo and Thaler, JHEP 1006 (2010); Belanger et al, JCAP 1204 (2012), arXiv:1403.4960 [hep-ph]; Ivanov and Keus, Phys. Rev. D 86, (2012), etc.

Introduction

Multicomponent DM system

e.g.)

- **Model with $Z_2 \times Z_2'$**

$\underline{m_3 > m_2 > m_1}$

- $m_3 > m_1 + m_2$

$\chi_3 \rightarrow \chi_1 \chi_2$ **2 DM particle**

- $m_3 < m_1 + m_2$

3 DM particles

	Z_2	Z_2'
χ_1	−	+
χ_2	+	−
χ_3	−	−

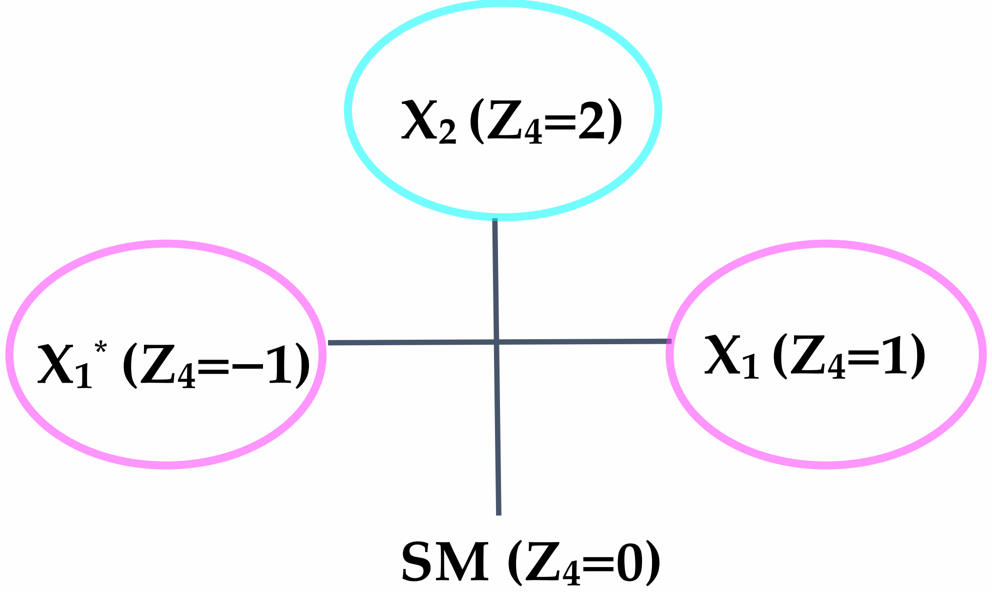
- **Model with Z_4 symmetry**

- $m_2 > m_1 + m_1$

$\chi_2 \rightarrow \chi_1 \chi_1$ **1 DM particle**

- $m_2 < m_1 + m_1$

2 DM particles

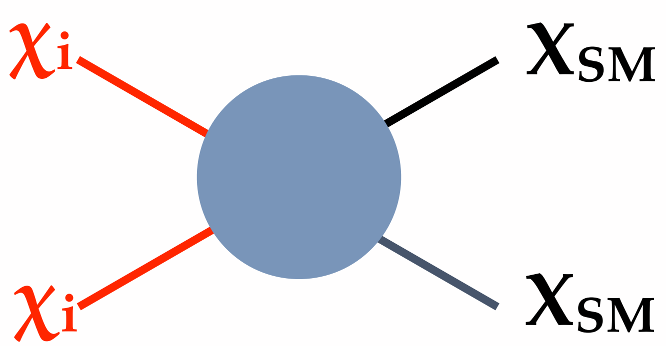


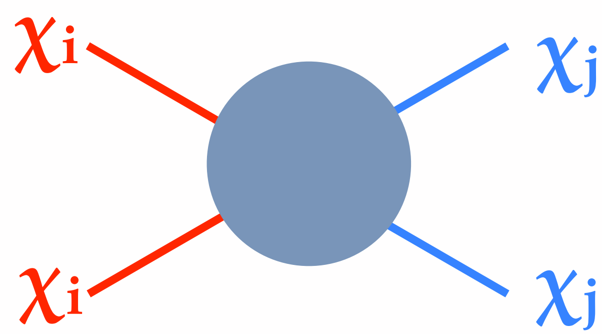
Introduction

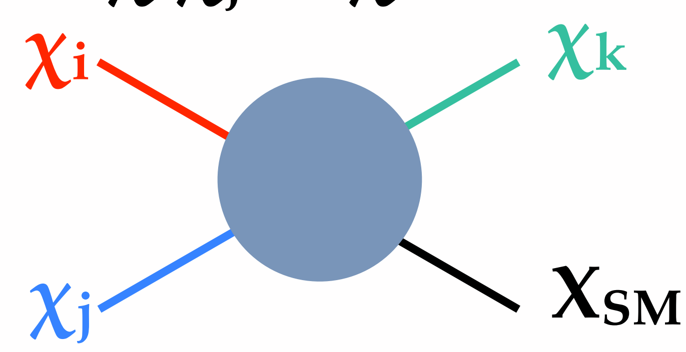
DM annihilation processes

In addition to the standard annihilation processes, there can be nonstandard DM annihilation processes.

Standard	DM Conversion	Semi-annihilation
$\chi_i\chi_i \to X_{SM}X_{SM}$	$\chi_i\chi_i \to \chi_j\chi_j$	$\chi_i\chi_j \to \chi_k X_{SM}$







$$\dot{n}_{\chi_1} + 3Hn_{\chi_1} = -\Big\{ \langle\sigma_{\chi_1\chi_1\to X_{\rm SM}X_{\rm SM}}|v|\rangle (n_{\chi_1}^2 - \bar{n}_{\chi_1}^2) + \langle\sigma_{\chi_1\chi_1\to\chi_2\chi_2}|v|\rangle (n_{\chi_1}^2 - \bar{n}_{\chi_1}^2 \frac{n_{\chi_2}^2}{\bar{n}_{\chi_2}^2}) + \langle\sigma_{\chi_1\chi_2\to\chi_3 X_{\rm SM}}|v|\rangle (n_{\chi_1}n_{\chi_2} - \bar{n}_{\chi_1}\bar{n}_{\chi_2}\frac{n_{\chi_3}}{\bar{n}_{\chi_3}}) \Big\}$$

standard — DM conversion — semi-annihilation

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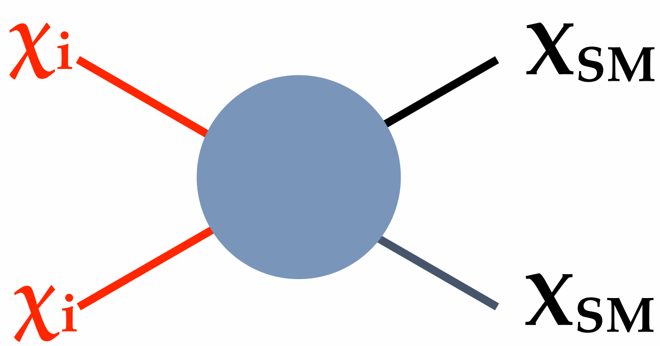

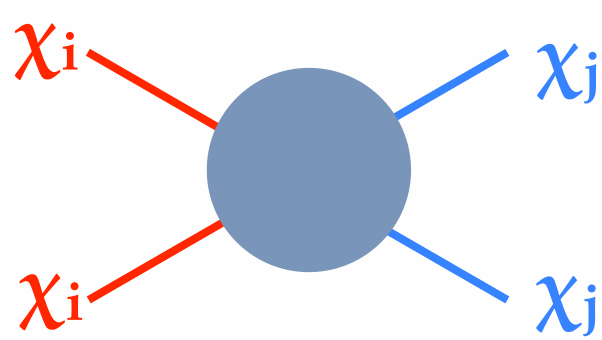

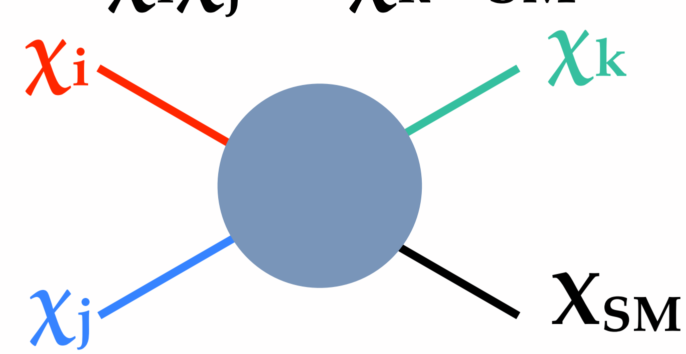

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standard — DM conversion — semi-annihilation

Semi-annihilation in the single component DM system

Single component DM : $\chi\chi \to \chi^* X_{SM}$

Z_3 symmetric DM, New Vector boson DM

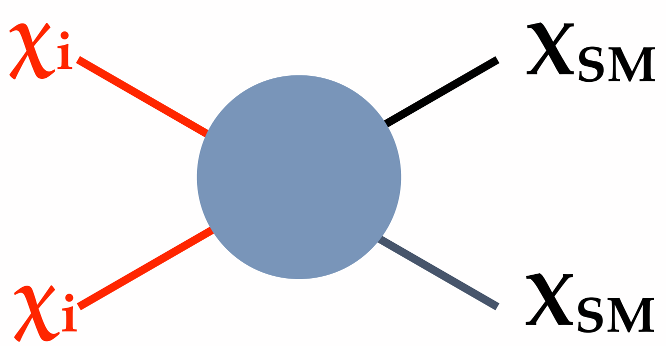
D'Eramo and Thaler, JHEP1006(2010); Belanger et al, JCAP1204(2012), JCAP(2013), arXiv:1403.4960 [hep-ph]; Hambye, JHEP0901(2009); Arina et al, JCAP1003(2010), etc.

DM annihilation processes

In addition to the standard annihilation processes, there can be nonstandard DM annihilation processes.

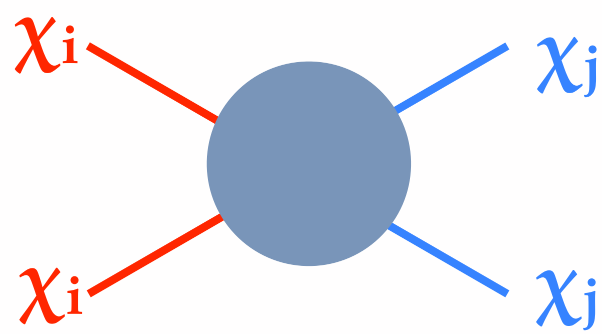
Standard

$\chi_i \chi_i \to X_{SM} X_{SM}$



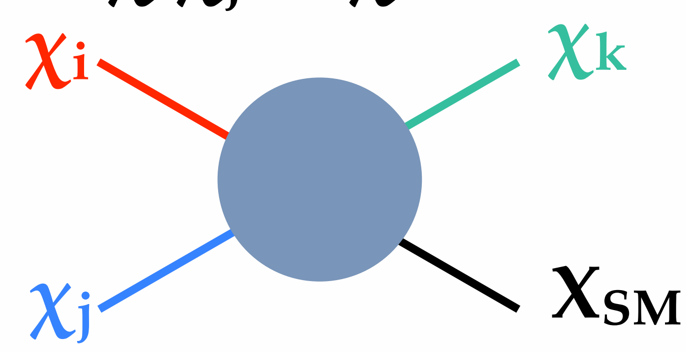
DM Conversion

$\chi_i \chi_i \to \chi_j \chi_j$



Semi-annihilation

$\chi_i \chi_j \to \chi_k X_{SM}$



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standard — DM conversion — semi-annihilation

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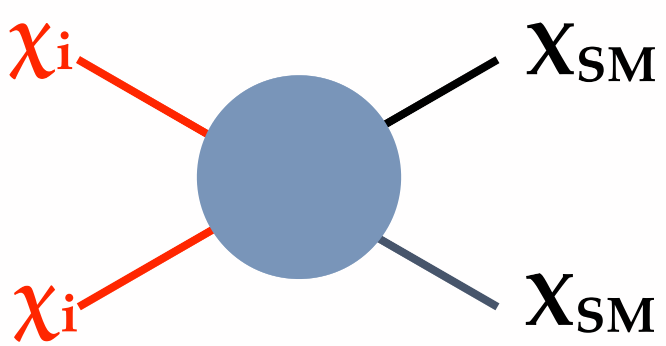
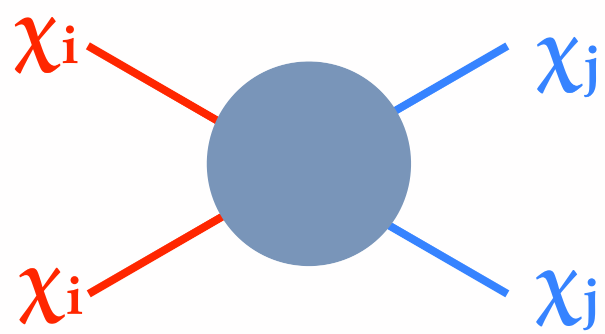
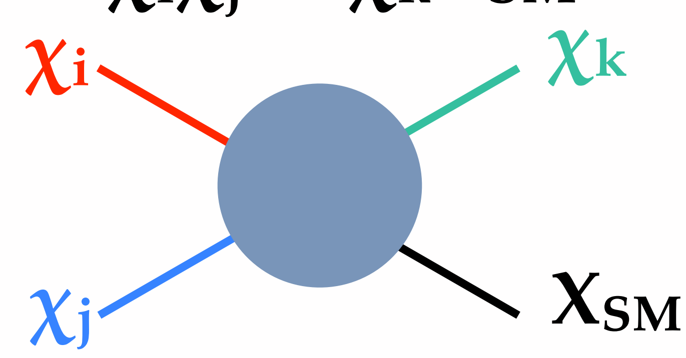






$$\dot n_{\chi_1} + 3Hn_{\chi_1} = -\Big\{ \underbrace{\langle\sigma_{\chi_1\chi_1\to X_{SM}X_{SM}}|v|\rangle (n_{\chi_1}^2 - \bar n_{\chi_1}^2)}_{\text{standard}} + \underbrace{\langle\sigma_{\chi_1\chi_1\to\chi_2\chi_2}|v|\rangle\left(n_{\chi_1}^2 - \bar n_{\chi_1}^2 \frac{n_{\chi_2}^2}{\bar n_{\chi_2}^2}\right)}_{\text{DM conversion}} + \underbrace{\langle \sigma_{\chi_1\chi_2\to\chi_3 X_{SM}}|v|\rangle \left(n_{\chi_1}n_{\chi_2} - \bar n_{\chi_1}\bar n_{\chi_2}\frac{n_{\chi_3}}{\bar n_{\chi_3}}\right)}_{\text{semi-annihilation}}\Big\}$$

Impact on the indirect signals :

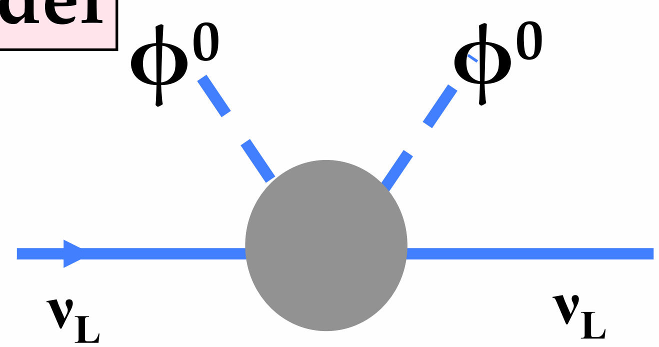
- PAMELA/Fermi positron excess,
- Fermi-Lat γ-line,
- Fermi-Lat diffuse γ from the Galactic center
- :

Boehm, Fayet, Silk, PRD69 (2004); Cao et al, arXiv:0711.3881 [hep-ph]; Huh, Kim, Kyae, PRD79 (2009); Zurek, PRD79 (2009); D'Eramo, McCullough,Thaler, JCAP1304, (2013); Biswas et al, arXiv:1301.3668 [hep-ph]; MA, Kubo, Takano, PRD87 (2013);Gu, Phys.Dark Univ. 2 (2013), etc

Introduction

DM stabilizing symmetry ⟺ Neutrino mass generation mechanism

Radiative seesaw model



***N*-loop:** $m_\nu^{ij} = \left(\frac{1}{16\pi^2}\right)^N \frac{f_{ij}}{\Lambda}\langle\phi^0\rangle^2$

Neutrino masses are generated via the radiative effect.

$\Rightarrow$ Due to the loop suppression factor, Λ can be lower.

Neutrino masses would be explained by the TeV-scale physics.

Introduction

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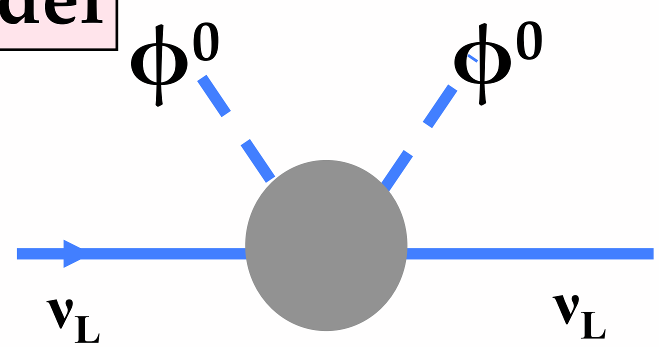
Radiative seesaw model



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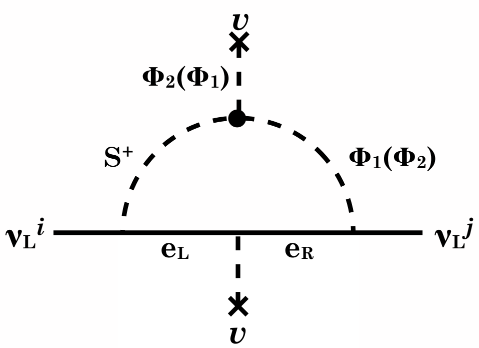
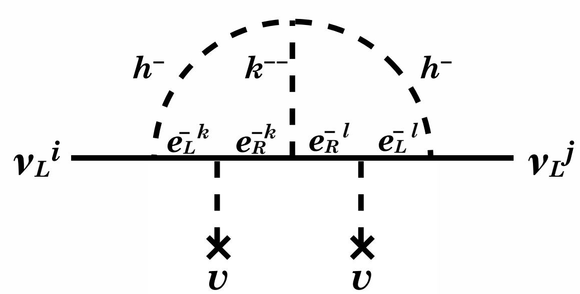
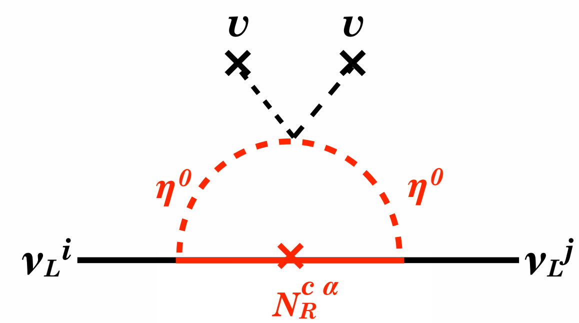


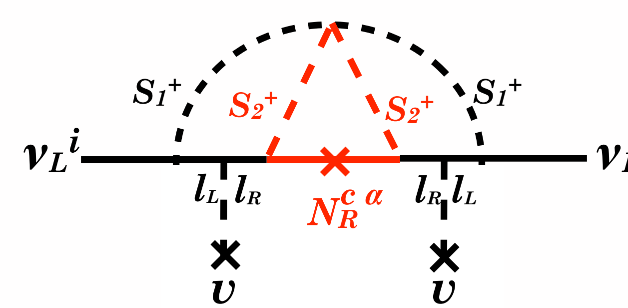
Zee, PLB93,389 (1980), PLB161,141 (1985)



Zee, NPB264,99 (1986)
Babu, PLB203,132 (1988)



Ma, PRD73, 077301 (2006)



Krauss, Nasri, Trodden PRD67,085002 (2003)

Exact discrete symmetry is imposed.

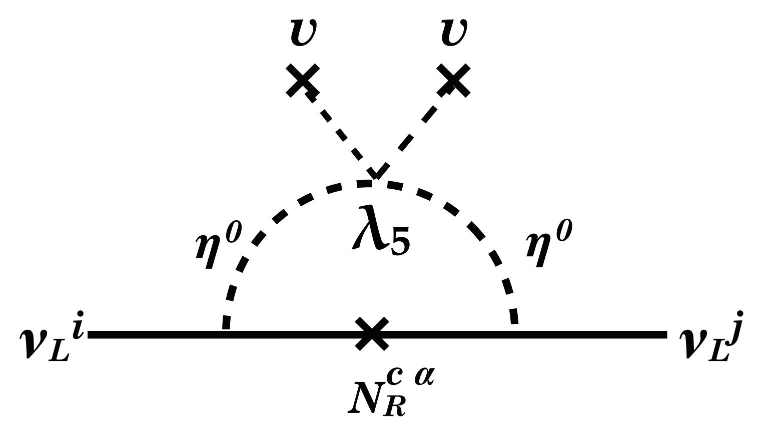
We study the multicomponent DM system in the extended Ma model.

Ma model

Ma model SM+N_R + η

Ma, PRD73, 077301 (2006)

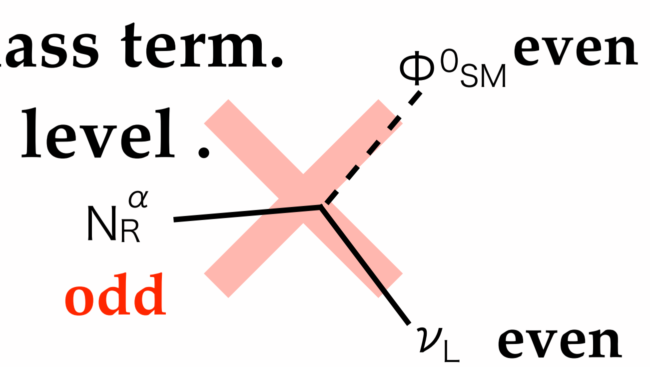
field	$SU(2)_L$	$U(1)_Y$	Z_2
(ν_{Li}, l_i)	2	$-1/2$	$+$
l_i^c	1	1	$+$
N_i^c	1	0	$-$
$H = (H^+, H^0)$	2	$1/2$	$+$
$\eta = (\eta^+, \eta^0)$	2	$1/2$	$-$



- **Inert doublet scalar**

$$\eta = \begin{pmatrix} \eta^+ \\ (\eta_R^0 + i\eta_I^0)/\sqrt{2} \end{pmatrix}, \qquad \langle \eta \rangle = 0$$

- **Z_2 symmetry is introduced to forbid the Dirac neutrino mass term.**
  →Then the neutrino masses are generated at the one-loop level .



- **Relevant Lagrangian**

$$\mathcal{L} = Y_{ik}^{\nu} L_i \epsilon \eta N_k^c - \left[\frac{1}{2} M_k N_{Rk}^c N_{Rk}^c + \frac{1}{2}\lambda_5 (H^\dagger \eta)^2 + h.c.\right]$$

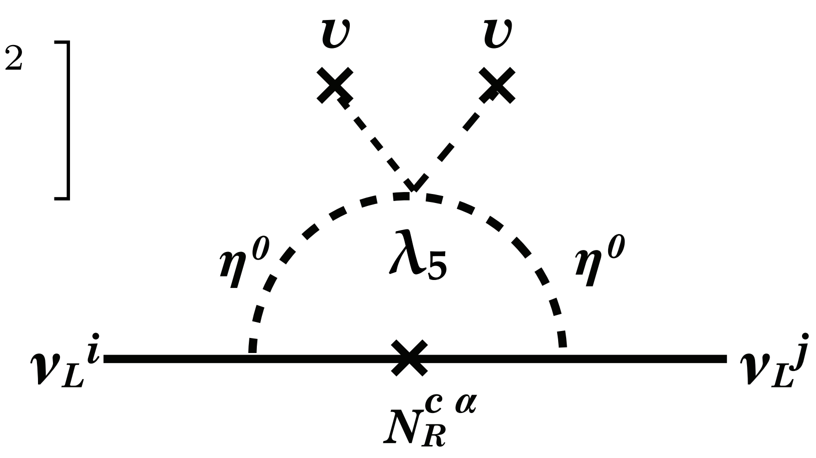
- **Single component DM**

N_R, $\eta^0{}_R$ **or** $\eta^0{}_I$

Ma model

- **Neutrino masses**

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{Y^\nu_{ik} Y^\nu_{jk} M_k}{16\pi^2} \left[\frac{m^2_{\eta^0_R}}{m^2_{\eta^0_R} - M_k^2} \ln \left(\frac{m_{\eta^0_R}}{M_k} \right)^2 - \frac{m^2_{\eta^0_I}}{m^2_{\eta^0_I} - M_k^2} \ln \left(\frac{m_{\eta^0_I}}{M_k} \right)^2 \right]$$



- small λ_5 case ($\lambda_5 << m_0$)

$$2\lambda_5 v^2 = m^2_{\eta_R} - m^2_{\eta_I} \qquad m_0^2 = \frac{m^2_{\eta^0_R} + m^2_{\eta^0_I}}{2}$$

$$(M_\nu)_{ij} \simeq \frac{Y_{ik} Y_{jk} \lambda_5 v^2}{8\pi^2} \frac{M_k}{m_0^2 - M_k^2} \left\{ 1 - \frac{M_k^2}{m_0^2 - M_k^2 \ln \frac{m_0^2}{M_k^2}} \right\}$$

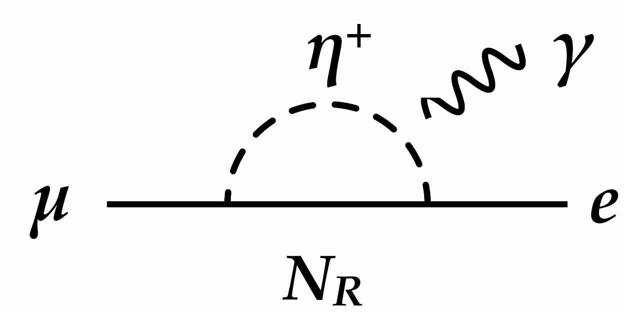
→ **$M\nu$ = 0.1 eV, New masses ~O(100) GeV → $|Y_\nu Y_\nu \lambda_5| \sim 10^{-10}$**

- **Lepton Flavor Violation :**

- $\mu \to e\gamma$ constraint :

$B(\mu \to e\gamma)^{exp} \lesssim 5.7\times10^{-13}$ MEG(2013)

→ $Y_\nu Y_\nu \lesssim 10^{-4}$

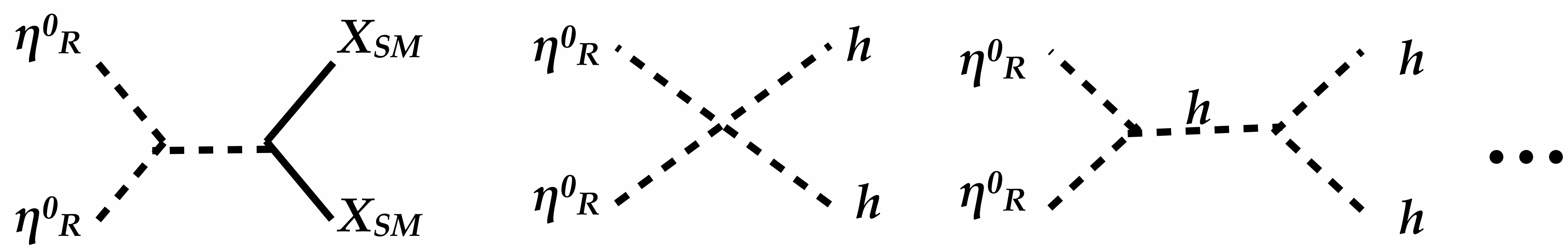


Ma model

- **Dark Matter**

N_R, η^0_R or η^0_I

η DM :



Two mass regions of DM consistent with the data.

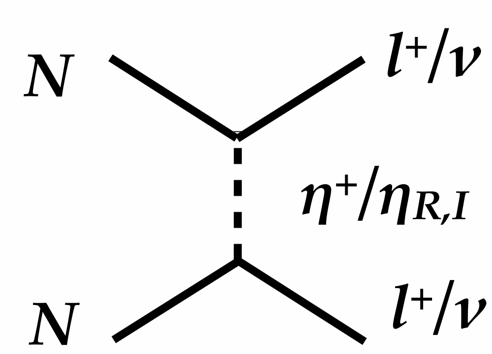
- **low-mass region (40 GeV < m_η < 80 GeV)**
- **high-mass region (> 500 GeV)**

Lopez Honorez et al., JCAP0702(2007); Gustafsson et al. PRD86 (2012)

N_R DM :

$$\Omega h^2 \sim 0.12 \;\rightarrow\; Y_\nu \sim 1$$

Kubo et al. PLB642 (2006)



Ma model

- **Neutrino masses :** $|Y_\nu Y_\nu \lambda_5| \sim 10^{-10}$
- **LFV :** $Y_\nu Y_\nu \lesssim 10^{-4}$
- **N_R DM relic abundance :** $Y_\nu \sim 1$

- **There is the tension between the LFV and the relic abundance.**
- **We need some fine tuning to obtain the small λ_5 for Y_ν~0.01.**

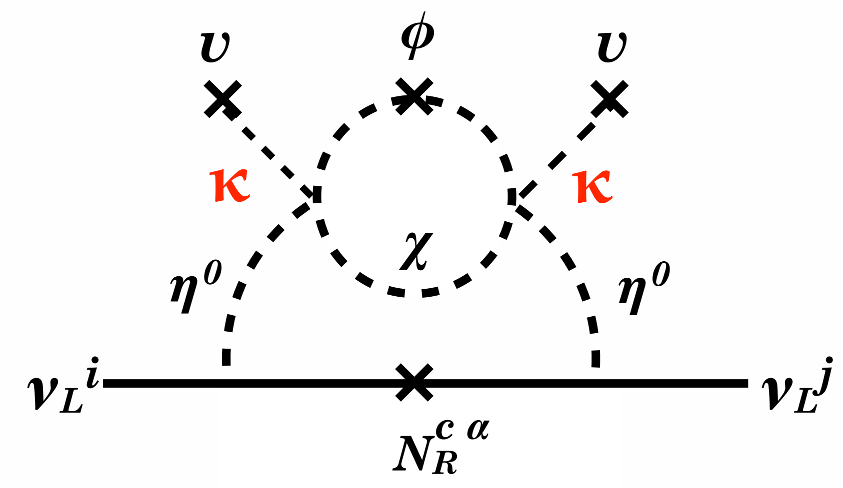
$\lambda_5 \sim 10^{-5}$ for $Y_\nu \sim 0.01$

→ Extension the Ma model

Model

Two-loop radiative seesaw model

field	$SU(2)_L$	$U(1)_Y$	Z_2	Z_2'	L
(ν_L, l_L)	2	$-1/2$	+	+	1
l_R^c	1	1	+	+	-1
N_R^c	1	0	−	+	0
$H=(H^+,H^0)$	2	$1/2$	+	+	0
$\eta=(\eta^+,\eta^0)$	2	$1/2$	−	+	-1
χ	1	0	+	−	0
ϕ	1	0	−	−	1



$\phi = (\phi_R + i\phi_I)/\sqrt{2}$.

- **The λ_5 term , $\lambda_5\,(H^\dagger\eta)^2$+$h.c.$, in Ma model is forbidden by #L.**
- **The $\lambda_5^{\rm eff}$ is generated at the 1-loop level.**
- **New relevant terms for neutrino mass :**

$$V \supset \frac{\kappa}{2}\left[(H^\dagger\eta)\chi\phi + h.c.\right] + \frac{1}{2}m_5^2[\,\phi^2 + (\phi^*)^2\,]$$

- **#L is softly violated at m_5^2 term.**
- **$m_{\eta R} = m_{\eta I}$ at the tree level. The degeneracy is lifted by $\lambda_5^{\rm eff}$.**
- **DM candidates are** N_R, $\eta^0_{R/I}$, χ, $\phi^0_{R/I}$ **Multicomponent DM system**

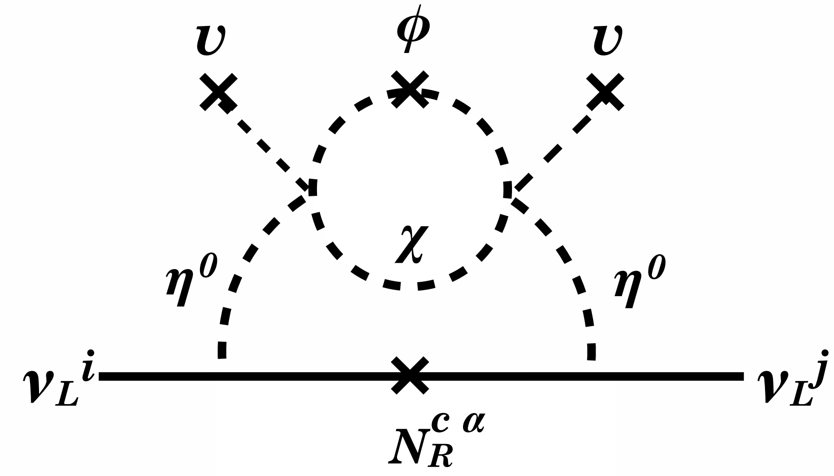
(Z_2, Z_2') = (−,+), (+,−), (−,−)

Neutrino mass

- **Neutrino mass**

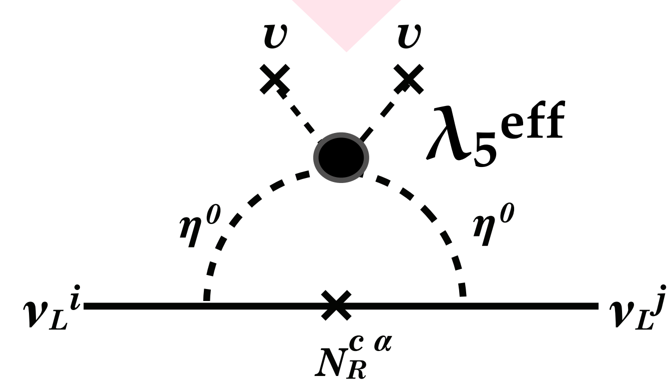
$$(\mathcal{M}_\nu)_{ij} \simeq -\frac{\lambda_5^{\rm eff} v_h^2}{8\pi^2} \sum_k \frac{Y_{ik}^\nu Y_{jk}^\nu M_k}{m_{\eta^0}^2 - M_k^2} \left[1 - \frac{M_k^2}{m_{\eta^0}^2 - M_k^2} \ln \frac{m_{\eta^0}^2}{M_k^2} \right].$$

$$m_{\eta^0} = m_{\eta_R^0} \simeq m_{\eta_I^0}$$



$\lambda_5^{\rm eff}$ term (for $m_5^2 = m_{\phi R}^2 - m_{\phi I}^2 << m_{\phi R}^2$)

$$\lambda_5^{\rm eff} \simeq -\frac{\kappa^2}{64\pi^2} \frac{m_5^2}{m_{\phi_R}^2 - m_\chi^2} \left[1 - \frac{m_\chi^2}{m_{\phi_R}^2 - m_\chi^2} \ln \frac{m_{\phi_R}^2}{m_\chi^2} \right]$$



- The neutrino mass is proportional to $|Y_\nu \kappa|^2 m_5^2$.
- $M\nu$ = 0.1 eV, New physical masses ~O(100) GeV → $\kappa Y_\nu m_5 \sim 10^{-2}$ GeV
- κ~0.1, Yν~0.01 → m_5 ~ 10 GeV, **$\lambda_5^{\rm eff} \sim 10^{-5}$**

The smallness of λ_5 is explained by the radiative generation.

Dark matter

We assume N_R, χ and ϕ_R are the DM. ⇒ **Three-component DM system.**

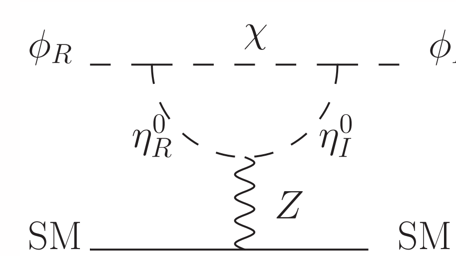
DM annihilation processes: **We assume $m_\phi > m_\chi$.**

$$\text{Standard annihilation}: NN \to XX',\ \phi_R\phi_R \to XX',\ \chi\chi \to XX',$$
$$\text{DM conversion}: \phi_R\phi_R \to \chi\chi,$$
$$\text{Semiannihilation}: N\phi_R \to \chi\nu,\ \chi N \to \phi_R\nu,\ \phi_R\chi \to N\nu,$$

- Annihilation processes of ϕ_I

$$\text{Standard annihilation}: \phi_I\phi_I \to XX',$$
$$\text{DM conversion}: \phi_I\phi_I \to \chi\chi,$$
$$\text{Semiannihilation}: N\phi_I \to \chi\nu,\ \chi N \to \phi_I\nu,\ \phi_I\chi \to N\nu.$$

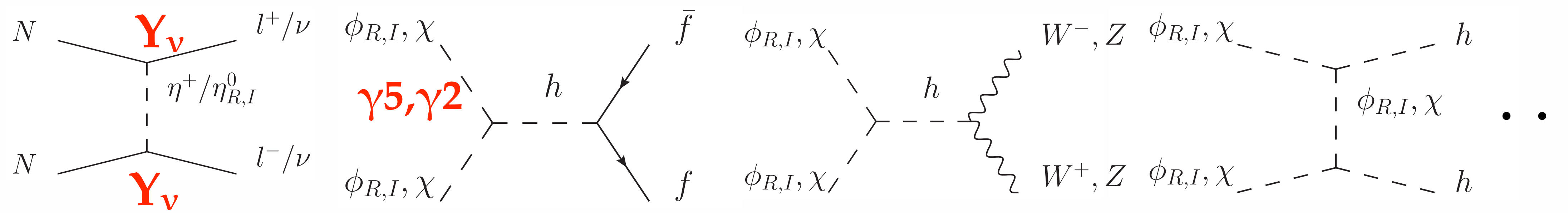
- Conversion between $\phi_I \rightleftarrows \phi_R$



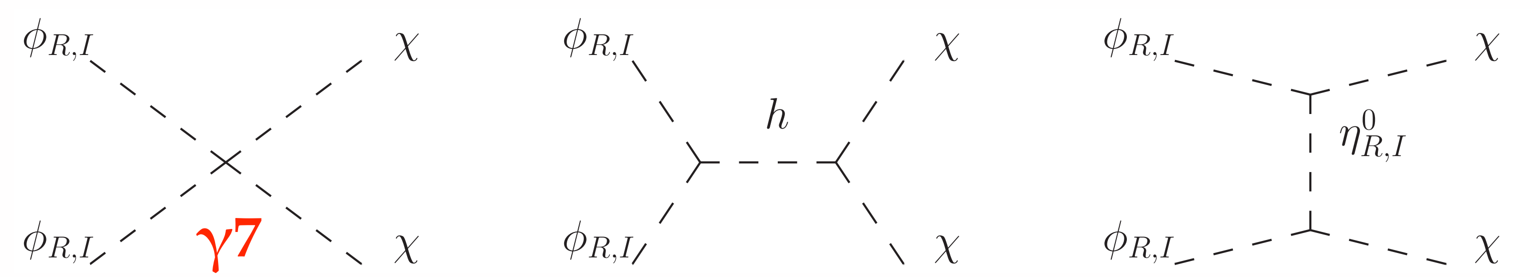
- We sum up the number densities of ϕ_I and ϕ_R, $n_\phi = n_{\phi I} + n_{\phi R}$, and solve the Boltzmann equation of n_N , n_ϕ and n_χ .

Dark matter

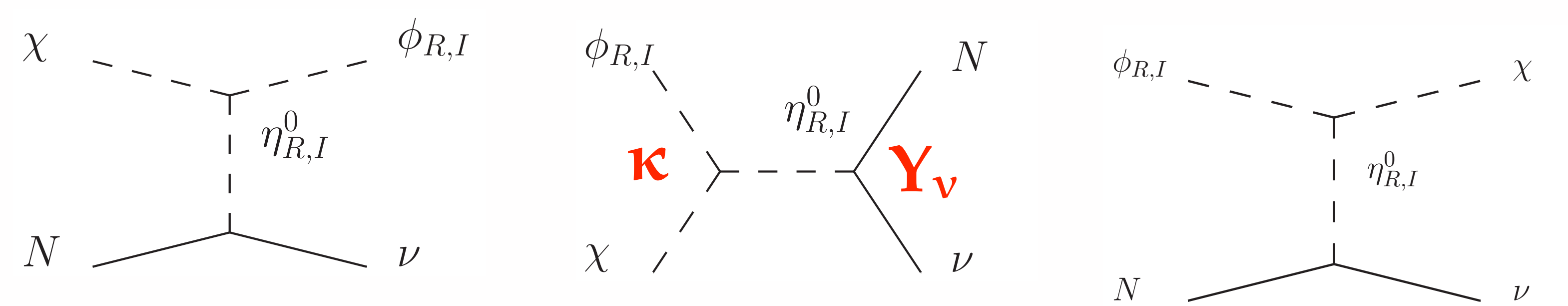
Standard



DM Conversion:

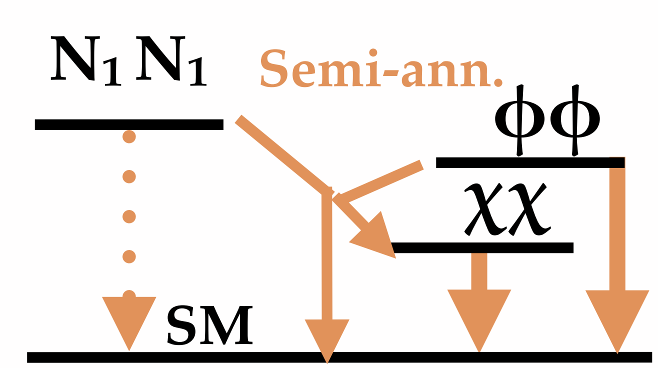


Semi-annihilation:



- In the Ma model, the $\Omega_N h^2$ tends to be larger than 0.12. However, in this model, the contribution from the semi-annihilation can enhance the annihilation rate for N_R .

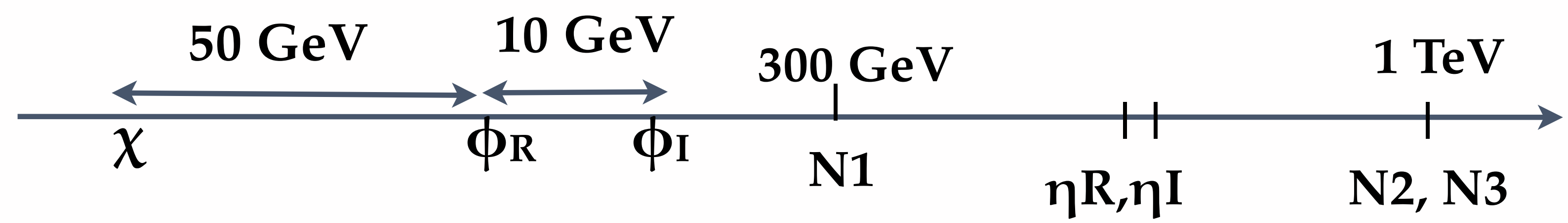
→ The tension between the constraints of LFV and $\Omega_N h^2$ becomes mild.



Relic abundance

Benchmark Point

M_1	300 GeV
$m_{\eta_R^0}$	$m_\chi + m_{\phi_R} - 10$ GeV
m_{ϕ_I}	$m_\chi + 60$ GeV
m_{ϕ_R}	$m_\chi + 50$ GeV
$\gamma \equiv \gamma_{2,5,7}$	0.1
κ	0.4



- **Neutrino mass scale**
- **Vacuum stability**
- **Perturbativity** $|\lambda_i|, |\gamma_i|, |\kappa| < 1$

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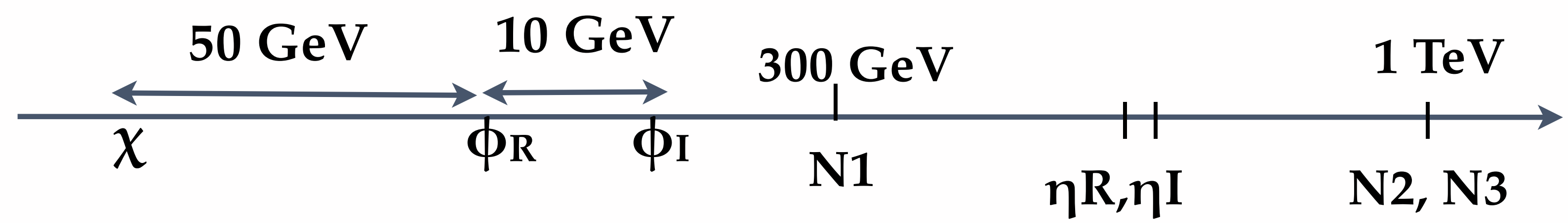

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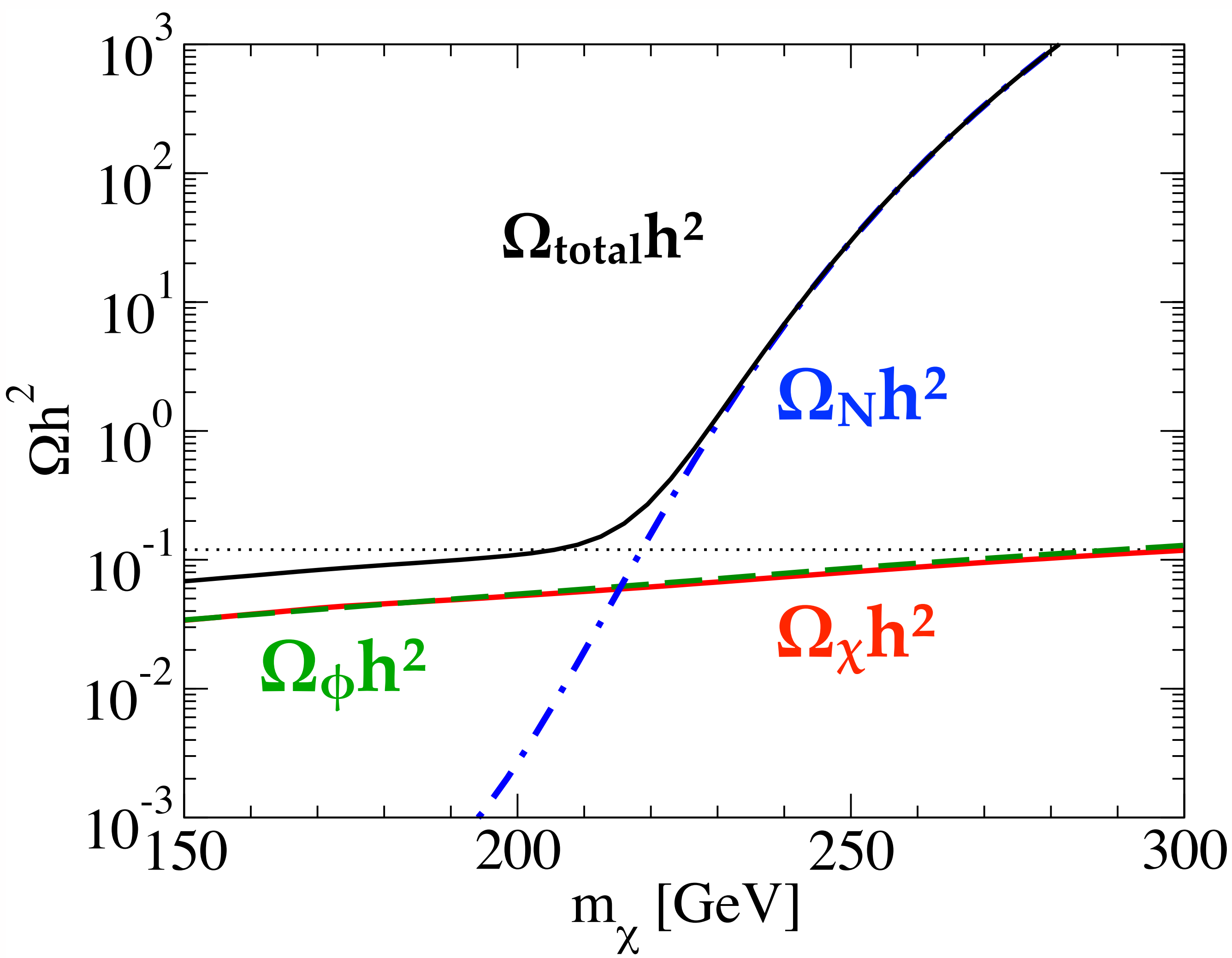

Semi-annihilation tends to decrease the relic density of the N DM.

- γ=0.1 → mχ~200 GeV for Ωh^2~0.12 Scalar DM
- γ > 0.2 → mχ~220 GeV N DM
- γ~0.08 → mχ~150 GeV Scalar DM

- mχ>220 GeV → $\Omega_N h^2$>0.12

Direct detection

The current upper bound for the DM-nucleon cross section is estimated assuming the single component DM scenario.

⇒ Constraint on the detection rate in the multicomponent DM scenario.

effective cross section : $\sigma_i^{\text{eff}} = \sigma_i \left(\frac{\Omega_i h^2}{\Omega_{\text{total}} h^2} \right)$

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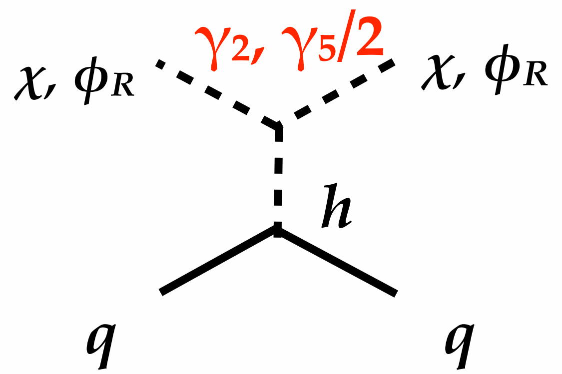

Our model

- **χ and ϕ_R have interactions to the quarks.**
- **The effective cross sections :**

$$\sigma_{\phi_R}^{\rm eff} = \sigma_{\phi_R} \left(\frac{\Omega_{\phi_R} h^2}{\Omega_{\rm tot} h^2} \right) \qquad \sigma_{\chi}^{\rm eff} = \sigma_{\chi} \left(\frac{\Omega_{\chi} h^2}{\Omega_{\rm tot} h^2} \right)$$

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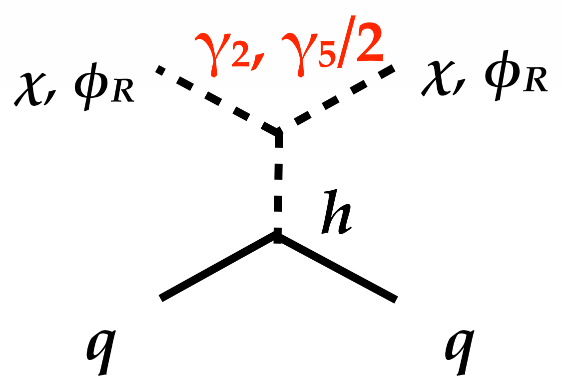

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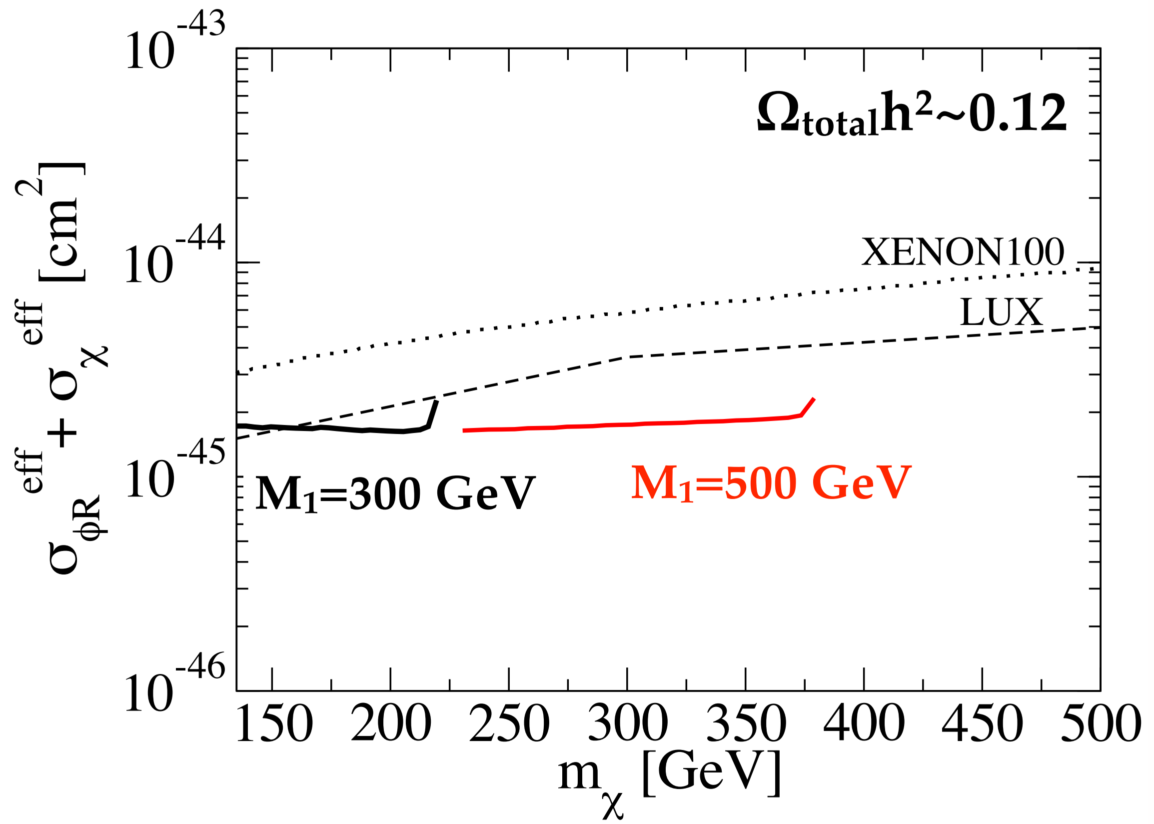
- At mχ=220 (380) GeV for M_1=300 (500)GeV
→ large γ , small Ωχ,ϕ

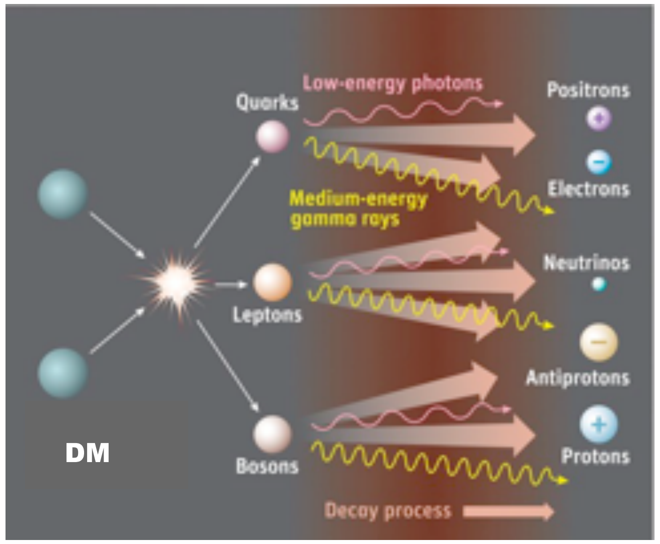
- The obtained cross section is accessible to XENON1ton.



Indirect detection

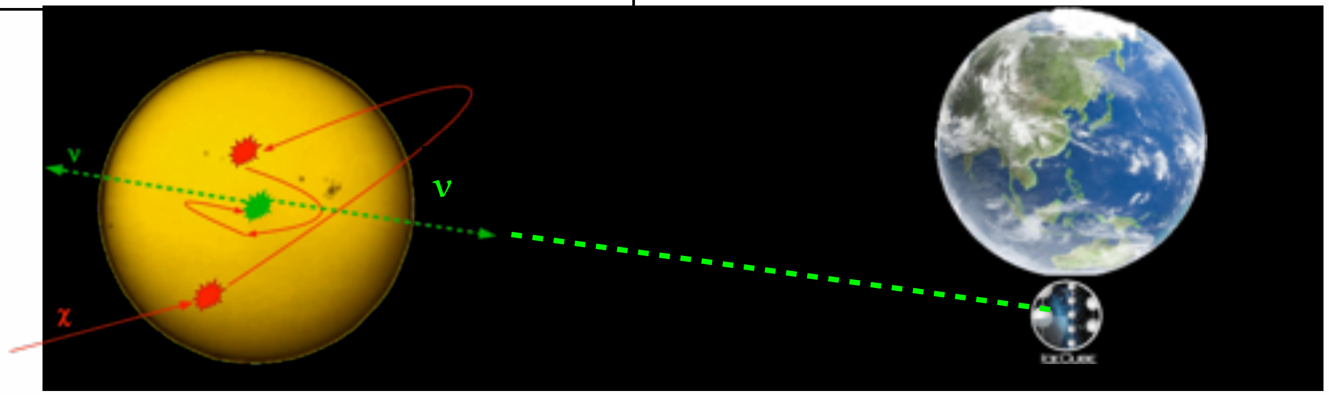
Cosmic ray from the DM annihilation.

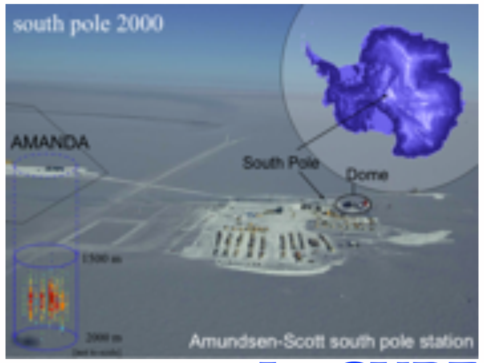
Indirect signals



We discuss the neutrinos from the annihilation of captured DM in the Sun.

Neutrino from the Sun





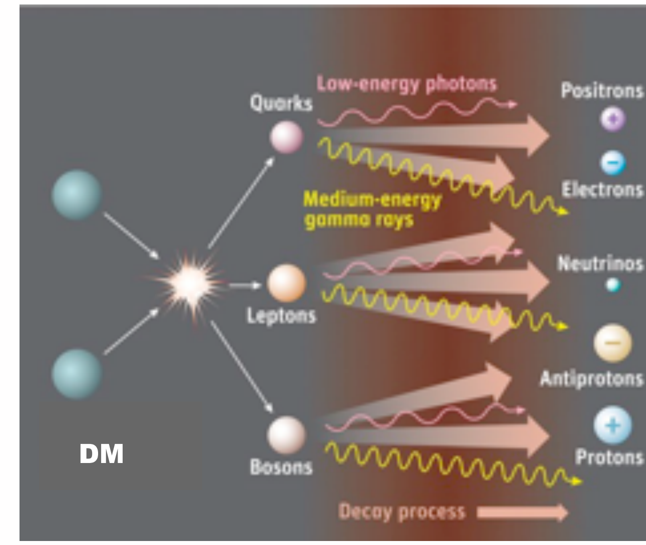
IceCUBE

Indirect detection

Cosmic ray from the DM annihilation.

↓

Indirect signals



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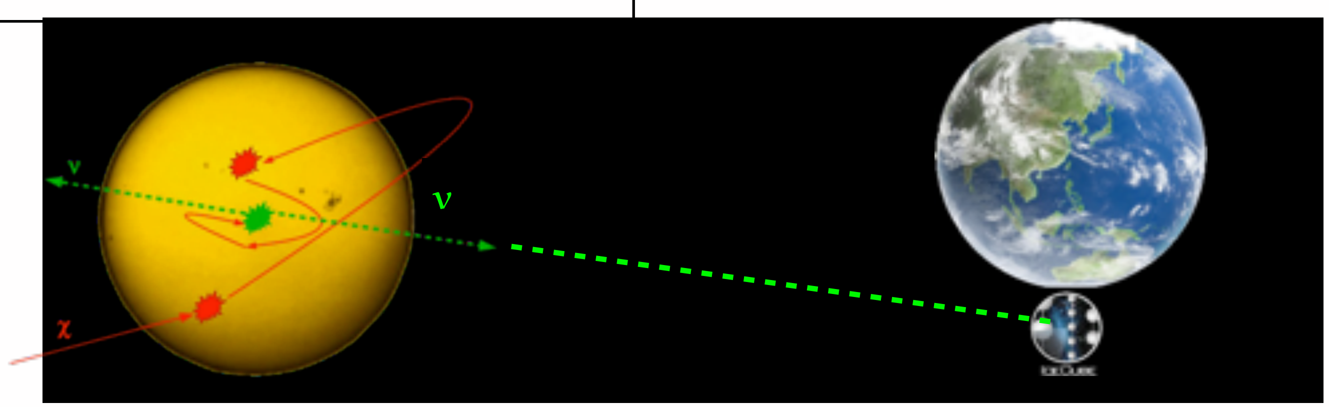
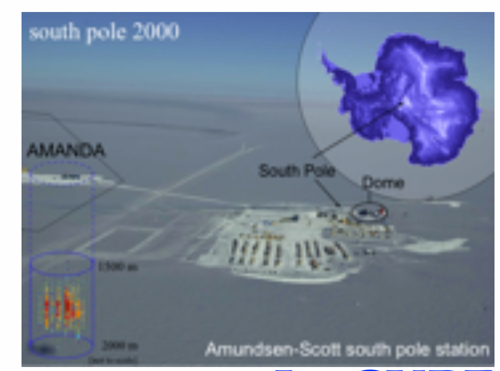
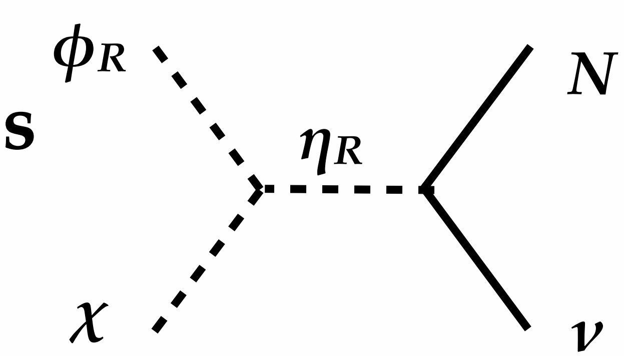




IceCUBE

In our model, the semi-annihilation process produces a monochromatic neutrino.

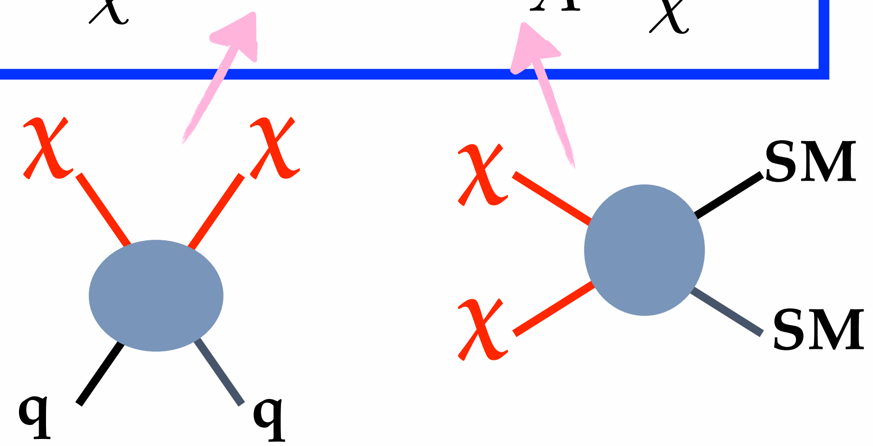


Indirect detection

Single component DM : χ

- Time evolution of n_χ in the Sun

$$\dot{n}_\chi = C - C_A n_\chi^2$$



n_χ : Number of DM in the Sun

C : Capture rate in the Sun.

C_A : Annihilation rate $C_A = \langle \sigma v \rangle / V_{eff}$

$$C_A(\chi\chi \leftrightarrow XX') = \frac{< \sigma(\chi\chi \to XX')v >}{V_{\rm eff}}$$

V_{eff} : Effective Volume of the Sun

$$V_{\rm eft} = 5.7 \times 10^{27} \left(\frac{100\ {\rm GeV}}{m_\chi}\right)^{3/2} {\rm cm}^3$$

- At the time of birth of the Sun the n_χ were zero.
- The n_χ increase with time and approach the fixed point values.

Fixed point at $C = C_A n_\chi^2$

→ equilibrium → The number of DM reaches its maximal value.

- DM annihilation rate : $\Gamma = C_A n_\chi^2/2 = C/2$.
- Neutrino production rate : $\Gamma_\nu = \Gamma\, Br(\chi\chi \to XX'\nu\nu)$

Indirect detection

IceCUBE (2013)

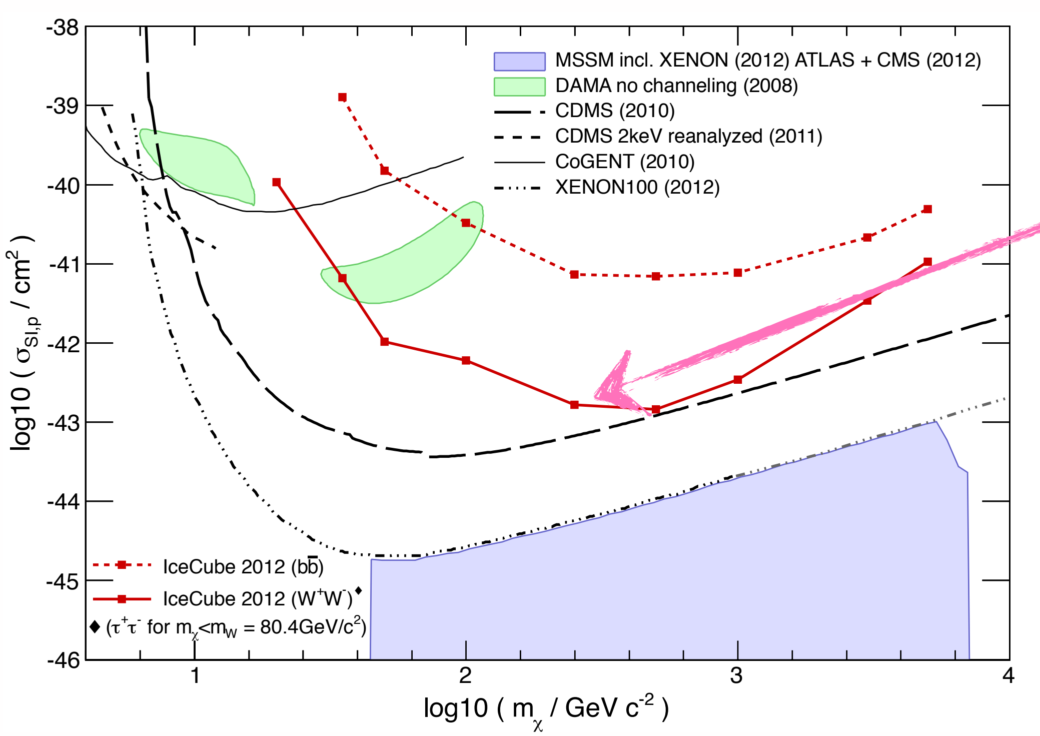
IceCube Collaboration
Phys.Rev.Lett. 110 (2013) 13, 131302

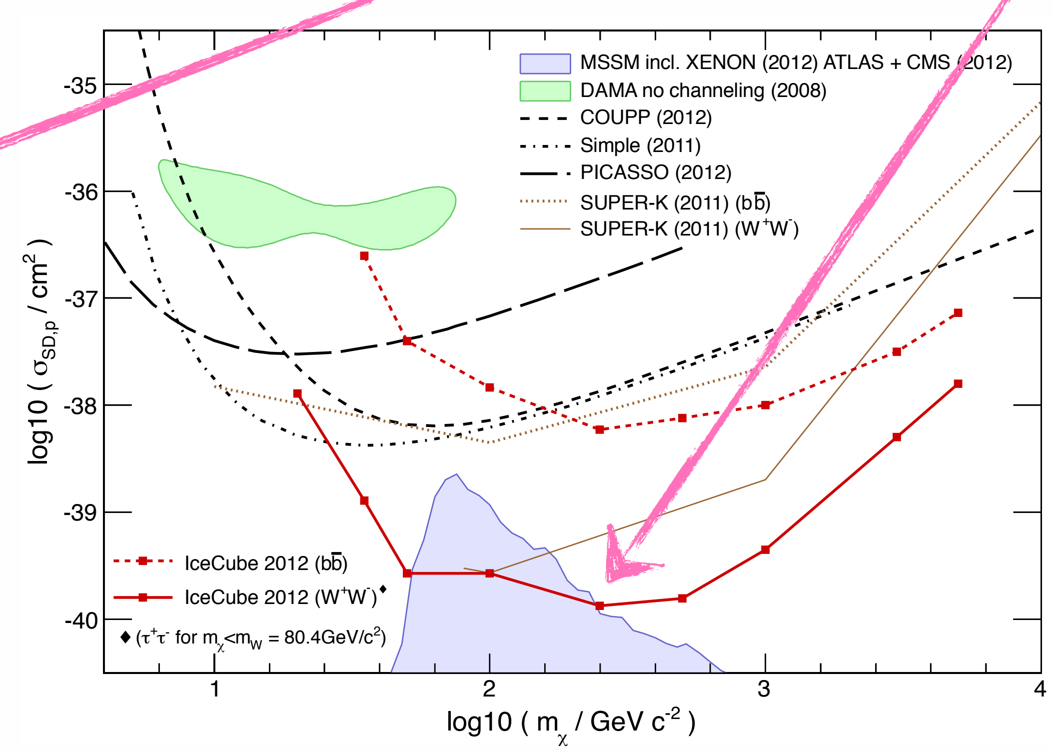
Neutralino DM

$\chi\chi \to WW \to XX'\nu\nu$

m_χ=250 GeV :

m_χ (GeV/c^2)	Channel	Φ_ν (km^{-2}y^{-1})	$\sigma_{\mathrm{SI},p}$ (cm^2)	$\sigma_{\mathrm{SD},p}$ (cm^2)
20	$\tau^+\tau^-$	2.35×10^{15}	1.08×10^{-40}	1.29×10^{-38}
35	$\tau^+\tau^-$	1.02×10^{14}	6.59×10^{-42}	1.28×10^{-39}
35	$b\bar{b}$	6.29×10^{15}	1.28×10^{-39}	2.49×10^{-37}
50	$\tau^+\tau^-$	1.17×10^{13}	1.03×10^{-42}	2.70×10^{-40}
50	$b\bar{b}$	5.64×10^{14}	1.51×10^{-40}	3.96×10^{-38}
100	W^+W^-	1.23×10^{12}	6.01×10^{-43}	2.68×10^{-40}
100	$b\bar{b}$	6.34×10^{13}	3.30×10^{-41}	1.47×10^{-38}
250	W^+W^-	9.72×10^{10}	1.67×10^{-43}	1.34×10^{-40}
250	bb	4.59×10^{12}	7.37×10^{-42}	5.90×10^{-39}





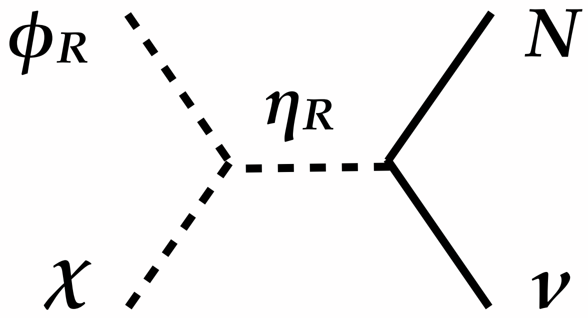
Indirect detection

Multicomponent DM : ϕ_R, χ, N_R

$$\dot{n}_i = C_i - C_A(ii \to \mathrm{SM})n_i^2 - \sum_{m_i > m_j} C_A(ii \to jj)n_i^2 - C_A(ij \to k\nu)n_i n_j$$

Standard / Conversion / Semi-annihilation

- Since $C_N=0$, the n_N cannot increase.
- $\phi\chi \to N\nu$ is the only ν production process.



- Monochromatic ν production rate :

$$\Gamma_\nu = C_A(\chi\phi \to N_R^c \nu)n_\chi n_\phi$$

- Neutrino flux : $\Phi_\nu = \Gamma_\nu/(4\pi R^2)$

R: the distance to the Sun

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Standard **Conversion** **Semi-annihilation**

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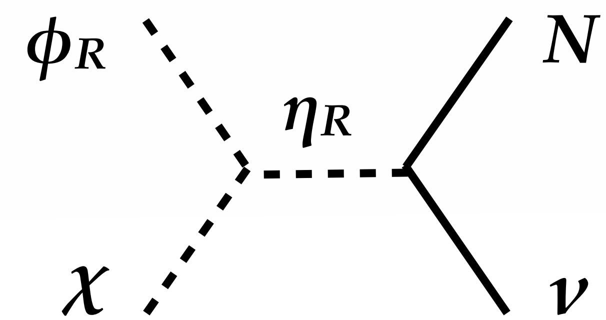

$$\delta = m_\chi + m_{\phi_R} - m_{\eta_R^0}$$

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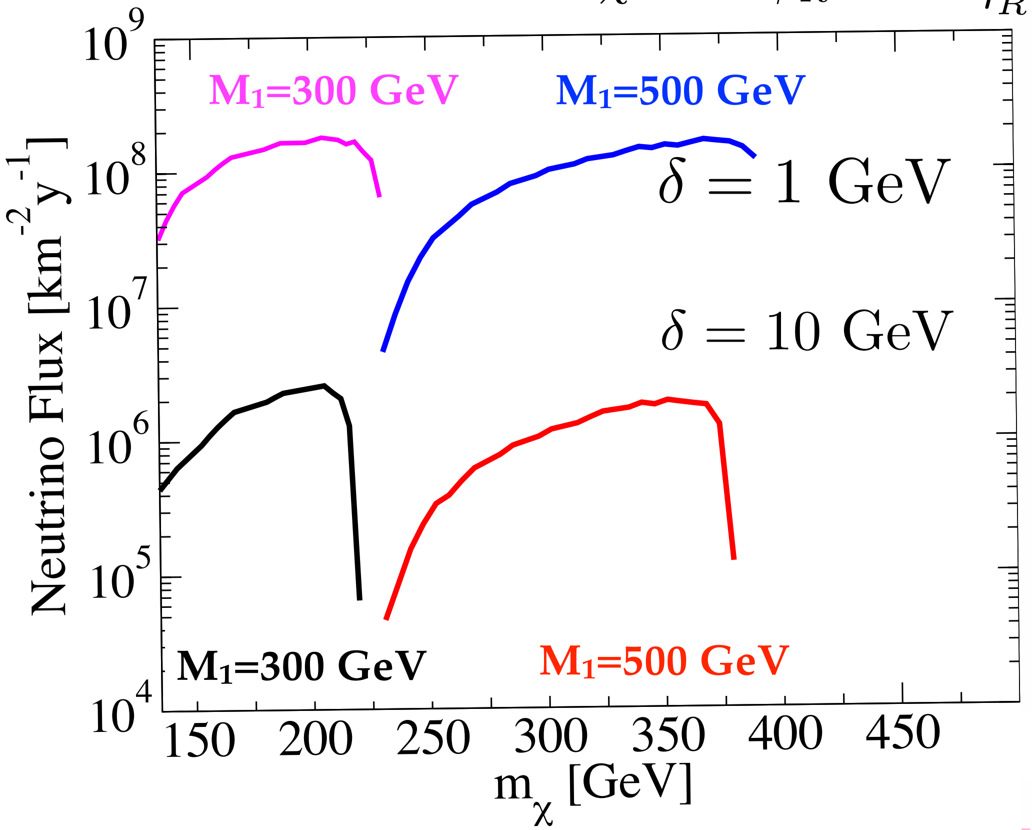

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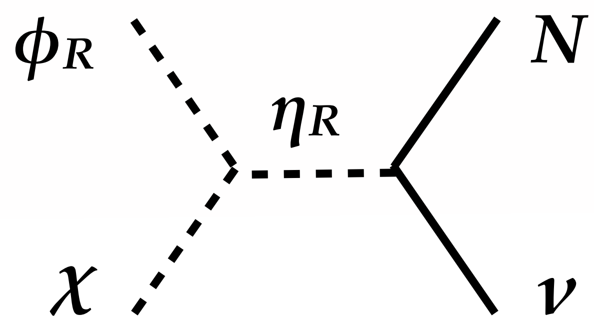

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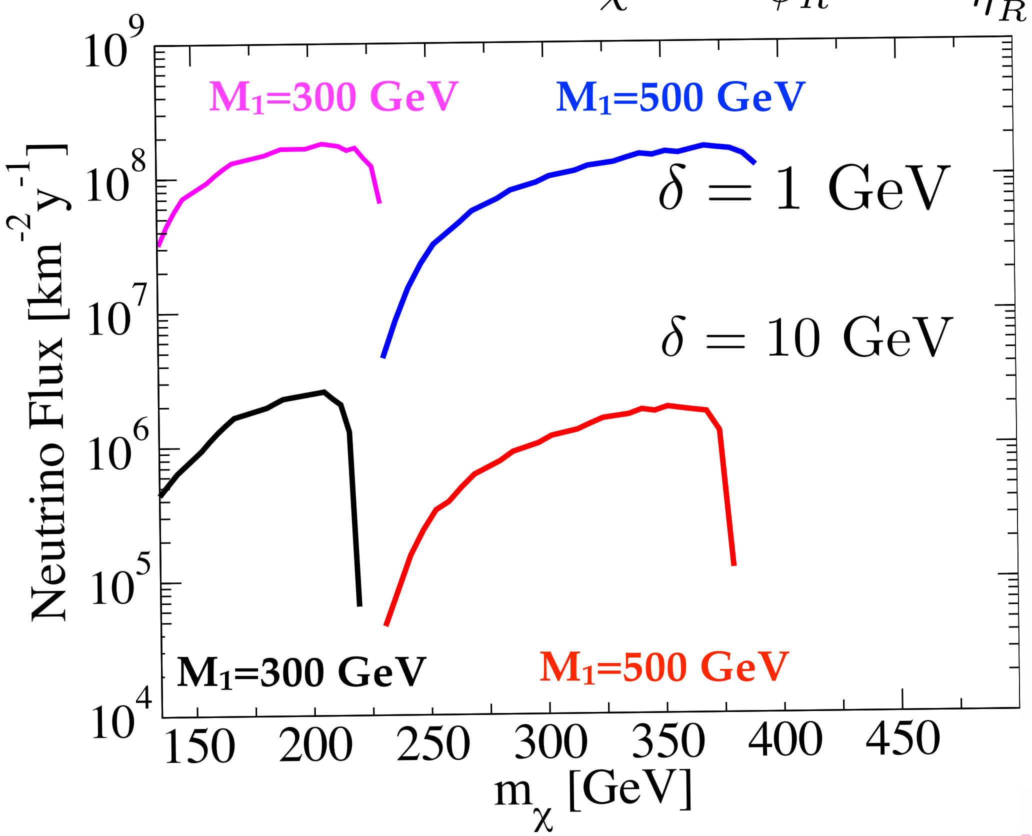

- When δ=1GeV, the larger neutrino flux can be obtained.
- The IceCUBE limit is at least 10^3 times larger than these results.

Summary

We have proposed the radiative seesaw model with multicomponent DM system.

Two-loop extension of Ma model with $Z_2 \times Z_2$ symmetry.

- **The small $\lambda 5$ coupling is realized by the radiative correction.**

Three-component (N, χ, ϕ_R) DM system.

- **$\Omega_N h^2$ is reduced by the semi-annihilation processes.**
- **For the direct detection, the predicted value will be covered by XENON1T.**
- **The monochromatic neutrino is produced by the semi-annihilation.**
- **The neutrino flux from the Sun is enhanced by the resonant effect. However, the flux is very small compared with the IceCUBE sensitivity.**

Thank you for your attention.