Multi-Component Dark Matter Systems and Their Observation Prospects

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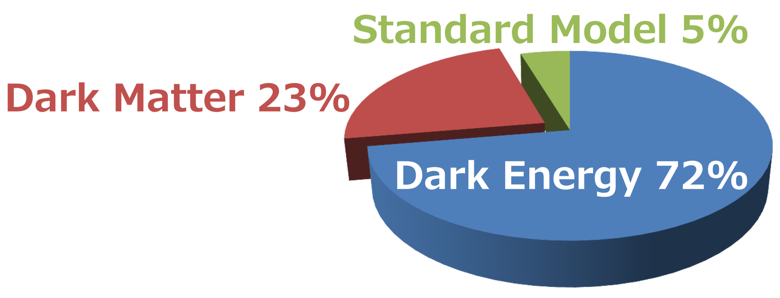
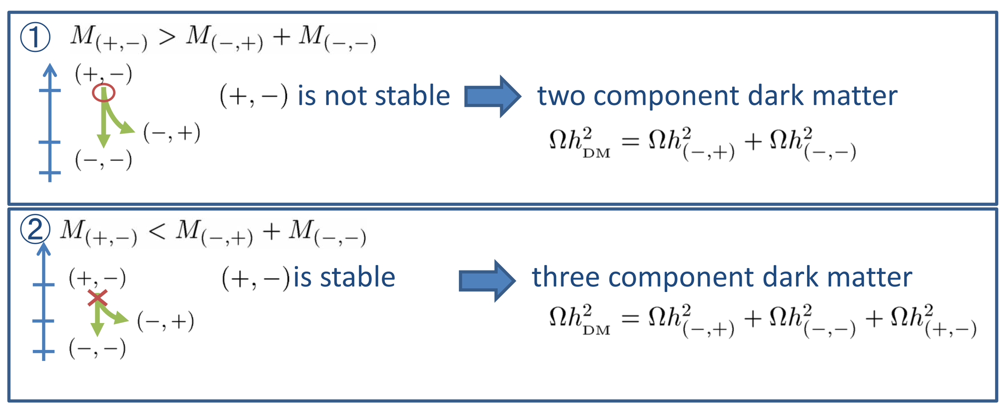
Introduction

- WIMP DM candidates
  - Inert scalar DM (Inert model)
  - Z_2 odd RH neutrino (Radiative seesaw model)
  - Neutralino (SUSY model)
  - etc…



We can naturally consider the Multi-component DM systems.

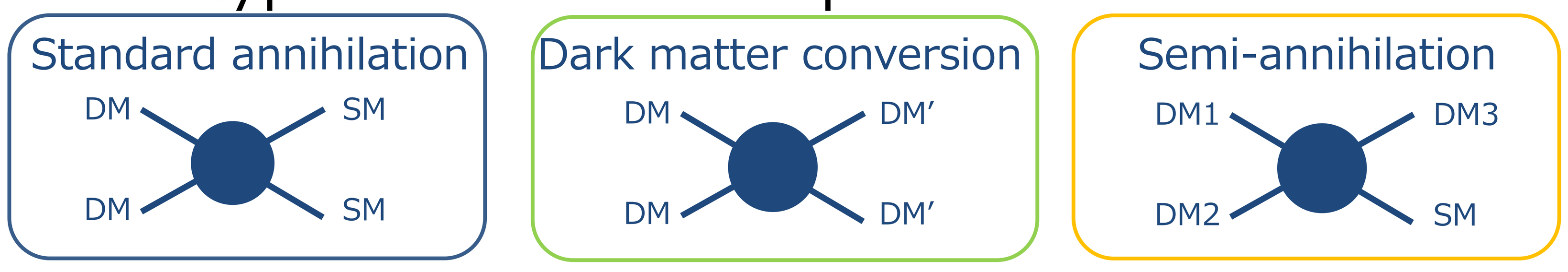
- Example of Multi-component DM model
  - $Z_2 \times Z'_2$ symmetry (DM=(+,-) or (-,+) or (-,-))
    - A) Two R parity from N=2 SUSY
    - B) SUSY & Z_2 symmetry from U(1)
    - C) SUSY & Z_2 symmetry
    - D) etc



- How different is MCDM from 1CDM?
- How can we detect MCDM?

Formulation

- Three types of annihilation processes



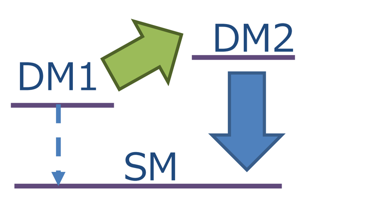
- Boltzmann equations

$$\dot{n}_i + 3Hn_i = -\Big[\langle\sigma|v|\rangle_{ii\to SM}(n_i^2 - \bar{n}_i^2) + \sum_j \langle\sigma|v|\rangle_{i\to j}(n_i^2 - \bar{n}_i^2\frac{n_j^2}{\bar{n}_j^2}) + \sum_{j,k}\langle\sigma|v|\rangle_{ij\to kSM}(n_i n_j - \bar{n}_i\bar{n}_j\frac{n_k}{\bar{n}_k}) - \sum_{j,k}\langle\sigma|v|\rangle_{jk\to iSM}(n_j n_k - \bar{n}_j n_k\frac{n_i}{\bar{n}_i})\Big]$$

standard annihilation, dark matter conversion, semi-annihilation

- Sample calculation (two dark matter)
  - fixed standard annihilation cross section
  - Relatively weak interacting DM1 and much interacting DM2.

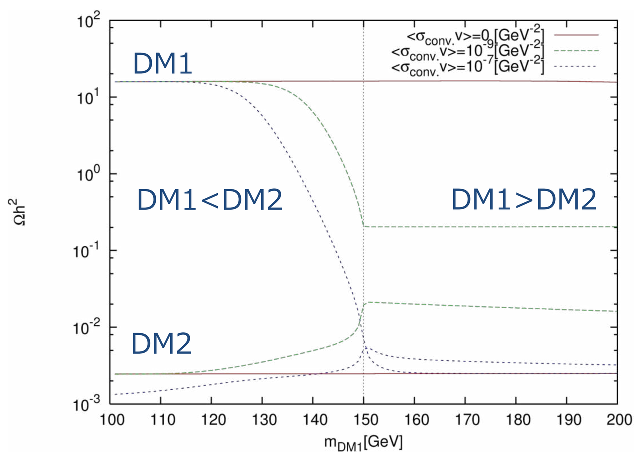
$100[\mathrm{GeV}] < m_1 < 200[\mathrm{GeV}]$, $\langle\sigma v\rangle_{1,1\to SM} = 10^{-11}[\mathrm{GeV}^{-2}]$,
$m_2 = 150[\mathrm{GeV}]$, $\langle\sigma v\rangle_{2,2\to SM} = 10^{-7}[\mathrm{GeV}^{-2}]$

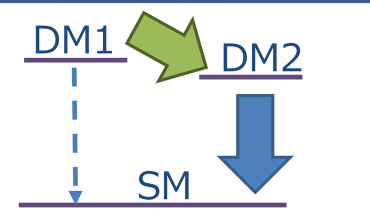


Conversion process is suppressed by Boltzmann factor.

$\sim exp(-2(m_2 - m_1)/T)$

Coupling related to DM conversion can be large. (Kubo's talk)





It is good approximation to assume that DM2 is in thermal equilibrium at the decoupling temperature of DM1.

$$\langle\sigma v\rangle_{\mathrm{TOTAL}} = \langle\sigma v\rangle_{11} + \langle\sigma v\rangle_{\mathrm{conv.}}$$
$$\frac{1}{\Omega h^2_{\tilde\chi}} \sim \frac{1}{\Omega h^2_{11}} + \frac{1}{\Omega h^2_{\mathrm{conv.}}}$$

Example 1: SUSY DM + Inert DM

- SUSY Ma model E.Ma,Annales Fond.Broglie 31, 285 (2006)
  - Superpotential

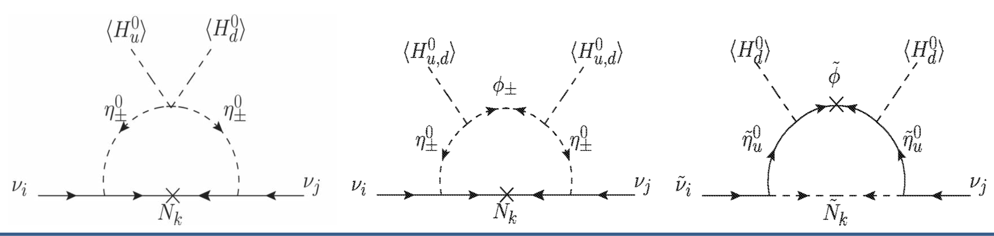
$$Y^u_{ij}\mathbf{Q}_i\mathbf{U}^c_j\mathbf{H}^u + Y^d_{ij}\mathbf{Q}_i\mathbf{D}^c_j\mathbf{H}^d + Y^e_{ij}\mathbf{L}_i\mathbf{E}^c_i\mathbf{H}^d - \mu_H\mathbf{H}^u\mathbf{H}^d + Y^\nu_{ik}\mathbf{L}_i\mathbf{N}^c_k\boldsymbol{\eta}^u + \lambda^u\boldsymbol{\eta}^u\mathbf{H}^d\boldsymbol{\phi} + \lambda^d\boldsymbol{\eta}^d\mathbf{H}^u\boldsymbol{\phi} + \mu_\eta\boldsymbol{\eta}^u\boldsymbol{\eta}^d + \frac{1}{2}(M_N)_k\mathbf{N}^c_k\mathbf{N}^c_k + \frac{1}{2}\mu_\phi\boldsymbol{\phi}\boldsymbol{\phi}$$

superfield	$SU(2)_L$	$U(1)_Y$	R	$\mathbb{Z}_2$
$\mathbf{N}^c_k$	1	0	−	−
$\boldsymbol{\eta}^u$	2	$+\frac{1}{2}$	+	−
$\boldsymbol{\eta}^d$	2	$-\frac{1}{2}$	+	−
$\boldsymbol{\phi}$	1	0	+	−

- Neutrino mass H. Fukuoka, J. Kubo and D. Suematsu, Phys. Lett. B 678 (2009) 401; D. Suematsu, T. Toma, Nucl. Phys. B847 (2011) 567
  one loop radiative seesaw

mass of $\mathbb{Z}_2$ odd particles: $\mathcal{O}(1)$TeV

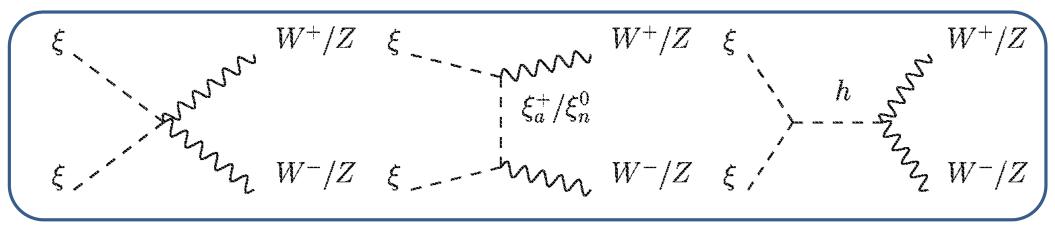
$\bar\lambda Y^\nu Y^\nu \sim 10^{-10}$ $(\bar\lambda \equiv \frac{\lambda^u\lambda^d}{\tan\beta + \cot\beta})$



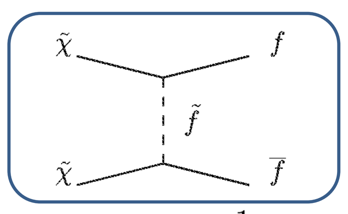
- Dark matter candidates Aoki, Mayumi et al. Phys.Lett. B707 (2012) 107-115

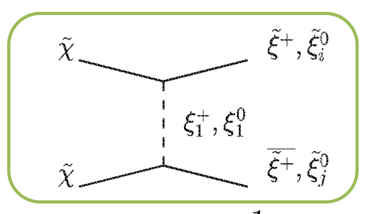
Inert Higgs ξ > Neutralino $\tilde\chi$ (Bino like) > Inert Higgsino $\tilde\xi$

- Inert Higgs (doublet like)
  SU(2) gauge interaction
  + DM conversion
  $m_\xi \sim \mathcal{O}(100)$GeV ⇒ $\Omega h^2_\xi \lesssim 10^{-2}$

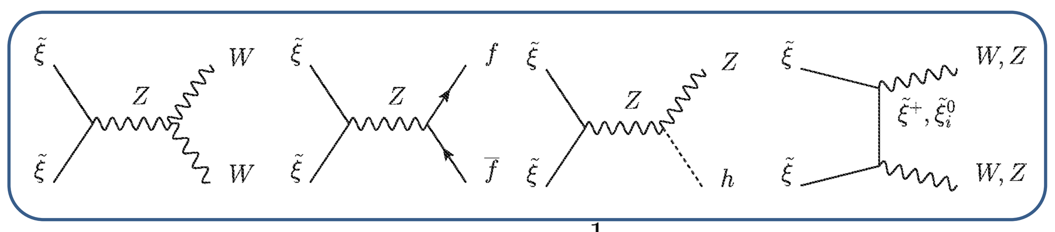


- Neutralino (Bino like)
  U(1) gauge interaction
  +DM conversion
  $\langle\sigma v\rangle_{\mathrm{TOTAL}} = \langle\sigma v\rangle_{\mathrm{MSSM}} + \langle\sigma v\rangle_{\mathrm{conv.}}$
  ⇒ $\frac{1}{\Omega h^2_{\tilde\chi}} \sim \frac{1}{\Omega h^2_{\mathrm{MSSM}}} + \frac{1}{\Omega h^2_{\mathrm{conv.}}}$

$\langle\sigma v\rangle_{\mathrm{MSSM}}$  $\Omega h^2_{\mathrm{MSSM}} \propto \frac{1}{\langle\sigma v\rangle_{\mathrm{MSSM}}}$

$\langle\sigma v\rangle_{\mathrm{conv.}}$  $\Omega h^2_{\mathrm{conv.}} \propto \frac{1}{\langle\sigma v\rangle_{\mathrm{conv.}}}$

- Inert Higgsino (doublet like)
  SU(2) gauge interaction
  $M_{\tilde\xi} \sim \mathcal{O}(100\mathrm{GeV})$ ⇒ $\Omega h^2_{\tilde\xi} \sim 10^{-3}$



$\Omega h^2_{\tilde\xi} \propto \frac{1}{\langle\sigma v\rangle_{\tilde\xi}}$

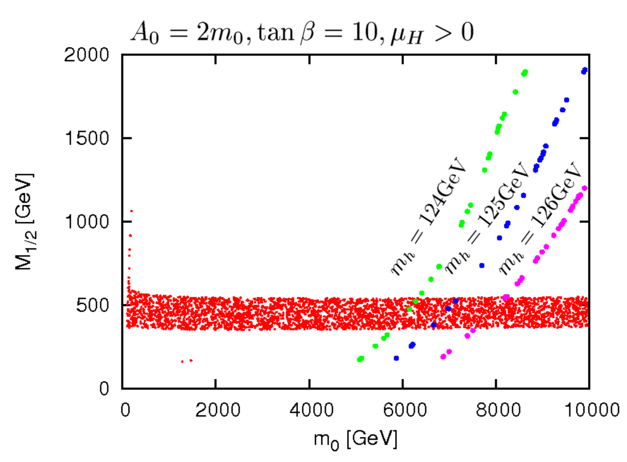
- SUSY Ma as a Modification of CMSSM

$m_0, M_{\frac{1}{2}}, A_0, \tan\beta, sign(\mu_H)$ | $\mu_\eta, \mu_\phi, M_N, B_\mu, B_\phi, B_N, (\lambda^u, \lambda^d, Y^\nu)$

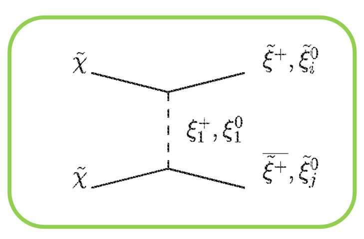
Neutralino relic density in CMSSM ⇒ Neutralino relic density in SUSYMa

$M_{\tilde\xi}, m_\xi$

- Relic density of the additional DM
- Extra annihilation channel
- $M_{\frac{1}{2}}^{SUSYMa} \sim 1.2 M_{\frac{1}{2}}^{MSSM}$

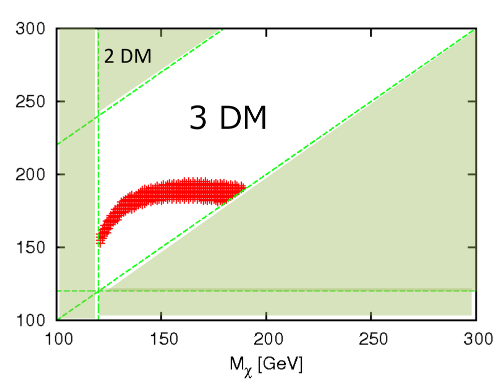


Neutralino	Inert higgsino	Inert higgs
$\tilde\chi \sim \tilde B$	$\tilde\xi \sim \frac{i}{\sqrt{2}}(\tilde\eta^u - \tilde\eta^d)$	$\xi \sim \frac{1}{\sqrt{2}}(\eta_R^{u0} - \eta_R^{d0})$
mass : $\sim 0.5 M_{\frac{1}{2}}$	$\sim \mu_\eta$	$\sim m_0^2 + \mu_\eta^2 + 0.4M^2_{1/2} - B_\eta$



$150\mathrm{GeV} \lesssim m_\xi \lesssim 200\mathrm{GeV}$

$$\frac{1}{\Omega h^2_{\mathrm{conv.}}} \gtrsim 2 \times \frac{1}{\Omega h^2_{\mathrm{MSSM}}}$$



DM conversion can relax the constraint on the CMSSM parameters from DM relic density.

Example 2: Inert DM + singlet DM

- Inert doublet (Ma model) + singlet fermion χ + singlet scalar ϕ
  - Lagrangian

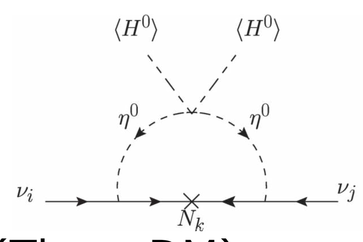
$$\mathcal{L}_Y = Y^e_{ij}H^\dagger L_i l^c_j + Y^\nu_{ik}L_i\epsilon\eta N^c_k + Y^\chi_k\chi N^c_k\phi + h.c.$$
$$V = m_1^2H^\dagger H + m_2^2\eta^\dagger\eta + \frac{1}{2}m_3^2\phi^2 + \frac{1}{2}\lambda_1(H^\dagger H)^2 + \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2 + \lambda_3(H^\dagger H)(\eta^\dagger\eta) + \lambda_4(H^\dagger\eta)(\eta^\dagger H) + \frac{1}{2}\lambda_5[(H^\dagger\eta)^2 + h.c.] + \frac{1}{4!}\lambda_6\phi^4 + \frac{1}{2}\lambda_7(H^\dagger H)\phi^2 + \frac{1}{2}\lambda_8(\eta^\dagger\eta)\phi^2$$

field	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$	$\mathbb{Z}'_2$
(η^+, η^0)	2	1/2	−	+
χ	1	0	−	−
ϕ	1	0	+	−

- Neutrino mass

$M_k, m_0 \sim \mathcal{O}(1)$TeV $\left(m_0 \equiv \frac{m_{\eta^0_R} + m_{\eta^0_I}}{2}\right)$

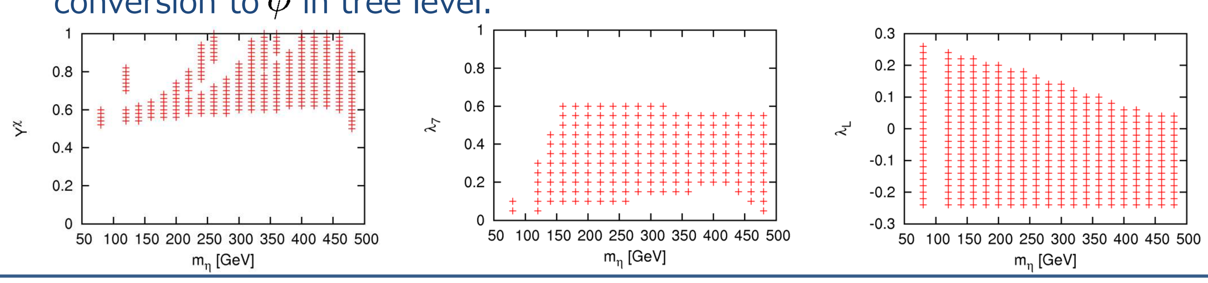
$Y^\nu_{ik}Y^\nu_{jk}\lambda_5 \sim 10^{-9}$



- Dark matter candidates (Three DM)
  Inert doublet η^0_R > singlet fermion χ > singlet scalar ϕ

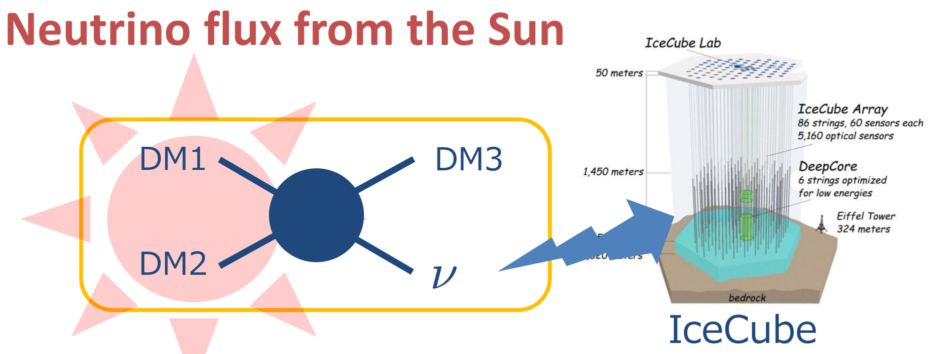
$M_k = 1$TeV
$m_{\eta^\pm}, m_{\eta^0_I} = m_{\eta^0_R} + 10$GeV
$m_{\eta^0_R} = [80, 500]$GeV
$m_\chi = m_{\eta^0_R} - 10$GeV
$m_\phi = m_{\eta^0_R} - 20$GeV
m_h = 125 GeV

χ can annihilate only via conversion to ϕ in tree level.



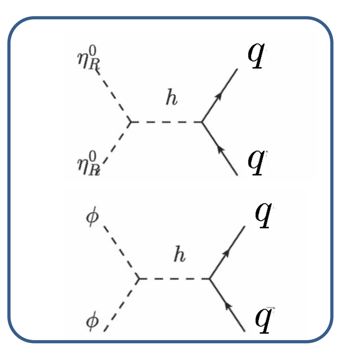
- Indirect detection

Neutrino flux from the Sun

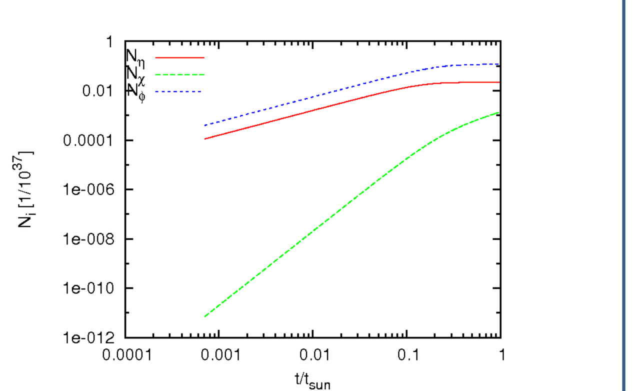


$\Gamma_{\mathrm{detect}} = AP(E_\nu)\Gamma_{\mathrm{inc}}$
Detector area $A \simeq 1\mathrm{km}^2$
Detection probability: $P(E_{\nu(\bar\nu)}) \simeq 2.0(1.0) \times 10^{-11}(\frac{L}{\mathrm{km}})(\frac{E_{\nu(\bar\nu)}}{\mathrm{GeV}})$
Incoming flux $\Gamma_{\mathrm{inc}} = \Gamma/4\pi R_\odot^2$ $(L \sim 1\mathrm{km})$

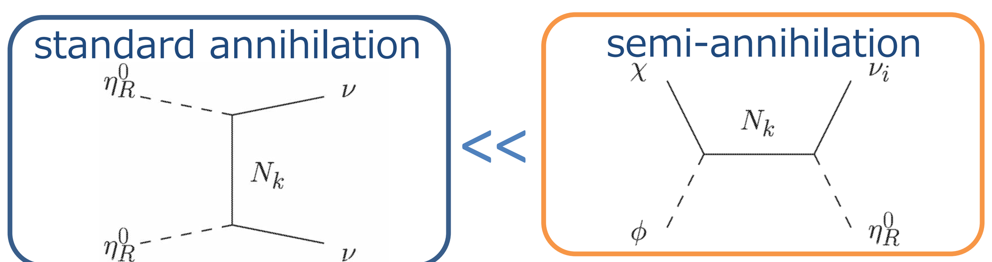
Capture rate in the Sun



$$\dot{N}_i = C_i - C_A(ii \leftrightarrow \mathrm{SM})N_i^2 - C_A(ii \leftrightarrow jj)N_i^2 - C_A(ij \leftrightarrow k\mathrm{SM})N_iN_j$$
$$C_A(ij \leftrightarrow \bullet) = \frac{<\sigma(ij;\bullet)v>}{V_{ij}}, \quad V_{ij} = 5.7 \times 10^{27}\left(\frac{100\ \mathrm{GeV}}{\mu_{ij}}\right)^{3/2}\mathrm{cm}^3$$

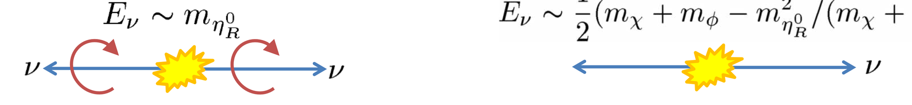


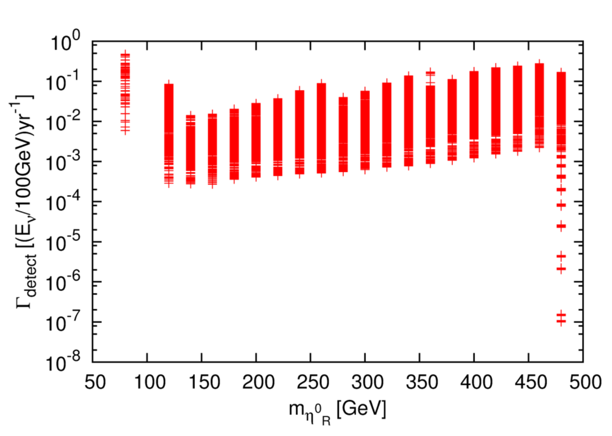
- detection rate for Monochromatic neutrino



$E_\nu \sim m_{\eta^0_R}$ $E_\nu \sim \frac{1}{2}(m_\chi + m_\phi - m^2_{\eta^0_R}/(m_\chi + m_\phi))$

Helicity suppression





Conclusion

1. Multicomponent DM can be realized when the symmetry larger than Z_2 exists.
2. Multicomponent dark matter annihilation processes are classified into three types.
3. Non-standard annihilation can affects to the DM relic density considerably.
4. The semi-annihilation characterize the multicomponent DM system. If semi-annihilation produce nomochromatic neutrino, it can be detected by indirect search experiments earlier than standard annihilation effect.