Multi-component Dark Matter Systems and Their Observation Prospects

Hiroshi Takano
Institute for Theoretical Physics, Kanazawa University, Kanazawa 920-1192, Japan

Multi-component dark matter system is studied in models with an exact $Z_2 \times Z_2'$ symmetry. We discuss the general formulation of the time dependences of dark matter density. A supersymmetric version and a simple extension of radiative seesaw model are introduced as the concrete models of the multi-component dark matter. In the former model, we discuss the effects of non-standard annihilation process on the relic density of the supersymmetric dark matter. The indirect detection possibility of the monochromatic neutrino from the sun is discussed in the latter model.

I. INTRODUCTION

The existence of dark matter is almost certain from various cosmological observations. As a dark matter candidate which can be experimentally observable in near future, the weak interacting massive particle (WIMP) have been studied very well in various extensions of the standard model (SM). The relic density of dark matter in the universe is precisely obtained by WMAP [1] and Planck [2] observation. However, it is unknown whether the dark matter is single-component or multi-component. As a more general possibility of dark matter physics, we study the non-trivial phenomenology of the multi-component dark matter systems. The non-standard annihilation process of the dark matter particles can affect their relic densities and their detection probabilities. The current experimental constraints on the interaction between the dark matter and the SM particles are determined in the single-component scenario. When we consider the multi-component scenario, we need to translate the constraints to those of the multi-component scenario.

The simplest possibility of the symmetry stabilizing dark matter is an exact Z_2 symmetry. There are various origins of Z_2 symmetry. For example, the R parity in the supersymmetric models is introduced to forbid the fast proton decay, and the Z_2 symmetry in the radiative seesaw model is introduced to forbid the tree level neutrino masses. If we assume that several Z_2 symmetries exist in the extended model of the SM, the model can be the multi-component dark matter model.

This talk is based on the works [3, 4]. In the Sec. II, we introduce the general formulation of time dependence of dark matter density in the model with the exact $Z_2 \times Z_2'$ symmetry, and estimate the effects of non-standard annihilation process. In the Sec. III, we introduce two concrete models of the multi-component dark matter. We study the supersymmetric radiative seesaw model and estimate the impact of presence of additional dark matters for the Constrained Minimal Supersymmetric Standard Model (CMSSM). The possibility of the indirect detection of the multi-component dark matter via the non-standard dark matter annihilation process is discussed in the simple extension of the radiative seesaw model to the multi-component scenario.

II. GENERAL FORMULATION

We consider the model having exact $Z_2 \times Z_2'$ symmetry as an example of the multi-component dark matter system. In this symmetry, Z_2's are conserved individually and there are three candidates of dark matter. The lightest two particles of different Z_2 parity are stable at a time but the heaviest candidate can decay to two lighter dark matters in general. If the heaviest candidate is enough light to forbid its decay kinematically, there can exist three components of dark matter.

Because the energy density of dark matter is the product of the mass and the number density, the number densities of the multi-component dark matter cannot be summed up. The Boltzmann equations which describe the number densities n_i of the dark matter i can be written as

$$\dot{n}_i + 3Hn_i = -\mathrm{C}[n_i, n_j, \cdots] \ , \tag{1}$$

where H is the Hubble parameter and $\mathrm{C}[n_i, n_j, \cdots]$ is the collision term. The collision processes can be classified into three types[5–7],

$$\begin{aligned}
&\mathrm{DM}_i\ \mathrm{DM}_i \ \leftrightarrow\ \mathrm{SM\ SM} && \text{(Standard annihilation)}\ , && (2)\\
&\mathrm{DM}_i\ \mathrm{DM}_i \ \leftrightarrow\ \mathrm{DM}_j\ \mathrm{DM}_j && \text{(Dark matter conversion)}\ , && (3)\\
&\mathrm{DM}_i\ \mathrm{DM}_j \ \leftrightarrow\ \mathrm{SM\ DM}_k && \text{(Semi-annihilation)}\ . && (4)
\end{aligned}$$

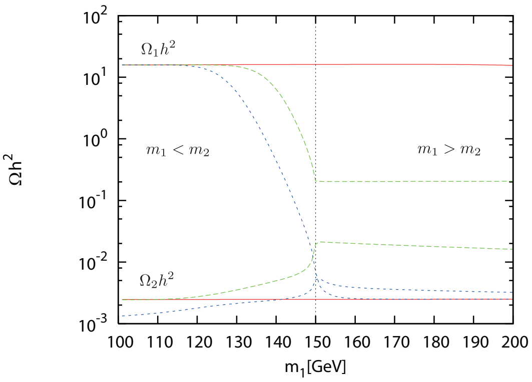

FIG. 1: The relic density of DM1 and DM2 with $m_2 = 150$ GeV, $\langle\sigma|v|\rangle_{11\to\mathrm{SM}} = 10^{-11}\mathrm{GeV}^{-2}$ and $\langle\sigma|v|\rangle_{22\to\mathrm{SM}} = 10^{-7}\mathrm{GeV}^{-2}$.

The standard annihilation depends on the density of dark matter only. Because we assume SM particles are in thermal equilibrium while dark matter decoupling, their number density can be obtained analytically. The collision term of the standard annihilation is approximately written as

$$\langle\sigma|v|\rangle_{ii\to\mathrm{SM}}(n_i^2 - \bar{n}_i^2) \ , \tag{5}$$

where $\langle\sigma|v|\rangle_{ii\to\mathrm{SM}}$ is the thermal averaged cross section and $\bar{n}_i$ is the thermal number density of dark matter i. The process of dark matter conversion is similar to that of the standard annihilation. The final states of the conversion are the pair of the other dark matter particles j which is not in thermal equilibrium during the decoupling of the dark matter i in general. This process depends on the two dark matter densities and the collision term can be written as

$$\sum_j \langle\sigma|v|\rangle_{i\to j}(n_i^2 - \bar{n}_i^2\frac{n_j^2}{\bar{n}_j^2}) = -\sum_j \langle\sigma|v|\rangle_{j\to i}(n_j^2 - \bar{n}_j^2\frac{n_i^2}{\bar{n}_i^2}) \ , \tag{6}$$

where we used the relation $\langle\sigma|v|\rangle_{i\to j} = \frac{\bar{n}_j^2}{\bar{n}_i^2}\langle\sigma|v|\rangle_{j\to i}$. The semi-annihilation is allowed in the case of the three component dark matter. The collision term of i is given by

$$\sum_{j,k} \langle\sigma|v|\rangle_{ij\to k\mathrm{SM}}(n_i n_j - \bar{n}_i\bar{n}_j\frac{n_k}{\bar{n}_k}) - \sum_{j,k} \langle\sigma|v|\rangle_{jk\to i\mathrm{SM}}(n_j n_k - \bar{n}_j\bar{n}_k\frac{n_i}{\bar{n}_i}) \ , \tag{7}$$

where i, j and k are different species of dark matter. Because this process is the additional possibility of production of the SM particles, it can be important for the indirect dark matter detection. Then, the Boltzmann equations of the multi-component dark matter system can be written as

$$\begin{aligned} \dot{n}_i + 3Hn_i \ &= \ -\Big[\langle\sigma|v|\rangle_{ii\to\mathrm{SM}}(n_i^2 - \bar{n}_i^2) + \sum_j \langle\sigma|v|\rangle_{i\to j}(n_i^2 - \bar{n}_i^2\frac{n_j^2}{\bar{n}_j^2}) \\ &\quad + \sum_{j,k} \langle\sigma|v|\rangle_{ij\to k\mathrm{SM}}(n_i n_j - \bar{n}_i\bar{n}_j\frac{n_k}{\bar{n}_k}) - \sum_{j,k} \langle\sigma|v|\rangle_{jk\to i\mathrm{SM}}(n_j n_k - \bar{n}_j\bar{n}_k\frac{n_i}{\bar{n}_i})\Big] \ . \end{aligned} \tag{8}$$

The non-standard annihilation process can affect the relic densities of dark matters. To see the effect of the dark matter conversion, we consider a two component dark matter DM1 and DM2. The dark matter conversion will be particularly important when the difference of the cross sections for the standard annihilation between DM1 and DM2 is large. If the standard annihilation cross section of DM1 is very small and one of DM2 is large, the relic density of DM1 become very large in the absence of conversion process. If the dark matter conversion of DM1 to DM2 exists, total relic density can be more small. Fig. 1 shows the relation of mass difference of dark matter and relic densities $\Omega_i h^2$. In this calculation we fixed to be $m_2 = 150$GeV, $\langle\sigma|v|\rangle_{11\to\mathrm{SM}} = 10^{-11}\mathrm{GeV}^{-2}$ and $\langle\sigma|v|\rangle_{22\to\mathrm{SM}} = 10^{-7}\mathrm{GeV}^{-2}$. The conversion cross section of heavier dark matter to lighter one is $\langle\sigma|v|\rangle_{\mathrm{conv.}} = 0$ (red/solid lines), $10^{-9}\mathrm{GeV}^{-2}$ (green/dashed lines), and $10^{-7}\mathrm{GeV}^{-2}$ (blue/dotted line). Because the dark matter particles are non-relativistic, the conversion process from the

TABLE I: The field contents and the quantum number. $R \times Z_2$ is the unbroken discrete symmetry. The quarks of the MSSM are suppressed in the Table.

superfield	$\mathbf{L}$	$\mathbf{E}^C$	$\mathbf{N}^C$	$\mathbf{H}^u$	$\mathbf{H}^d$	$\boldsymbol{\eta}^u$	$\boldsymbol{\eta}^d$	$\boldsymbol{\phi}$
$SU(2)_L$	**2**	**1**	**1**	**2**	**2**	**2**	**2**	**1**
$U(1)_Y$	$-1/2$	1	0	$1/2$	$-1/2$	$1/2$	$-1/2$	0
$R \times Z_2$	$(-,+)$	$(-,+)$	$(-,-)$	$(+,+)$	$(+,+)$	$(+,-)$	$(+,-)$	$(+,-)$

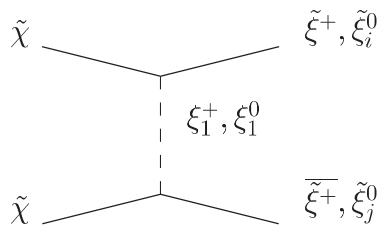

FIG. 2: Conversion process.

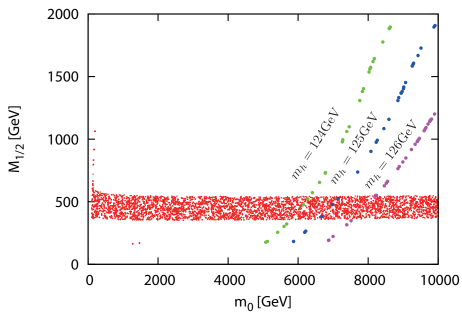

FIG. 3: The allowed region in the m_0-$M_{1/2}$ plane with a set of the CMSSM parameter $A_0 = 2m_0$, $\tan\beta = 10$, $\mu_H > 0$.

lighter particles to the heavier particles is suppressed by Boltzmann factor. In this case, the interaction of DM1 and SM is too small to explain the WMAP data [1]. So we expect that the conversion process of DM1 to DM2 reduce the density of DM1. If DM1 is heavier than DM2 (in the right side of Fig. 1), it is good approximation to assume that DM2 is in thermal equilibrium during the decoupling of DM1. Then, the collision term of DM1 can be written as

$$\begin{aligned} & -\Big[\langle\sigma|v|\rangle_{11\to\mathrm{SM}}(n_1^2-\bar{n}_1^2)+\langle\sigma|v|\rangle_{11\to 22}(n_1^2-\bar{n}_1^2\frac{n_2^2}{\bar{n}_2^2})\Big] \\ \simeq\ & -\Big[\big(\langle\sigma|v|\rangle_{11\to\mathrm{SM}}+\langle\sigma|v|\rangle_{11\to 22}\big)(n_1^2-\bar{n}_1^2)\Big]\ . \end{aligned} \tag{9}$$

There is no suppression and the relic density of DM1 can be small easily. If DM1 is lighter than DM2 (in the left side of Fig. 1), the dark matter conversion is suppressed by the Boltzmann factor $\exp(-2(m_1-m_2)/T)$. To reduce the relic density of DM1, we need the larger conversion cross section or the smaller mass difference.

III. CONCRETE MODELS

We introduce two concrete models of the multi-component dark matter system. Here, the radiative seesaw model of [8], which have an exact Z_2 symmetry and generate the neutrino masses from the one loop level radiative correction, is extended to the models which have an additional Z_2 symmetry.

A. supersymmetric radiative seesaw model

In the CMSSM, the R-odd dark matter is Bino-like neutralino in the wide region of parameter space. Typically, the cross section of the standard annihilation of Bino is too small to obtain the correct relic density. Also it can be enlarged by the mixing of Wino and Higgsino or the co-annihilation process, the allowed parameter region for the correct dark matter density is restricted to only a narrow area [9]. We can relax this situation in the supersymmetric radiative seesaw model [10], which is a multi-component dark matter extension of CMSSM [3].

The field contents of the supersymmetric radiative seesaw model is given in Table I. The superpotential of the model is follows.

$$\begin{aligned} W\ =\ & Y_{ij}^u\mathbf{Q}_i\mathbf{U}_j^c\mathbf{H}^u+Y_{ij}^d\mathbf{Q}_i\mathbf{D}_j^c\mathbf{H}^d+Y_i^e\mathbf{L}_i\mathbf{E}_i^c\mathbf{H}^d-\mu_H\mathbf{H}^u\mathbf{H}^d \\ & +Y_{ik}^\nu\mathbf{L}_i\mathbf{N}_k^c\boldsymbol{\eta}^u+\lambda^u\boldsymbol{\eta}^u\mathbf{H}^d\boldsymbol{\phi}+\lambda^d\boldsymbol{\eta}^d\mathbf{H}^u\boldsymbol{\phi}+\mu_\eta\boldsymbol{\eta}^u\boldsymbol{\eta}^d+\frac{1}{2}(M_N)_k\mathbf{N}_k^c\mathbf{N}_k^c+\frac{1}{2}\mu_\phi\boldsymbol{\phi}\boldsymbol{\phi}\ , \end{aligned} \tag{10}$$

TABLE II: The field contents of the model and the corresponding quantum numbers. $Z_2 \times Z_2'$ is the unbroken discrete symmetry. The quarks are suppressed in the Table.

field	L_i	l_i^c	N_i^c	H	η	χ	ϕ
$SU(2)_L$	**2**	**1**	**1**	**2**	**2**	**1**	**1**
$U(1)_Y$	$-1/2$	1	0	1/2	1/2	0	0
$Z_2 \times Z_2'$	$(+,+)$	$(+,+)$	$(-,+)$	$(+,+)$	$(-,+)$	$(+,-)$	$(-,-)$

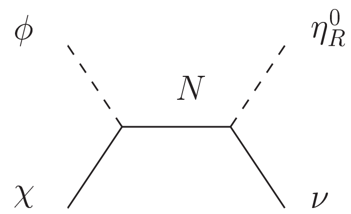

FIG. 4: The semi-annihilation process.

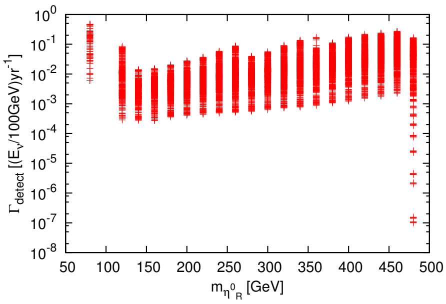

FIG. 5: The detection rate for the monochromatic neutrino from the sun.

where $\mathbf{L}$, $\mathbf{H}^u$,$\mathbf{H}^d$ and $\boldsymbol{\eta}^u$, $\boldsymbol{\eta}^d$ are $SU(2)_L$ doublets of the leptons, the MSSM higgses, and the inert doublets respectively. The quark fields are $\mathbf{Q}$, $\mathbf{U}^c$ and $\mathbf{D}^c$. The right handed fields of charged leptons and neutrinos are $\mathbf{E}^C$ and $\mathbf{N}^C$. $\boldsymbol{\phi}$ is an additional inert singlet field which is needed to generate the neutrino masses radiatively.

There are R-parity of supersymmetry and Z_2 symmetry for the radiative seesaw mechanism which stabilize dark matter. In this model, we can consider three types of $R \times Z_2$ parity odd dark matter candidates. We choose the lightest particles of each parity, Bino-like neutralino $\tilde{\chi} \sim \tilde{B}$ for $(R, Z_2) = (-,+)$, doublet-like inert higgsino $\tilde{\xi}^0 \sim (\tilde{\eta}^{u0} - \tilde{\eta}^{d0})/\sqrt{2}$ for $(-,-)$, and doublet-like inert higgs $\xi_R^0 \sim (\eta_R^{u0} - \eta_R^{d0})/\sqrt{2}$ for $(+,-)$. The standard annihilation cross section of the pure Bino is too small while that of $SU(2)$ doublet dark matter is too large [11, 12] to explain the dark matter relic density in the consideration region. As shown in Sec. II, it can be considered that the conversion of the Bino to the other dark matter particles reduce the relic density. If we choose the mass hierarchy of dark matter candidates,

$$M_{\tilde{\xi}^0}, M_{\tilde{\xi}^+} < M_{\tilde{\chi}} < m_{\xi^0_{R,I}}, m_{\xi^+} \ , \tag{11}$$

then the conversion process of the neutralino to the inert higgsino (Fig. 2), which is determined only by their masses, is not suppressed.

Here, the relic density of dark matter in this model is calculated with $M_{\tilde{\xi}^0} = 120$ GeV. Fig. 3 shows the allowed region (red dots) of $\Omega_\chi h^2 = 0.1126 \pm 0.0036$ [1] with the parameter $A_0 = 2m_0$, $\tan\beta = 10$, $\mu_H > 0$. We have used the approximation of Eq. (9) for the annihilation process of the neutralino. The allowed region is expanded to the wide region from the CMSSM by the effect of the conversion process of the neutralino. The relic density of $\tilde{\xi}^0$ and ξ^0 are $\lesssim 10^{-2}$, and the density of the neutralino is dominant. Because the neutralino mass is approximately written by $M_{\tilde{\chi}} \sim 0.5 M_{1/2}$, the conversion cross section is not sensitive to m_0. So the conversion cross section depends on only $M_{1/2}$, and the allowed region is expanded to the horizontal wide region.

B. radiative seesaw model + additional 2 DM's

As another concrete model, we discuss the simple extension of the radiative seesaw model [8] with the additional dark matter particles. In this model, we introduce a gauge singlet real scalar ϕ and a gauge singlet Majorana fermion χ and impose the additional Z_2' symmetry by hand (Table II). The $Z_2 \times Z_2'$ invariant Yukawa couplings of the lepton sector are given by

$$\mathcal{L}_Y = Y_{ij}^e H^\dagger L_i l_j^C + Y_{ik}^\nu L_i \epsilon \eta N_k^C + Y_k^\chi \chi N_k^C \phi + h.c. \ , \tag{12}$$

and Majorana mass term of the right handed neutrino and the singlet fermion χ are

$$\mathcal{L}_{\rm Maj} = \frac{1}{2} M_k N_k^C N_k^C + \frac{1}{2} M_\chi \chi^2 + h.c. \ . \tag{13}$$

The scalar potential is

$$\begin{aligned} V &= m_1^2 H^\dagger H + m_2^2 \eta^\dagger \eta + \frac{1}{2} m_3^2 \phi^2 + \frac{1}{2}\lambda_1 (H^\dagger H)^2 + \frac{1}{2}\lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) \\ &+ \frac{1}{2}\lambda_5 [(H^\dagger \eta)^2 + h.c.] + \frac{1}{4!}\lambda_6 \phi^4 + \frac{1}{2}\lambda_7 (H^\dagger H)\phi^2 + \frac{1}{2}\lambda_8 (\eta^\dagger \eta)\phi^2 \ . \end{aligned} \tag{14}$$

As a possibility of the indirect detection, we consider the monochromatic neutrino from the sun in this model. The dark matter candidates are the right handed neutrino N_k^C, the inert doublet η^0, the singlet fermion χ, and the singlet scalar ϕ. χ and ϕ can not annihilate into the neutrino pair at tree level. The monochromatic neutrino can be produced via the standard annihilation of N_k^C or η^0. N_k^C annihilation depends on the Yukawa coupling Y^ν_{ik}, which is constrained to be very small by the neutrino mass and lepton flavor violation $\mu \to e\gamma$. So this annihilation cross section can not be large enough to detect the produced neutrino. η^0 annihilation depends on the $SU(2)$ gauge interaction. But the neutrino anti-neutrino pair production is helicity suppressed. So the monochromatic neutrino production from the standard annihilation is small in this model.

To consider the possibility of semi-annihilation, we choose three component dark matter condition. We assume that dark matter particles are η^0, χ and ϕ. The monochromatic neutrino can be produced by the semi-annihilation diagram (Fig. 4). There are three channels of annihilation and the energy of the produced neutrino is $E_\nu \sim \frac{1}{2}(m_i + m_j - \frac{m_k^2}{(m_i+m_j)})$ for the channel of $ij \to k\nu$. Since the Yukawa coupling Y_k^χ is not constrained, this cross section can be relatively large.

Generally the time dependence of the number of dark matter N_i in the sun can be written as

$$\begin{aligned} \dot{N}_i &= C_i - C_A(ii \to {\rm SM}) N_i^2 - \sum_{m_i > m_j} C_A(ii \to jj) N_i^2 \\ &- [C_A(ij \to k\nu) N_i N_j - C_A(jk \to i\nu) N_j N_k] \ , \end{aligned} \tag{15}$$

where C_i is the capture rate in the sun and C_A's are the annihilation rate in the sun obtained by

$$C_A(ij \to \bullet) = \frac{\langle \sigma(ij \to \bullet)|v| \rangle}{V_{ij}} \ , \ V_{ij} = 5.7 \times 10^{27} \left(\frac{100{\rm GeV}}{\mu_{ij}} \right)^{3/2} {\rm cm}^3 \ . \tag{16}$$

Here V_{ij} is an effective volume of the sun with $\mu_{ij} = 2m_i m_j/(m_i + m_j)$ in non-relativistic limit. The neutrino production rate in the sun is given by

$$\begin{aligned} \Gamma(\nu\nu) &= C_A(\eta\eta \to \nu\nu) N_\eta^2/2 \ , \\ \Gamma(\nu) &= C_A(\eta\phi \to \chi\nu) N_\eta N_\phi + C_A(\eta\chi \to \phi\nu) N_\eta N_\chi + C_A(\chi\phi \to \eta\nu) N_\chi N_\phi \ . \end{aligned} \tag{17}$$

As for the monochromatic neutrino detection rate, we use [13]

$$\Gamma_{\rm detect} = A P(E_\nu) \Gamma_{\rm inc} \ , \tag{18}$$

where $A \sim 1{\rm km}^2$ is the IceCube detector area facing the incident beam, $P(E_\nu) \sim 10^{-11}(L/{\rm km})(E_\nu/{\rm GeV})$ is the possibility for detection as a function of the neutrino energy E_ν (L is the depth of the detector), and $\Gamma_{\rm inc} \sim \Gamma/4\pi R_\odot^2$ is the incoming neutrino flux ($R_\odot$ is the distance to the sun).

Fig. 5 shows the the detection rate of the monochromatic neutrino from the semi-annihilation in the sun for the IceCube experiment [13]. We obtain up to $\mathcal{O}(10^{-1})$ events per year in this model. In this estimation, we have used following mass condition

$$\begin{aligned} & M_k = 1 \ {\rm TeV} \ , \ 80 \ {\rm GeV} \le m_{\eta_R^0} \le 500 \ {\rm GeV} \ , \ m_{\eta_I^0} = m_{\eta^\pm} = m_{\eta_R^0} + 10 \ {\rm GeV} \ , \\ & m_\chi = m_{\eta_R^0} - 10 \ {\rm GeV} \ , \ m_\phi = m_{\eta_R^0} - 20 \ {\rm GeV} \ , \end{aligned} \tag{19}$$

and couplings which consistent with neutrino oscillation data, WMAP data [1], constraints of collider experiments and XENON100 [14] . In this model, the monochromatic neutrino from the standard annihilation of inert higgs can not be large because of the helicity suppression. However, there is no suppression mechanism for the monochromatic neutrino from the semi-annihilation in general. So we expect that the monochromatic neutrino will be the hint of the multi-component dark matter.

IV. CONCLUSION

We have considered the dark matter conversion and the semi-annihilation of dark matter in the multi-component dark matter system in the $Z_2 \times Z_2'$ models. These non-standard annihilation processes can affect their relic density considerably. We discussed two concrete models. In the supersymmetric radiative seesaw model, we can consider the multi-component dark matter of neutralino, inert higgs and inert higgsino. The dark matter conversion of the neutralino can affect to the relic density. This effect would expand the allowed region for the relic density of dark matter in the m_0-$M_{1/2}$ plane considerably. In the simple extension of the radiative seesaw model, we introduced the additional dark matter particles, the singlet fermion and singlet scalar. Due to the semi-annihilation processes, the monochromatic neutrinos are radiated. We estimated the observation rates of the monochromatic neutrinos. Observations of high-energy monochromatic neutrinos from the sun may indicate a multi-component dark matter system.

[1] E. Komatsu *et al.* [WMAP Collaboration], "Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation," Astrophys. J. Suppl. **192** (2011) 18 [arXiv:1001.4538 [astro-ph.CO]].

[2] P. A. R. Ade *et al.* [Planck Collaboration], "Planck 2013 results. XVI. Cosmological parameters," arXiv:1303.5076 [astro-ph.CO].

[3] M. Aoki, J. Kubo, T. Okawa and H. Takano, "Impact of Inert Higgsino Dark Matter," Phys. Lett. B **707** (2012) 107 [arXiv:1110.5403 [hep-ph]].

[4] M. Aoki, M. Duerr, J. Kubo and H. Takano, "Multi-Component Dark Matter Systems and Their Observation Prospects," Phys. Rev. D **86** (2012) 076015 [arXiv:1207.3318 [hep-ph]].

[5] F. D'Eramo and J. Thaler, "Semi-annihilation of Dark Matter," JHEP **1006** (2010) 109 [arXiv:1003.5912 [hep-ph]].

[6] G. Belanger and J.-C. Park, "Assisted freeze-out," JCAP **1203** (2012) 038 [arXiv:1112.4491 [hep-ph]].

[7] G. Belanger, K. Kannike, A. Pukhov and M. Raidal, "Impact of semi-annihilations on dark matter phenomenology - an example of Z_N symmetric scalar dark matter," JCAP **1204** (2012) 010 [arXiv:1202.2962 [hep-ph]].

[8] E. Ma, "Verifiable radiative seesaw mechanism of neutrino mass and dark matter," Phys. Rev. D **73** (2006) 077301 [arXiv:hep-ph/0601225].

[9] J. Ellis and K. A. Olive, "Revisiting the Higgs Mass and Dark Matter in the CMSSM," Eur. Phys. J. C **72** (2012) 2005 [arXiv:1202.3262 [hep-ph]].

[10] E. Ma, "Supersymmetric Model of Radiative Seesaw Majorana Neutrino Masses," Annales Fond. Broglie **31** (2006) 285 [arXiv:hep-ph/0607142].

[11] L. Lopez Honorez, E. Nezri, J. F. Oliver and M. H. G. Tytgat, "The Inert Doublet Model: An Archetype for Dark Matter," JCAP **0702** (2007) 028 [arXiv:hep-ph/0612275].

[12] E. M. Dolle and S. Su, "The Inert Dark Matter," Phys. Rev. D **80** (2009) 055012 [arXiv:0906.1609 [hep-ph]].

[13] F. Halzen and S. R. Klein, "IceCube: An Instrument for Neutrino Astronomy," Rev. Sci. Instrum. **81** (2010) 081101 [arXiv:1007.1247 [astro-ph.HE]].

[14] E. Aprile *et al.* [XENON100 Collaboration], "Dark Matter Results from 100 Live Days of XENON100 Data," Phys. Rev. Lett. **107** (2011) 131302 [arXiv:1104.2549 [astro-ph.CO]].