Impact of Semi-annihilation of Dark Matter with Radiative Neutrino Masses

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Invisibles 14 Workshop
Paris, France, 14-18 Jul. 2014

Based on M. Aoki and T. T., arXiv:1405.5870

Outline

- Introduction
  - Neutrino mass generation mechanisms and DM
- $\mathbb{Z}_3$ Symmetric Model with Radiative Neutrino Masses
  - Dirac Fermion and Complex Scalar Dark Matter
  - Relic Density of $\mathbb{Z}_3$ Dark Matter
  - Signatures of $\mathbb{Z}_3$ Dark Matter
- Summary

Introduction

Neutrino mass differences are confirmed by the neutrino oscillations.

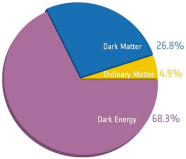
- $\Delta m^2_{\rm atm} \approx 2.5 \times 10^{-3}$ $[{\rm eV}^2]$, $\Delta m^2_{\rm sol} \approx 7.5 \times 10^{-5}$ $[{\rm eV}^2]$
- Mixing angles of the PMNS matrix
  $\sin^2\theta_{12} \approx 0.30$, $\sin^2\theta_{23} \approx 0.41$, $\sin^2\theta_{13} \approx 0.023$.

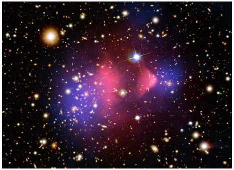
Theoretically neutrinos should be massive.

There are many experimental evidences of DM.

- Rotation curves of spiral galaxy
- CMB observations
- Gravitational lensing
- Large scale structure of the universe

Existence of DM is crucial.





Neutrino Mass Generation

- Seesaw mechanism (Type I, Type II, Type III...)
  In Type I seesaw, superheavy right-handed neutrinos N_R are introduced.

$$\begin{aligned}\mathcal{L} &= -\phi^\dagger \overline{\ell_L} y_\nu N_R - \frac{1}{2}\overline{N_R^c} M N_R + \mathrm{h.c.} \\ &\to -\overline{\nu_L} m_D N_R - \frac{1}{2}\overline{N_R^c} M N_R + \mathrm{h.c.} \qquad m_D = y_\nu \langle\phi\rangle\end{aligned}$$

  Mass matrix

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \quad \to \quad \begin{array}{l} m_\nu = -m_D M^{-1} m_D^T + \cdots \\ (\text{if } m_D \ll M) \end{array}$$

  Typical scale
  · If Yukawa coupling is $\mathcal{O}(1)$, $m_D \sim 100$ GeV and $M \sim 10^{14}$ GeV.
  Super heavy $N_R \to$ light neutrino masses.

- Inverse seesaw mechanism
  Small lepton number violation ($\not{L}$) $\rightarrow$ small neutrino masses.
  Singlets S_L are introduced.

$$\mathcal{L} = -\overline{\nu_L} m_D N_R - \overline{N_R^c} M S_L^c - \frac{1}{2}\overline{S_L}\mu S_L^c$$

Mass matrix

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix} \quad \rightarrow \quad \begin{array}{l} m_\nu \sim m_D M^{-1} \mu {M^T}^{-1} m_D^T \\ (\text{if } \mu \ll m_D,\ M) \end{array}$$

Typical scale of μ is keV.
$M \sim 10$ TeV, $m_D \sim 100$ GeV $\rightarrow m_\nu \sim 0.1$ eV.

Note : generally $\frac{1}{2}\overline{N_R}\mu' N_R$ also exists.

- Radiative neutrino mass generation

  · forbid Dirac mass term

  Type I seesaw

$$\begin{pmatrix} \text{loop} & 0 \\ 0 & M \end{pmatrix} \quad \rightarrow \quad m_\nu \sim -\frac{1}{(4\pi)^2} m_D M^{-1} m_D^T$$

  Inverse seesaw

$$\begin{pmatrix} \text{loop} & 0 & 0 \\ 0 & 0 & M \\ 0 & M^T & \mu \end{pmatrix} \quad \rightarrow \quad m_\nu \sim \frac{1}{(4\pi)^2} m_D M^{-1} \mu M^{T-1} m_D^T$$

  where $m_D \sim y_\nu \langle \phi \rangle$

- Features

  · Smallness of neutrino masses is natural.

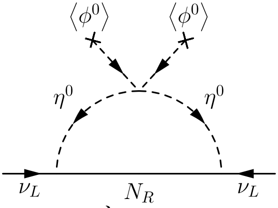
  · Existence of DM is correlated with neutrino mass generation.

Examples of Models with DM

- Ma model (2006)

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
N_i	**1**	0	-1
η	**2**	$1/2$	-1

· Neutrino mass (1-loop level)
· DM candidates (N_1 or η^0)

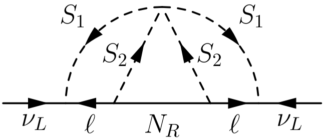


$$\mathcal{V} = \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2$$

- Krauss-Nasri-Trodden model (2002)

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
S_1^+	**1**	1	$+1$
S_2^+	**1**	1	-1
N_i	**1**	0	-1

· Neutrino mass (3-loop level)
· DM candidate (N_1)



$$\mathcal{V} = \lambda_s\left(S_1^+S_2^-\right)^2$$

$\mathbb{Z}_3$ Symmetric Model with Radiative Neutrino Masses

The Model

- In the most of radiative models, $\mathbb{Z}_2$ symmetry is imposed. $\rightarrow$ The simplest way to forbid Dirac neutrino mass term and stabilize DM.
- A different symmetry may lead a different DM physics. $\rightarrow$ $\mathbb{Z}_3$ symmetry

New particles:

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_3$	L number
ψ_i	**1**	0	1	$+1/3$
η	**2**	$1/2$	1	$-2/3$
χ	**1**	0	1	$-2/3$

- At least two fermion ψ are required.
- Lepton number is softly broken in the scalar potential.
- $\langle\eta\rangle = \langle\chi\rangle = 0$ is assumed. $\rightarrow$ vacuum conditions

- Interactions

$$\mathcal{L}_Y = y^\nu \eta \overline{\psi} P_L L + \frac{y^L}{2}\overline{\psi^c} P_L \psi + \frac{y^R}{2}\overline{\psi^c} P_R \psi + \mathrm{h.c.}$$

$$\mathcal{V} \supset \mu'_\chi \left(\phi^\dagger \eta\right) \chi^\dagger + \frac{\mu''_\chi}{3!}\chi^3 + \mathrm{h.c.}$$

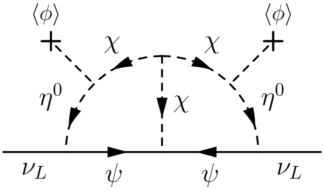
- After the symmetry breaking η and χ mix each other, but do not mix with ϕ.

$$\begin{pmatrix} \eta^0 \\ \chi \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \varphi_H \\ \varphi_L \end{pmatrix}$$

- Neutrino mass generation at 2-loop level.

$$m_\nu \sim \frac{{y^\nu}^2 \sin^2 2\alpha}{16(4\pi)^4} \mu''_\chi (y^L + y^R) I_{\mathrm{loop}}$$

For example, when $y^\nu \sim 0.01$, $\sin\alpha \sim 0.1$, $I_{\mathrm{loop}} \sim 0.1$, $\mu''_\chi \sim 10$ GeV, we obtain $m_\nu \sim 0.1\ \mathrm{eV}$.



Costraints

- Neutrino mass $m_\nu \sim 0.1\ \mathrm{eV}$ and mixing

$$U_{PMNS}^T m_\nu U_{PMNS} = \mathrm{diag}\left(m_1, m_2, m_3\right)$$

- Lepton flavor violation (LFV)
  The strongest constraint: $\mathrm{Br}(\mu \to e\gamma) \leq 5.7 \times 10^{-13}$
  $\to y^\nu$ is strongly constrained. cf: $\mathcal{L} \supset y^\nu \eta \overline{\psi} P_L L$

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha_{\mathrm{em}}}{64\pi G_F^2} \left| \sum_i \frac{y_{ie}^{\nu *} y_{i\mu}^\nu}{m_i^2} F_i^{\mathrm{loop}} \right|^2$$

  $\to$ (i) $y^\nu \lesssim 0.01$
  (ii) $y^\nu = \mathcal{O}(1)$ with a specific flavor structure
- ElectroWeak Precision Test (EWPT)
  $\to$ Constraint on $\mathbb{Z}_3$ charged scalar masses

$$\cos^2\alpha \left(m_{\eta^+} - m_H\right)^2 + \sin^2\alpha \left(m_{\eta^+} - m_L\right)^2 \lesssim (140\ \mathrm{GeV})^2$$

Costraints

- Thermal relic density of DM
  - DM candidate: Dirac fermion ψ or complex scalar φ_L.
- Vacuum conditions for $\langle\eta\rangle = \langle\chi\rangle = 0$

$$\lambda_1, \lambda_2, \lambda_\chi, \lambda_{\phi\chi}, \lambda_{\eta\chi} > 0, \quad \lambda_3 + \lambda_4 > 0$$
$$\frac{\mu_\chi''^2}{9\lambda_\chi} + \frac{\mu_\chi'^2}{\lambda_3 + \lambda_4} < \mu_\chi^2$$

$\rightarrow$ upper bounds for μ'_χ and μ''_χ

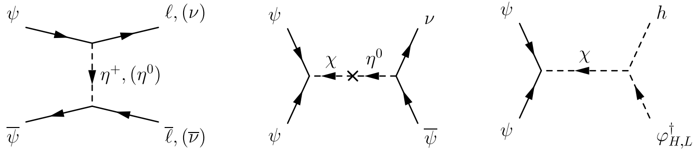
$\rightarrow$ relevant with neutrino masses and mixing angle of scalars

cf: Full scalar potential

$$\mathcal{V} = \mu_\phi^2|\phi|^2 + \mu_\eta^2|\eta|^2 + \mu_\chi^2|\chi|^2 + \frac{\lambda_1}{4}|\phi|^4 + \frac{\lambda_2}{4}|\eta|^4 + \frac{\lambda_\chi}{4}|\chi|^4$$
$$+\lambda_3|\phi|^2|\eta|^2 + \lambda_4(\phi^\dagger\eta)(\eta^\dagger\phi) + \lambda_{\phi\chi}|\phi|^2|\chi|^2 + \lambda_{\eta\chi}|\eta|^2|\chi|^2$$
$$+\left(\mu'_\chi(\phi^\dagger\eta)\chi^\dagger + \frac{\mu''_\chi}{3!}\chi^3 + \mathrm{h.c.}\right)$$

Dark Matter

- Dirac fermion DM ψ (Complex scalar DM φ)
- Semi-annihilation processes exist due to $\mathbb{Z}_3$ symmetry.
  It gives an important contribution.
  Ex.



For Dirac DM ψ

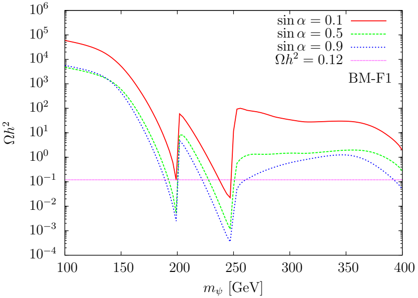
$$\mathcal{L} = y^\nu \eta \overline{\psi} P_L L + \frac{y^L}{2} \overline{\psi^c} P_L \psi + \frac{y^R}{2} \overline{\psi^c} P_R \psi + \text{h.c.}$$

LFV constraint

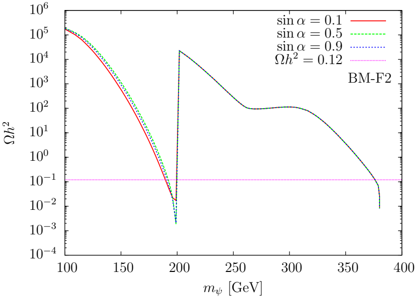
(1) $y^\nu \ll 1$ $\rightarrow$ annihilation cross section is suppressed.

(2) diagonal y^ν $\rightarrow$ neutrino mixings are derived from y_L, y_R.

Dirac fermion DM for small Yukawa



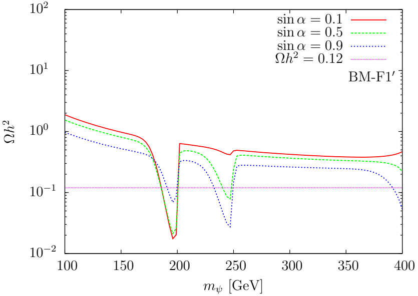
$m_H = 500$ GeV, $m_L = 400$ GeV

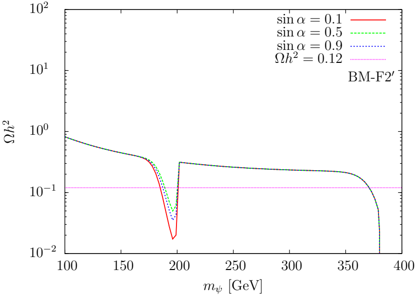


$m_H = 400$ GeV, $m_L = 400$ GeV

- Small Yukawa $y^\nu \sim 0.01$ for LFV
- Damps at $2m_\psi \approx m_{H,L}$ because of the semi-annihilations.
- Only when semi-annihilations or co-annihilations are effective, the correct relic density is obtained.

Dirac fermion DM for large Yukawa





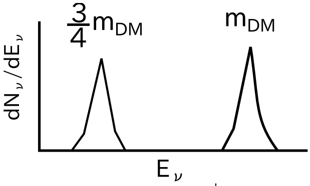
$m_H = 500$ GeV, $m_L = 400$ GeV $\qquad$ $m_H = 400$ GeV, $m_L = 400$ GeV

- Large Yukawa $y^\nu \sim \mathcal{O}(1)$ and diagonal.
- DM mass dependence is milder.
- Semi-annihilations and standard annihilations can be comparable.
- Large parameter region can be consistent with Ωh^2.
- DM physics becomes interesting for large Yukawa.

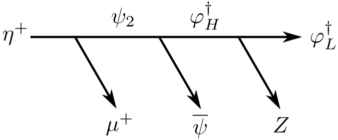
Characteristic signatures of the $\mathbb{Z}_3$ DM

- Direct Detection
  Basically no significant difference with $\mathbb{Z}_2$ DM. ($\sigma \sim 10^{-45}\ \mathrm{cm}^2$)
- Indirect Detection
  Because of the semi-annihilation channels, multi-peak of neutrinos is expected.

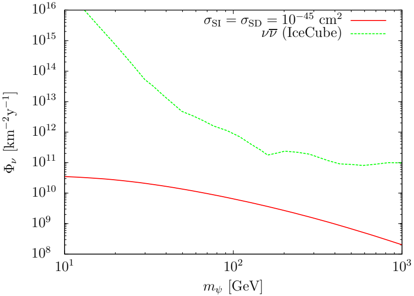
  Ex. $\psi\overline{\psi} \to \nu\overline{\nu}$ ($E_\nu = m_\psi$)
  $\psi\psi \to \nu\overline{\psi}$ ($E_\nu = 3m_\psi/4$)



- Collider prospects
  The final state includes one or two DM.
  $\rightarrow$ invariant mass distribution would be different from $\mathbb{Z}_2$ symmetric DM.



Indirect Detection



Neutrino flux from the Sun

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{C_\odot}{8\pi d^2}\left[2\mathrm{Br}_{\nu\overline{\nu}}\frac{dN_{\nu\overline{\nu}}}{dE_\nu} + \mathrm{Br}_{\nu\overline{\psi}}\frac{dN_{\nu\overline{\psi}}}{dE_\nu}\right]$$

d is distance between Earth and Sun.

Capture rate $C_\odot$ for 100 $\mathrm{GeV} \lesssim m_\psi \lesssim 1$ TeV

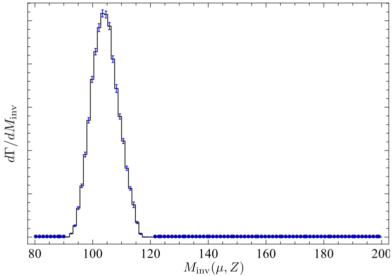
$$C_\odot \approx \left(\frac{1.2\times 10^{20}}{\mathrm{s}}\right)\left(\frac{100\ \mathrm{GeV}}{m_\psi}\right)^{1.8}\left(\frac{\sigma_{\rm SI} + 10^3\sigma_{\rm SD}}{10^{-45}\mathrm{cm}^2}\right)$$

Neutrino from the Sun

- At most two order of magnitude smaller than IceCube bound.

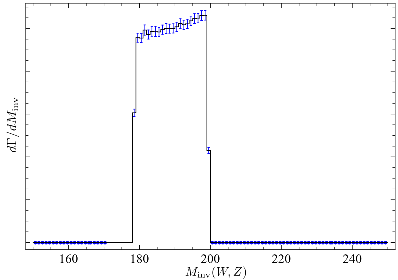
Collider prospects
Example of invariant mass distribution

For $\mathbb{Z}_3$ DM



$\eta^+ \to \overline{\psi}\varphi_L^\dagger \mu^+ Z$

For $\mathbb{Z}_2$ DM

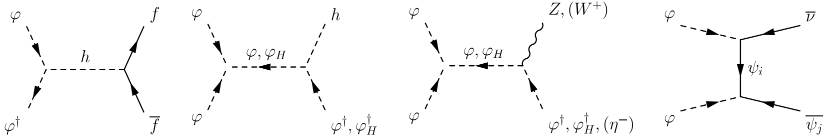


$\eta^+ \to \varphi_H W^+ \to \varphi_L Z W^+$

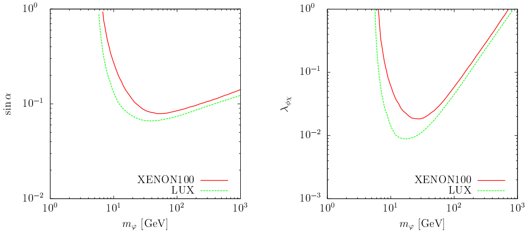
- Cusp distribution for $\mathbb{Z}_3$ DM.
- Flat distribution for $\mathbb{Z}_2$ DM.
- More serious analysis is needed.

Complex Scalar DM

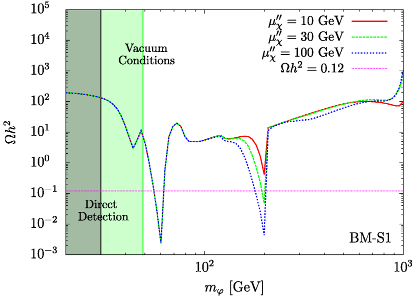
- Annihilations and semi-annihilations



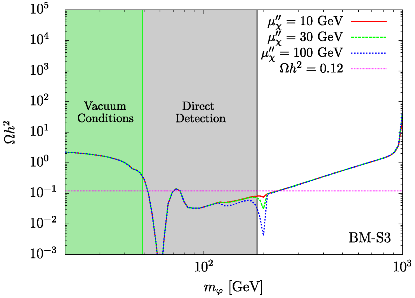
- Parameters are constrained by direct detection.
- Mixing angle and $\lambda_{\phi\chi}$ should be small. cf: $\mathcal{L} \supset \lambda_{\phi\chi}|\phi|^2|\chi|^2$
- $\sin\alpha \lesssim 0.05 \to$ DM is almost idetified as χ ($\varphi \approx \chi$).



Complex Scalar DM



$m_H - m_\varphi = 200$ GeV, $\lambda_{\phi\chi} = 0.01$



$m_H - m_\varphi = 200$ GeV, $\lambda_{\phi\chi} = 0.1$

- Vacuum conditions and direct detection constrain small mass region.
- $\varphi^\dagger\varphi \to h \to f\overline{f}$ (1st damp), φ_H resonance (2nd damp).

For indirect detection

- If $m_1 \neq m_2$, double peak could be seen by $\varphi\varphi \to \overline{\nu}\overline{\psi_i}$.

Summary

1. $\mathbb{Z}_3$ symmetric DM model has been studied. (radiative neutrino masses)
2. DM and neutrino physics are connected.
3. Semi-annihilations induced by $\mathbb{Z}_3$ symmetry become important.
4. Some different features of the $\mathbb{Z}_3$ DM are expected for indirect and collider searches.