Impact of Semi-annihilation of $\mathbb{Z}_3$ Symmetric Dark Matter with Radiative Neutrino Masses

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Astroparticle Physics 2014 [A joint TeVPA/IDM conference]
Amsterdam, Netherlands, 23-28 Jun. 2014

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

Outline

- Introduction
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- Relic Density and Signatures of $\mathbb{Z}_3$ Dark Matter
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Introduction

Neutrino mass differences are confirmed by the neutrino oscillations.

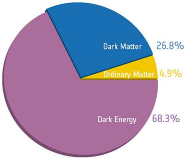
- $\Delta m_{ij}^2 \approx 10^{-3 \sim -5}$ $[\mathrm{eV}^2]$
- Mixing angles of the PMNS matrix
  $\sin^2\theta_{12} = 0.320$, $\sin^2\theta_{23} = 0.49$, $\sin^2\theta_{13} = 0.026$.

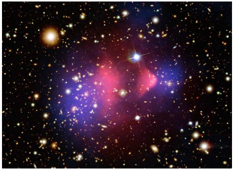
Theoretically neutrinos should be massive.

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, heavy right-handed neutrinos N_R are introduced.
  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.
- Radiative neutrino mass generation
  Neutrino masses are suppressed by loop factor.
  Sometimes dark matter is also accompanied.
  $\to$ Neutrino and DM physics are related each other.

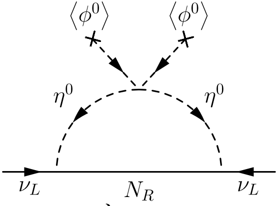
$\to$ Consider new kind of model with radiative neutrino masses.

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)

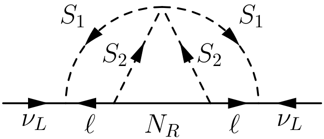


$$\mathcal{V} = \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2$$

- 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	$\mathbf{1}$	0	1	$+1/3$
η	$\mathbf{2}$	$1/2$	1	$-2/3$
χ	$\mathbf{1}$	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

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

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

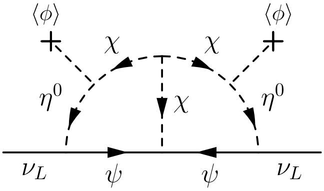
- After the symmetry breaking η and χ mix each other, but do not mix with ϕ.

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

- 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

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

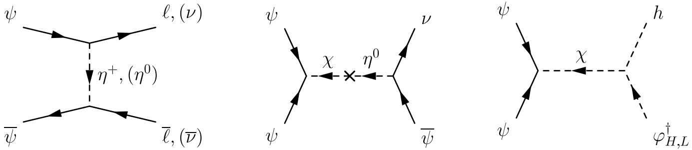
- Lepton flavor violation (LFV)
  The strongest constraint: $\mathrm{Br}(\mu \to e\gamma) \leq 5.7 \times 10^{-13}$
  $\to y^\nu$ is strongly constrained. cf: $\mathcal{L} \supset y^\nu \eta \overline{\psi} P_L L$
- ElectroWeak Precision Test (EWPT)

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

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

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

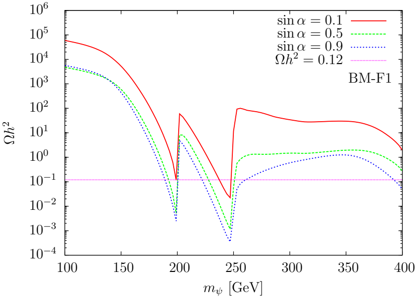
$$\mathcal{L} = y^\nu \eta \overline{\psi} P_L L + \frac{y^L}{2} \overline{\psi^c} P_L \psi + \frac{y^R}{2} \overline{\psi^c} P_R \psi + \mathrm{h.c.}$$

LFV constraint

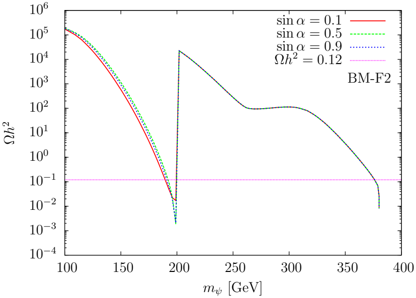
(1) $y^\nu \ll 1$ $\rightarrow$ annihilation cross section is suppressed.

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

Dirac fermion DM for small Yukawa



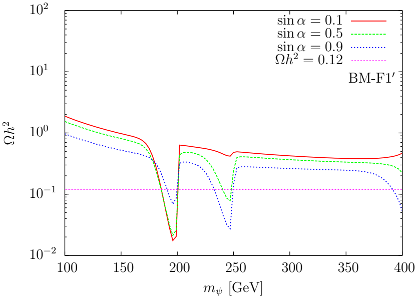
$m_H = 500$ GeV, $m_L = 400$ GeV

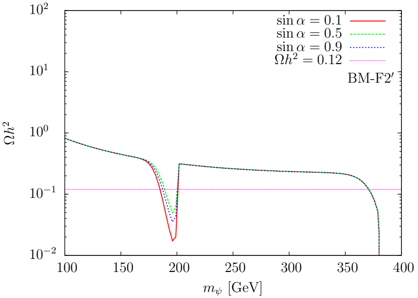


$m_H = 400$ GeV, $m_L = 400$ GeV

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

Dirac fermion DM for large Yukawa





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

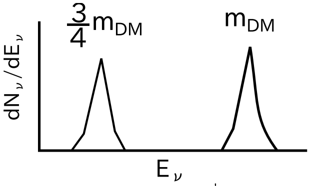
$m_H = 400$ GeV, $m_L = 400$ GeV

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

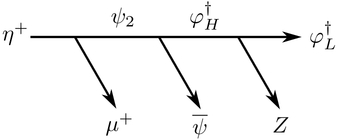
Characteristic signatures of the $\mathbb{Z}_3$ Model

- Direct Detection
  Basically no significant difference with $\mathbb{Z}_2$ DM.
- Indirect Detection
  Because of the semi-annihilation channels, multi-peak of neutrinos is expected.

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

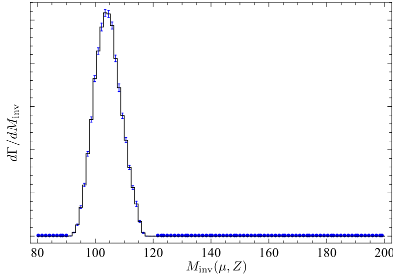


- Collider prospects
  The final state includes one or two DM.
  $\to$ invariant mass distribution would be different from $\mathbb{Z}_2$ symmetric DM.



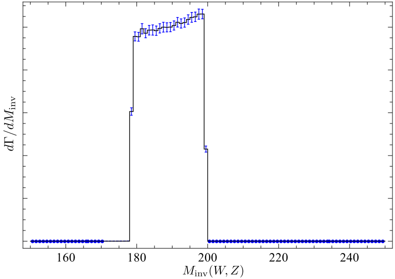
Example of invariant mass distribution

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.

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.