Coannihilation and Direct Detection of Dark Matter in a Radiative Neutrino Mass Model

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Outline

1. Introduction
2. Radiative Neutrino Mass Models
    - Neutrino Mass and Dark Matter (DM)
3. A Concrete Radiative Neutrino Mass Model
    - The Model
    - Constraints from LFV and DM Relic Abundance
    - Coannihilation Effect of DM
    - Direct Detection of DM
4. Summary

Introduction

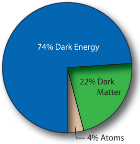
Neutrino mass differences are confirmed by the neutrino oscillations.

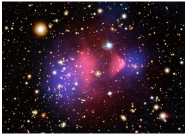
- $\Delta m_{ij}^2 \approx 10^{-3 \sim -5}$ $[\mathrm{eV}^2]$
- Mixing angles of the PMNS matrix
  $\sin^2\theta_{12} = 0.320$, $\sin^2\theta_{23} = 0.49$, $\sin^2\theta_{13} = 0.026$.

Neutrinos should be massive.

There are many experimental evidences of DM.

- Rotation curves of spiral galaxy
- CMB observation by WMAP
- Gravitational lensing
- Large scale structure of the universe





The existence of DM is crucial.

Extensions of the Standard Model

Neutrino mass

- Seesaw mechanism (Type I, Type II, Type III...)
  In Type I seesaw ($m_D \ll M$),

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \quad \rightarrow \quad m_\nu \approx -m_D M^{-1} m_D^T \quad \text{etc...}$$

- Inverse seesaw mechanism
  Majorana mass term μ ($\not{L}$) is small. $\rightarrow$ $m_\nu \propto \mu$
  Typical scale of μ is keV.

DM candidate

In order to include DM we have to stabilize a particle. $\rightarrow \mathbb{Z}_2$ parity

- Neutralino, Lightest KK Particle, (gravitino, axion) etc..

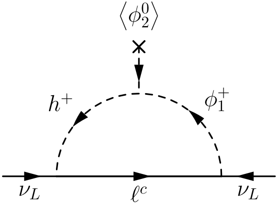
Radiative Neutrino Mass Models

Another possibility → Radiative neutrino mass models
Neutrino mass generation is related with the existence of DM.

- Zee model

	$SU(2)_L$	$U(1)_Y$
ϕ_2	**2**	1
h^+	**1**	1

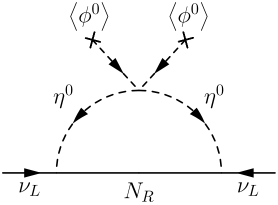
neutrino mass (1-loop level)



- Ma model

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

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

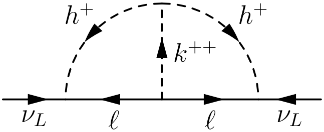


Radiative Neutrino Mass Models

- Zee-Babu model

	$SU(2)_L$	$U(1)_Y$
h^+	$\mathbf{1}$	1
k^{++}	$\mathbf{1}$	2

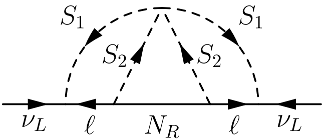
neutrino mass (2-loop level)



- Krauss-Nasri-Trodden model

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

neutrino mass (3-loop level)
DM candidate (N_R)



The Model

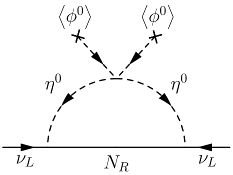
New particles

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

- Neutrino mass generation at 1-loop level
- Include DM candidate

$$\mathcal{L} = (D_\mu \eta)^\dagger (D^\mu \eta) + \overline{N_i} i \partial\!\!\!/ N_i - \frac{M_i}{2} \overline{N_i^c} N_i + h_{\alpha i} \overline{\ell_\alpha} \eta^\dagger N_i + \text{h.c.} - \mathcal{V}(\phi, \eta)$$

$$\mathcal{V}(\phi,\eta) = m_\phi^2 |\phi|^2 + m_\eta^2 |\eta|^2 + \frac{\lambda_1}{2}|\phi|^4 + \frac{\lambda_2}{2}|\eta|^4 + \lambda_3 |\phi|^2 |\eta|^2 + \lambda_4 (\phi^\dagger \eta)(\eta \phi) + \frac{\lambda_5}{2}\left[(\phi^\dagger \eta)^2 + (\eta^\dagger \phi)^2\right]$$



When $\lambda_5 \ll 1$

$$(m_\nu)_{\alpha\beta} \simeq \sum_{i=1}^{3} \frac{2\lambda_5 h_{\alpha i} h_{\beta i} \langle \phi^0 \rangle^2}{(4\pi)^2 M_i} I\left(\frac{M_i^2}{M_\eta^2}\right)$$

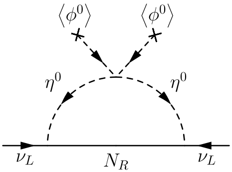
The structure of the neutrino mass matrix is determined by the Yukawa matrix $h_{\alpha i}$.
The flavor structure:

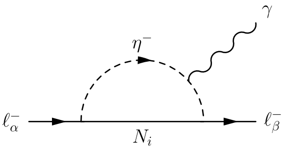
$$h_{\alpha i} = \begin{pmatrix} \epsilon_1 & \epsilon_2 & h_3' \\ h_1 & h_2 & h_3 \\ h_1 & h_2 & -h_3 \end{pmatrix}, \quad \epsilon_i \ll h_i$$

ϵ_i are understood as deviations from the Tri-bimaximal mixing.
$\rightarrow \sin^2\theta_{12} = \frac{1}{3} + \epsilon$, $\sin^2\theta_{23} = \frac{1}{2} + \epsilon'$, $\sin^2\theta_{13} = 0 + \epsilon''$.

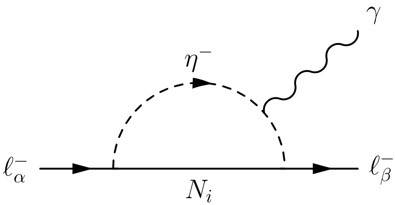
$$U_{PMNS}^T m_\nu U_{PMNS} = \mathrm{diag}\,(m_1, m_2, m_3)$$

- Non-diagonal flavor structure $\leftrightarrow$ Lepton Flavor Violation





Constraints from LFV



The experimental bounds

- $\mathrm{Br}\left(\mu \to e\gamma\right) < 2.4 \times 10^{-12}$
- $\mathrm{Br}\left(\tau \to \mu\gamma\right) < 4.4 \times 10^{-8}$
- $\mathrm{Br}\left(\tau \to e\gamma\right) < 3.3 \times 10^{-8}$

$$\mathrm{Br}\left(\ell_\alpha \to \ell_\beta\gamma\right) = \frac{3\alpha_{\mathrm{em}}}{64\pi G_F^2 M_\eta^4}\left|\sum_{i=1}^{3} h_{\alpha i}^* h_{\beta i} F_2\left(\frac{M_i^2}{M_\eta^2}\right)\right|^2 \mathrm{Br}\left(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta\right)$$

where $\mathrm{Br}\left(\mu \to e\nu_\mu\overline{\nu}_e\right) \simeq 1$, $\mathrm{Br}\left(\tau \to \mu\nu_\tau\overline{\nu}_\mu\right) \simeq 0.174$,
$\mathrm{Br}\left(\tau \to e\nu_\tau\overline{\nu}_e\right) \simeq 0.178$.

$\to$ the Yukawa couplings $h_{\alpha i}$ should be small.

Constraint from DM Relic Abundance

The lightest right-handed neutrino N_1 is assumed to be DM candidate.

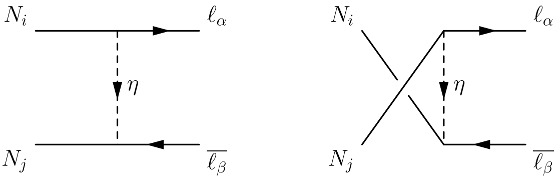
- The channel: $N_1 N_1 \to \ell_\alpha \overline{\ell_\beta}$
  Expansion in terms of v^2, $\sigma v = a + bv^2 + \mathcal{O}\left(v^4\right)$
- Fermionic DM has often helicity suppression.
- The annihilation cross section has no s-wave due to helicity suppression.

$$\sigma v = \sum_{\alpha=e}^{\tau} \frac{|h_{\alpha 1}|^4}{24\pi} \frac{M_1^2\left(M_1^4 + M_\eta^4\right)}{\left(M_1^2 + M_\eta^2\right)^4} v^2 \propto v^2$$

$\to$ the Yukawa couplings $h_{\alpha i}$ should be large.

Coannihilation of DM

If N_2 is degenerated with N_1 ($M_1 \approx M_2$), they can coannihilate:

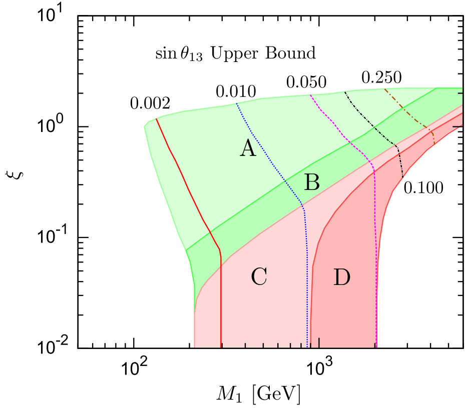


- The effective annihilation cross section $\sigma_{\rm eff}$ includes $N_1 N_2 \to \ell_\alpha \overline{\ell_\beta}$, $N_2 N_2 \to \ell_\alpha \overline{\ell_\beta}$.
- s-wave appears due to the coannihilation prcess $N_1 N_2 \to \ell_\alpha \overline{\ell_\beta}$ if the Yukawa $h_{\alpha i}$ are complex.
  $\sigma_{\rm eff} v = a_{\rm eff} + b_{\rm eff} v^2, \qquad a_{\rm eff} \propto {\rm Im}\left(h_1^* h_2\right) \neq 0.$

$\to$ Possible to be consistent with LFV and DM relic abundance.

Allowed parameter space from

- Neutrino mass and mixing
- LFV
- Perturbativity $|h_i| < 1.5$
- DM relic abundance $\Omega h^2 \sim 0.1$



$\xi \equiv \mathrm{Im}\,(h_1^* h_2)$

A: $2.00 < M_\eta/M_1 < 9.80$

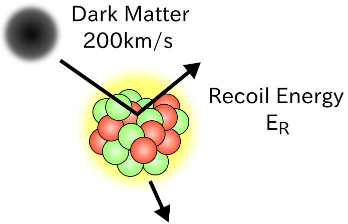
B: $1.20 < M_\eta/M_1 < 2.00$

C: $1.05 < M_\eta/M_1 < 1.20$

D: $1.00 < M_\eta/M_1 < 1.05$

- Region of A and B $\rightarrow$ coannihilation of N_1 and N_2
- Region of C and D $\rightarrow$ coannihilation of N_1, N_2 and η

Direct Detection



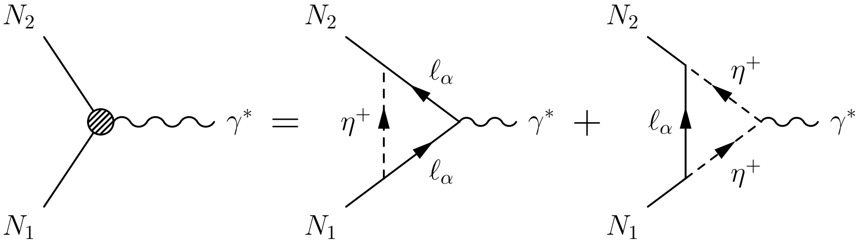
- Nuclei are made of quarks.
  → Interactions with quarks are important.
- Many direct detection experiments are performed. XENON100, CDMSII, DAMA, CoGeNT, CRESST, KIMS etc.

Detection Rate

$$\frac{dR}{dE_R} = \sum_{\text{nuclei}} \frac{\rho_\odot}{m_{DM}} \frac{1}{m_{\text{det}}} \int_{v>v_{\text{min}}} \frac{d\sigma}{dE_R} v f_\odot (\mathbf{v} + \mathbf{v}_e) d^3 v$$

- $d\sigma/dE_R$: cross section (Particle physics dependence)
- $\rho_\odot$, v: DM local density, velocity (Astrophysics dependence)

- Elastic scattering $N_1 A \to N_1 A$ is highly suppressed.
- Scattring with nuclei occurs inelastically in the model like $N_1 A \to N_2 A$.
- We need the effective coupling of $N_1 N_2 \gamma$.

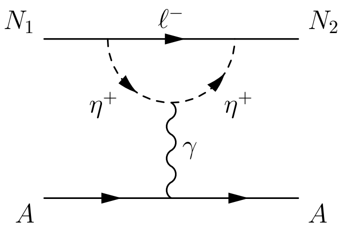


$$\mathcal{L}_{\text{eff}} = i a_{12} \overline{N_2} \gamma^\mu N_1 \partial^\nu F_{\mu\nu} + i \left(\frac{\mu_{12}}{2} \right) \overline{N_2} \sigma^{\mu\nu} N_1 F_{\mu\nu} + i c_{12} \overline{N_2} \gamma^\mu N_1 A_\mu$$

There are three types of interactions.

$$a_{12},\ \mu_{12},\ c_{12} \propto \xi \equiv \mathrm{Im}\left(h_2^* h_1 \right)$$

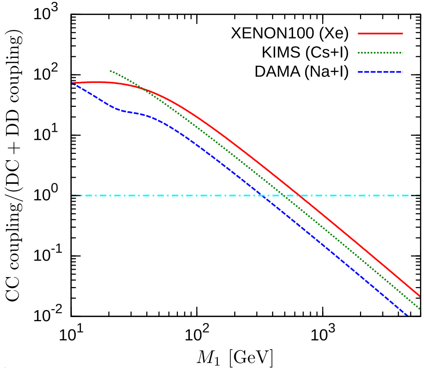
Scattering with nuclei

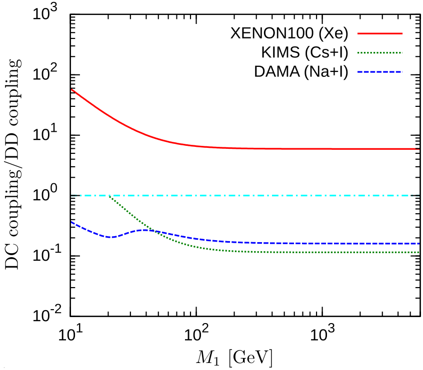


- Scattering with nuclei inelastically occurs.
- Propagete a photon with small transter energy E_R.
- Three types of cross sections are obtained.
  - Charge-Charge coupling: $\sigma_{CC} \propto g^2_{DM\text{-}\gamma} Z^2$
  - Dipole-Charge coupling: $\sigma_{DC} \propto \mu^2_{12} Z^2$
  - Dipole-Dipole coupling: $\sigma_{DD} \propto \mu^2_{12} \mu^2_N$

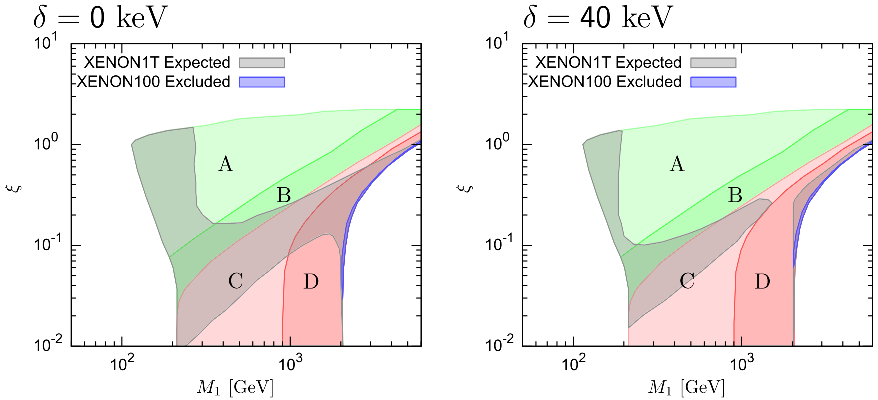
σ_{CD} is suppressed.

Comparison of the couplings for $M_\eta/M_1 = 1.5$





- CC coupling is dominant for rather small mass range.
- DD coupling is larger than DC coupling for DAMA and KIMS.
  $\to$ dependence of μ_N



- The inelastic cross section (CC coupling) is enhanced if DM and η are highly degenerated (light blue region).
  $\rightarrow$ the behavor of the loop function in the effective couplings.
- Some parameter space can be verified by XENON1T.

Summary

1. Some radiative neutrino mass models connect neutrino masses with the existence of DM.
2. Coannihilation plays an important role to obtain large effective annihilation cross section.
3. Due to small mass difference between N_1 and N_2, DM can scatter with nuclei inelastically even if the DM is leptophilic.
4. Verification by XENON1T is possible if mass difference is small enough.

Thank you for your attention!