Radiative Neutrino Mass Generation and Dark Matter

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Outline

Introduction

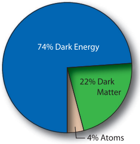
Neutrino mass differences are confirmed by the neutrino oscillations.

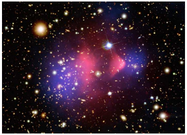
- $\Delta m_{ij}^2 \approx 10^{-3\sim-5}\ [\mathrm{eV}^2]$
- Mixing angles of the PMNS matrix
  $\sin^2\theta_{12} = 0.320$, $\sin^2\theta_{23} = 0.49$, $\sin^2\theta_{13} = 0.026$.

Neutrinos should be massive.

There are many experimental evidences of DM.

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





The existence of DM is crucial.

Neutrino Mass Generation

- Seesaw mechanism (Type I, Type II, Type III...)
  In Type I seesaw, some heavy 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 ($\not{L}$) $\rightarrow$ light neutrino masses.
  Three singlets S_L are added.

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

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 $\frac{1}{2}\overline{N_R^c}\mu' N_R$ 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 $m_D \sim y_\nu \langle \phi \rangle$

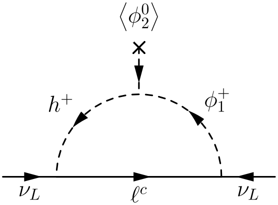
- features
  · Smallness of neutrino masses is natural.
  · Existence of DM is correlated with neutrino mass generation.

Examples of Models

- Zee model

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

· neutrino mass (1-loop level)

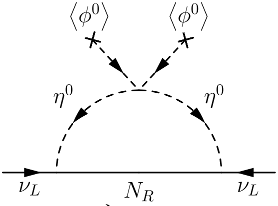


$$\mathcal{V} = \mu\phi_1^T\phi_2 h^-$$

- 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)



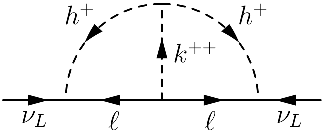
$$\mathcal{V} = \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2$$

Examples of Models

- Zee-Babu model

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

· neutrino mass (2-loop level)



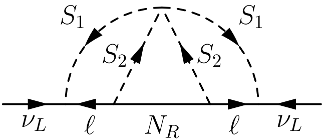
$$\mathcal{V} = \mu h^{-2} k^{++}$$

- 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)



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

Non-self conjugate coupling is required.

Dark Matter

- Nature of DM
  - · stable (or long lifetime)
  - · non-relativistic particle
  - · electrically neutral
  - · no electromagnetic interaction (at tree level)

- DM candidate

  In order to include DM we have to stabilize a particle.

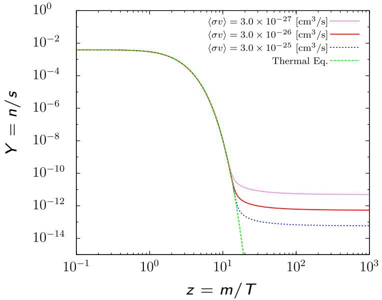
  $\rightarrow \mathbb{Z}_2$ parity

  · Neutralino, Lightest KK Particle, Right-handed neutrino, Gravitino, Axion etc..

DM Thermal Production

- DM number density is determined by decoupling from thermal bath in the universe.
- Number density follows the Boltzmann equation.

$$\frac{dY}{dz} = -\frac{\Gamma Y_{\rm eq}}{Hz}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right], \quad z \equiv \frac{m}{T}, \quad \Gamma \equiv \langle \sigma v \rangle\, n_{\rm eq}, \quad Y \equiv \frac{n}{s}$$



approximate solution

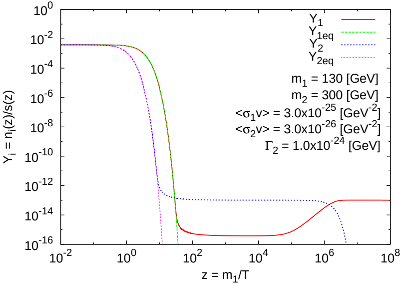
$$\Omega h^2 \approx \frac{1.04\times10^9\ [\mathrm{GeV}^{-1}]}{\sqrt{g_*}\, m_{\rm pl}\langle\sigma v\rangle} = 0.12 \quad (\texttt{Planck})$$

$$\leftrightarrow \quad \langle\sigma v\rangle \approx 3\times10^{-26}\ [\mathrm{cm}^3/\mathrm{s}] = 3\times10^{-9}\ [\mathrm{GeV}^{-2}]$$

- Non-thermal production of DM arXiv:0810.4147
  - · a metastable particle (χ_2) decays into DM (χ_1)
  - · simuletaneous Boltzmann equation

$$\frac{dY_1}{dz} = -\frac{\Gamma_{A1} Y_{1\mathrm{eq}}}{Hz}\left[\left(\frac{Y_1}{Y_{1\mathrm{eq}}}\right)^2 - 1\right] + N_{\mathrm{dec}}\frac{\Gamma_2}{Hz} Y_2$$

$$\frac{dY_2}{dz} = -\frac{\Gamma_{A2} Y_{2\mathrm{eq}}}{Hz}\left[\left(\frac{Y_2}{Y_{2\mathrm{eq}}}\right)^2 - 1\right] - \frac{\Gamma_2}{Hz} Y_2$$



- $\chi_2 \to N_{\mathrm{dec}}\chi_1 + X$
- $\langle \sigma v \rangle > 3 \times 10^{-26}$ $[\mathrm{cm}^3/\mathrm{s}]$
- $\Gamma_2^{-1} \lesssim 0.1$ s
- Explaination of the positron and gamma-ray excess in cosmic-ray observations?

A Concrete Model of Radiative Seesaw

The Simplest Model (Ma Model)

New particles

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

- Neutrino mass generation at 1-loop level
- Include DM candidates N_1 and η^0

Interactions

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

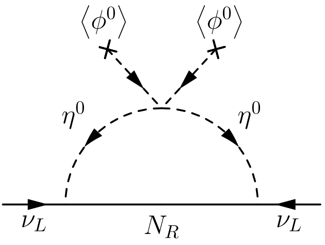
$$\begin{aligned} \mathcal{V}(\phi,\eta) = {} & m_\phi^2 |\phi|^2 + m_\eta^2 |\eta|^2 + \frac{\lambda_1}{2} |\phi|^4 + \frac{\lambda_2}{2} |\eta|^4 \\ & + \lambda_3 |\phi|^2 |\eta|^2 + \lambda_4 \left(\phi^\dagger \eta\right)\left(\eta^\dagger \phi\right) + \frac{\lambda_5}{2} \left[\left(\phi^\dagger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

- $\langle \eta \rangle = 0$ is assumed.
- ϕ and η do not mix after the symmetry breaking.
- assumed that new particles are less than a few TeV.

η^0 split after electroweak symmetry breaking.

$$\eta^0 = \frac{1}{\sqrt{2}}\eta_R + \frac{i}{\sqrt{2}}\eta_I, \qquad \text{mass eigenstates } (\eta_R, \eta_I)$$

$$\begin{aligned}(m_\nu)_{\alpha\beta} &= \sum_{i=1}^{3} \frac{h_{\alpha i} h_{\beta i} M_i}{(4\pi)^2} \left[\frac{m_R^2}{m_R^2 - M_i^2} \log\left(\frac{m_R^2}{M_i^2}\right) - \frac{m_I^2}{m_I^2 - M_i^2} \log\left(\frac{m_I^2}{M_i^2}\right) \right] \\ &\sim \left(h \Lambda h^T\right)_{\alpha\beta} \qquad \Lambda = \mathrm{diag}\left(\Lambda_1, \Lambda_2, \Lambda_3\right)\end{aligned}$$



When $\lambda_5 \ll 1$, $m_R^2 \approx m_I^2 = M_\eta^2$

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

$$I(x) = \frac{x}{1-x}\left(1 + \frac{x \log x}{1-x}\right)$$

The parameters are constrained by various aspects.

- Neutrino mass scale $m_\nu \sim 10^{-1}$ eV
- Neutrino mixing

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

- Lepton flavor violation (LFV)
  $\mu \to e\gamma$: $\mathrm{Br}(\mu \to e\gamma) \leq 2.4 \times 10^{-12} \quad \to \quad 5.7 \times 10^{-13}$ (now)
  $\mu \to 3e$?
- Thermal relic density of DM
  · N_1 is assumed to be DM here.
  · Leptophilic DM.
  · degenerated with N_2.

- To derive the neutrino mass scale

$$\frac{\lambda_5 h^2}{10^{-11}} \sim \frac{M_i}{\langle\phi\rangle}\left(\frac{\sqrt{\Delta m^2}}{0.05\ \mathrm{eV}}\right)$$

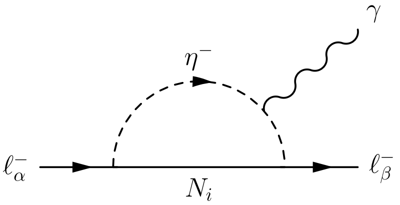
- The structure of the neutrino mass matrix is determined by the Yukawa matrix $h_{\alpha i}$.
  The flavor structure:

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

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

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

Constraints from LFV



The experimental bounds

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

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

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

$\to$ Yukawa couplings $h_{\alpha i}$ should be small.
or
Special structure of Yukawa matrix.

Constraint from DM Relic Density

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

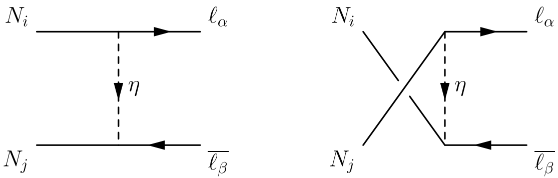
- The channel: $N_1 N_1 \to \ell_\alpha \overline{\ell_\beta}$ (t, u-channel)
  Expansion in terms of v^2, $\sigma v = a + bv^2 + \mathcal{O}\left(v^4\right)$
- Fermionic DM is often suppressed by chiral suppression.
- The annihilation cross section has no s-wave due to chiral suppression.

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

$\rightarrow$ 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:

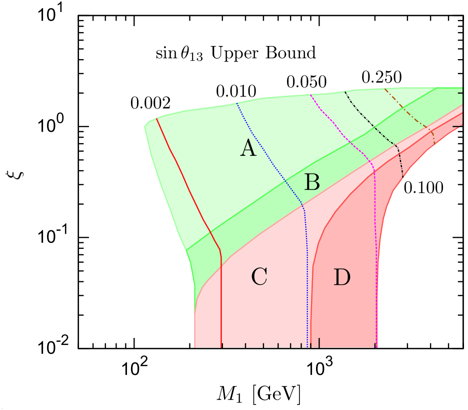


- The effective annihilation cross section $\sigma_{\rm eff}$ includes $N_1 N_2 \to \ell_\alpha \overline{\ell_\beta}$, $N_2 N_2 \to \ell_\alpha \overline{\ell_\beta}$.
- s-wave appears due to the coannihilation process $N_1 N_2 \to \ell_\alpha \overline{\ell_\beta}$ if the Yukawa $h_{\alpha i}$ are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

$\to$ It is possible to be consistent with LFV and DM relic abundance.

Allowed parameter region from

- Neutrino mass and mixing
- LFV
- Perturbativity $|h_i| < 1.5$
- DM relic abundance $\Omega h^2 = 0.12$

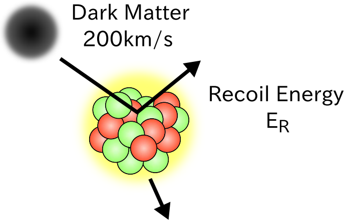


$\xi \equiv \mathrm{Im}\left(h_1^* h_2\right)$

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

$1 \lesssim$ DM mass $\lesssim 3$ TeV

Direct Detection



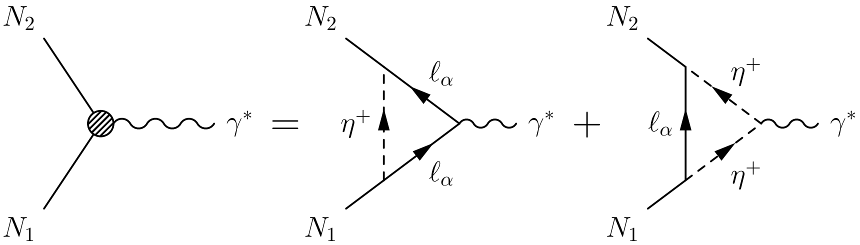
- Nuclei are made of quarks.
  $\rightarrow$ Interactions with quarks are important.
- Many direct detection experiments are performed.
  XENON100, CDMSII, DAMA, CoGeNT, CRESST, KIMS etc.

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)

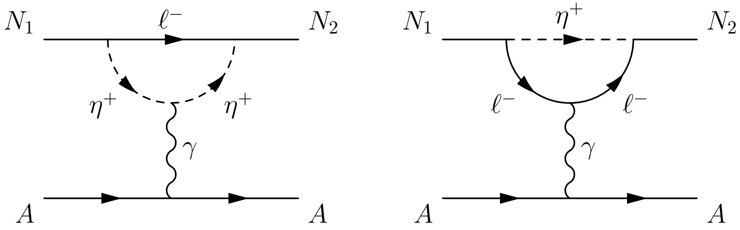
- Elastic scattering $N_1 A \to N_1 A$ is highly suppressed.
- Scattring with nuclei occurs inelastically in the model like $N_1 A \to N_2 A$.
- We need the effective coupling of $N_1 N_2 \gamma$.



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

There are three types of interactions. $a_{12}, \mu_{12}, c_{12} \propto \xi \equiv \mathrm{Im}\left(h_2^* h_1\right)$
$\to$ Charge int. a_{12} and c_{12}, Dipole int. μ_{12}.

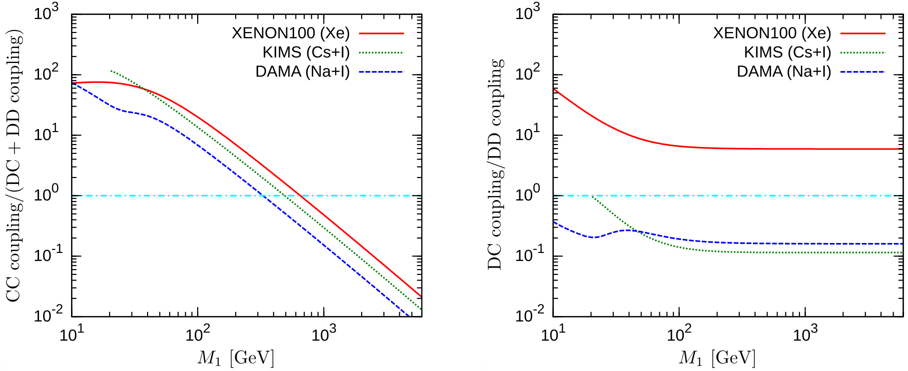
Scattering with nuclei



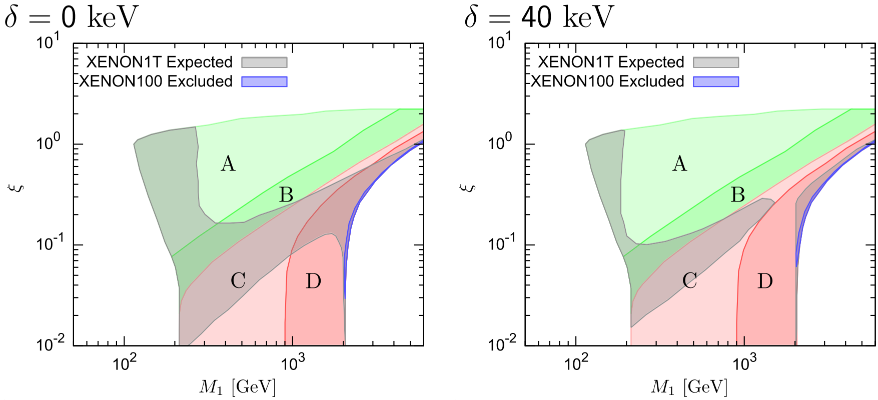
- Inelastic Scattering with nuclei occurs when $\delta m \lesssim 100$ keV
- Photon has small transter energy E_R.
- Three types of cross sections are obtained.
  - Charge-Charge coupling: $\sigma_{CC} \sim (a_{12} + c_{12})^2 Z^2$
  - Dipole-Charge coupling: $\sigma_{DC} \sim \mu_{12}^2 Z^2$
  - Dipole-Dipole coupling: $\sigma_{DD} \sim \mu_{12}^2 \mu_N^2$

  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.
  $\rightarrow$ 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.
  Enhanced by $a_{12} \propto \dfrac{M_1^2}{m_\ell^2}$ when $M_1 \approx M_\eta$
- Some parameter space can be investigated by XENON1T.

Extensions of Radiative Seesaw

1. Supersymmetry with anomalous $U(1)_A$

- A pair of inert Higgs η_u and η_d is required.
- Break gauge coupling unification at GUT scale because of additional inert Higgs doublets η
- $U(1)_A$ anomaly cancellation by Green-Schwarz mechanism

$$\delta\mathcal{L} = -\frac{g_A^2 \mathrm{Tr}\, Q_A}{32\pi^2}\alpha(x)\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

$$\mathcal{L} = a\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}, \quad a \to a + \delta_{GS}\alpha(x)$$

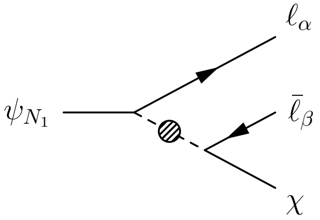
- Remain accidental $\mathbb{Z}_2$ parity after the $U(1)_A$ breaking

Interesting features

- $\mathbb{Z}_2$ is softly broken $\rightarrow$ metastable DM
- lifetime is determined by charge assignment of $U(1)_A$

$$\tau \propto \exp(\delta_{GS}^{-1}), \quad \delta_{GS} = \frac{\mathrm{Tr}\, Q_A}{48\pi^2}$$

- We have Multi-component DM (R-parity and softly broken $\mathbb{Z}_2$) Neutralino and the lightest $\mathbb{Z}_2$ odd particle.
- The positron excess of AMS-02 and PAMELA is explained by the decay of DM.



2. Flavor Symmetry

- Introduce flavor symmetry to derive neutrino mixing.

$$\theta_{12} = 34^\circ, \quad \theta_{23} = -45^\circ, \quad \theta_{13} = -9^\circ$$

- DM decay channel is also controlled by the symmetry.

Allowed interaction of DMs X and X'

$$\mathcal{L} = \frac{\lambda_X}{\Lambda^2} LLE^c X^c + \frac{\lambda_{X'}}{\Lambda^2} LLE^c X^{c\prime}$$

Decay rate

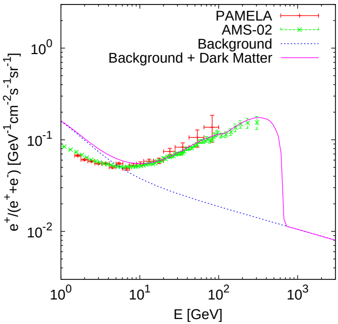
$$\frac{d\Gamma_X}{dx} = \frac{|\lambda_X|^2 m_X^5}{48(4\pi)^3\Lambda^4} x^2 \left(21 - 16x\right), \quad x = \frac{2E_e}{m_X}$$

$$\Gamma_X = \frac{|\lambda_X|^2 m_X^5}{16(4\pi)^3\Lambda^4}$$

Positron flux from DM

$$\frac{d\Phi}{dE} = \frac{v_e}{4\pi b(E)} \frac{\rho(r)}{m_X} \int_E^{m_X/2} dE' \frac{d\Gamma_X}{dE'} I(E, E')$$

Astrophysical dependences are in $I(E, E')$



- small dump around 120 GeV
- $e : \mu : \tau = 1 : 1 : 1$ because of the flavor symmetry
- Two-component DM
- Best fit :

$$m_X = 244 \text{ GeV}, \quad \Gamma_X = 1.2 \times 10^{28} s.$$
$$m_{X'} = 1360 \text{ GeV}, \quad \Gamma_{X'} = 2.4 \times 10^{27} s.$$

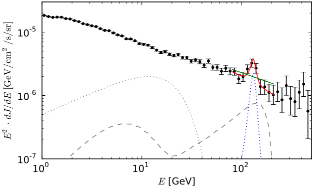
arXiv:1304.2680

Summary

1. The SM should be extended to include neutrino masses and DM.
2. In some Radiative Seesaw models, neutrino masses and DM are related.
3. Coannihilation plays an important role to be consistent with all the constraints.
4. Due to small mass difference between N_1 and N_2, inelastic scattering between DM and nuclei is possible even if the DM is leptophilic.

Future Works

1. Gamma-ray from DM annihilation.



- Required cross section : $\sigma v \sim 10^{-27}$ [cm^3/s]

  $\leftrightarrow$ relic density of DM $\sigma v \sim 10^{-26}$ [cm^3/s]

   Large cross section is required $\leftrightarrow$ DM relic density
2. Lepton Flavor Violation $\mu \to 3e$.
   When Yukawa coupling is large enough, $\mu \to 3e$ can be larger than $\mu \to e\gamma$
   $\to$ Radiative Seesaw or Inverse Seesaw
3. The other extensions of the SM.
   (model building of new radiative seesaw)

Thank you for your attention!