A Radiative Neutrino Mass Model with SIMP Dark Matter

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In collaboration with

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Introduction

Neutrino mass differences are confirmed by the neutrino oscillations.

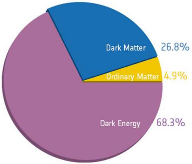
- $\Delta m_{21}^2 = 7.50 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m_{31}^2 = 2.524 \times 10^{-3}\ \mathrm{eV}^2$ (NH)
- Large mixing angles of the PMNS matrix arXiv:1611.01514
  $\sin^2\theta_{12} = 0.306$, $\sin^2\theta_{23} = 0.441$, $\sin^2\theta_{13} = 0.0217$.

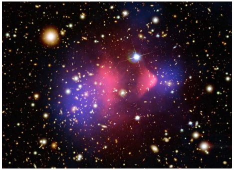
Neutrinos should be massive.

Dirac or Majorana? How much is CP phase?

There is much experimental evidence of DM.

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

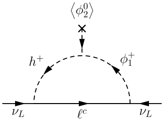




Existence of DM is crucial.

Radiative generation of neutrino masses

- Zee model A. Zee, Phys.Lett.B (1980,1985)
  First model (one-loop, no DM)
  $\to$ Already excluded by current ν oscillation data.



How to construct a model with DM
$\to$ Forbid Dirac mass term with a symmetry (ex. $\mathbb{Z}_2$)
Type I seesaw E. Ma, Phys.Rev.D (hep-ph/0601225)

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

$\to$ Correlate DM and neutrino phenomenology.

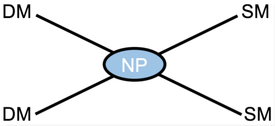
- A large number of models have been proposed.
- Most of models deal with canonical WIMP.

SIMP (Strongly Interacting Massive Particle)

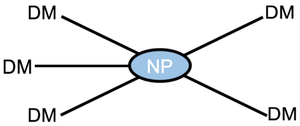
Y. Hochberg et al. PRL (2014) [arxiv:1402.5143]

- DM abundance can be determined by $3 \to 2$ or $4 \to 2$ processes in dark sector, but not $2 \to 2$ annihilating processes (WIMP).
- DM is in kinetic equilibrium with the SM at least until freeze-out of DM.

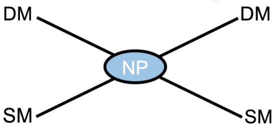
Condition for thermal SIMP: $\Gamma_{\rm ann} < \Gamma_{3\to2} < \Gamma_{\rm kin}$



Normal annihilation



3 to 2 process



Elastic scattering

- Typical scale of SIMP mass:
  $m_\chi \sim \mathcal{O}(10)$ MeV for $3 \to 2$ process
  ($m_\chi \sim \mathcal{O}(100)$ keV for $4 \to 2$ process)

Large self-interaction of DM can solve small scale structure problems.

A Radiative Neutrino Mass Model with SIMP

S. Ho, T.T., K. Tsumura, arxiv:1705.00592

Particle content

	L	H	N	η	χ	S
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$-1/2$	$1/2$	0	$1/2$	0	0
$\mathbb{Z}_5$	0	0	2	2	2	1
Spin	$1/2$	0	$1/2$	0	0	0

- $\mathbb{Z}_5$ symmetry can be derived by an extra $U(1)$ symmetry.

  S. Ho, T.T., K. Tsumura, Phys.Rev.D (arXiv:1604.07894)

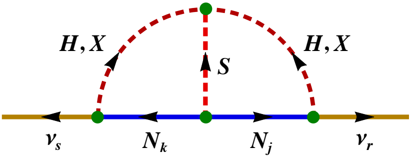
  $\rightarrow$ 3-to-2 annihilation occurs.

  $\mathbb{Z}_3$ symmetry is also possible (but excluded by perturbativity)

- S is a resonant particle to enhance annihilation cross section for $3\mathrm{DM} \rightarrow 2\mathrm{DM}$.

Neutrino Masses

- Neutrino masses are generated at two-loop level.



$$\begin{pmatrix} \eta^0 \\ \chi \end{pmatrix} = \begin{pmatrix} c_\xi & s_\xi \\ -s_\xi & c_\xi \end{pmatrix} \begin{pmatrix} H \\ X \end{pmatrix}$$

$$\mathcal{V} \supset \frac{\mu}{2} S \chi^2$$

$m_H = \mathcal{O}(100)$ GeV,
$m_X = \mathcal{O}(0.1)$ GeV

$$\mathcal{L}_Y = -y_{i\alpha}\eta \overline{N_i} P_L L_\alpha - \frac{y_{Lij}}{2} S \overline{N_i^c} P_R N_j - \frac{y_{Rij}}{2} S \overline{N_i} P_L N_j^c + \text{H.c.}$$

Neutrino Mass matrix: $m_\nu \sim \dfrac{\mu y^2 \sin^2\xi}{(4\pi)^4}\left(y_L f_L^{\text{loop}} + y_R f_R^{\text{loop}}\right)$

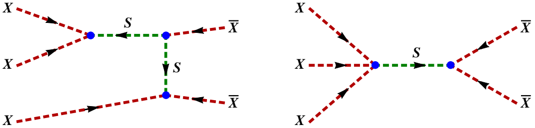
- If you take $y, y_{L,R} \sim 0.1$, $\mu \sim 0.1$ GeV, $s_\xi \sim 0.05$, $f_{L,R}^{\text{loop}} \sim 1$ $\to m_\nu \sim 0.01$ eV

Constraints

- LFV ($\ell \to \ell' \gamma$) $\to y$ is constrained.
- Electroweak precision data (STU parameters)
  $\to m_H \approx m_{\eta^+}$ and small $\sin\xi$
- Invisible decay modes ($h, Z \to X\overline{X}$) $m_X = \mathcal{O}(10)$ MeV
  $\to \sin\xi \lesssim 0.2 \left(\frac{100\ \mathrm{GeV}}{m_H}\right)$
- Perturbativity (scalar quartic couplings $< 4\pi$)
- Potential should be bounded from below (quartic couplings > 0) and vacuum stability ($\langle X \rangle$=0)
  $\to$ sufficient condition $\lambda_X > \dfrac{\mu_2^2}{m_S^2}$ $\lambda_S > \dfrac{\mu_1^2}{m_S^2}$ (μ_i: cubic couplings)
- SIMP condition $\Gamma_{\mathrm{ann}} < \Gamma_{3\to 2} < \Gamma_{\mathrm{kin}}$
- DM abundance $\Omega h^2 \approx 0.12$
- $\sigma_{\mathrm{self}}/m_X \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$ by collision of bullet cluster

Condition for SIMP

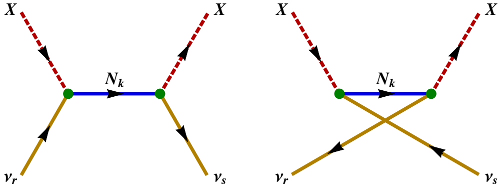
3 to 2 process $XXX \to \overline{XX}$ $\quad \Gamma_{3\to2} = \langle \sigma v^2 \rangle n_X^2$



$+\cdots$

$$\sigma v^2 \sim \frac{\mu_2^2}{m_X^3} \left| \frac{1}{4m_X^2 - m_S^2 + i m_S \Gamma_S} + \frac{1}{9m_X^2 - m_S^2 + i m_S \Gamma_S} + \cdots \right|^2$$

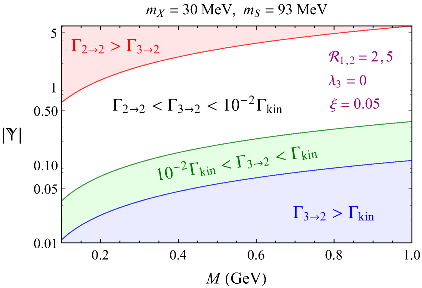
Elastic scattering with the SM particles (ν)

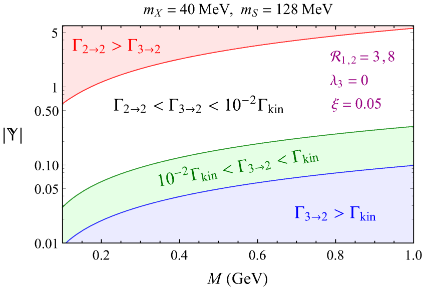


$$\langle \sigma_{\rm el} v \rangle \sim \frac{y^4 \sin^4 \xi m_X T}{8\pi (M_N^2 - m_X^2)^2}$$

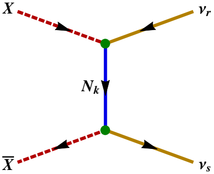
$$\Gamma_{\rm kin} = \langle \sigma_{\rm el} v \rangle n_\nu$$

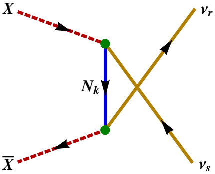
Condition for SIMP



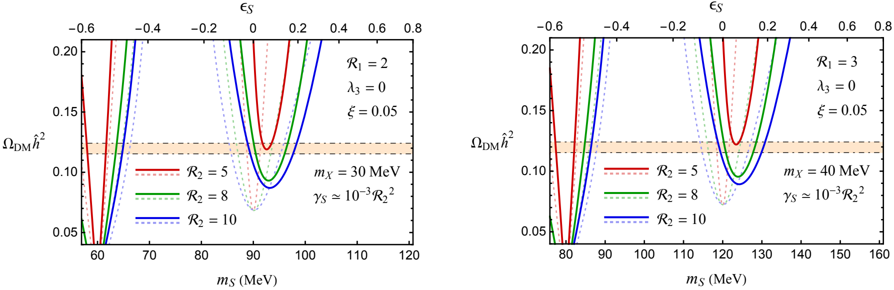


- Magnitude of Yukawa coupling is $y = \mathcal{O}(0.01 - 1)$.
- Fermion mass (N) is $0.1\ \text{GeV} \lesssim M \lesssim 1\ \text{GeV}$.
- $\Gamma_{\rm ann} = \langle \sigma_{\nu\nu} v \rangle n_X$
- $\mathcal{R}_{1,2} \equiv \dfrac{\mu_{1,2}}{m_X}$



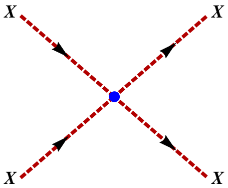


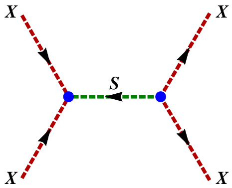
Relic Abundance



- Two resonances at $m_S \approx 2m_X, 3m_X$
- DM relic abundance can be sufficiently reduced when close to a resonance.
- Not to much parameter tuing ($\lesssim 10\%$).

Self-interacting Cross Section





$+\cdots$

$$\sigma_{\mathrm{self}} = \frac{1}{4}\left(\sigma_{XX} + \sigma_{X\overline{X}} + \sigma_{\overline{XX}}\right),$$

$\sigma_{\mathrm{self}}/m_X \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$
by bullet cluster

$$\sigma_{X\overline{X}} \approx \frac{1}{64\pi m_X^2}\left(\lambda_X - \frac{\mu_2^2}{m_S^2}\right)^2$$

$$\sigma_{XX} = \sigma_{\overline{XX}} \approx \frac{1}{128\pi m_X^2}\left(\lambda_X + \frac{\mu_2^2}{4m_X^2 - m_S^2}\right)^2$$

- Resonance at $m_S \approx 2m_X$ is excluded.

Summary

1. Radiative neutrino mass generation mechanism correlates small neutrino masses and DM.
2. We have constructed a model with radiative neutrino masses and SIMP DM.
3. A resonant particle is needed to satisfy all the constraints.