Imprint of the seesaw mechanism on feebly interacting dark matter and the baryon asymmetry

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Based on:
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Introduction

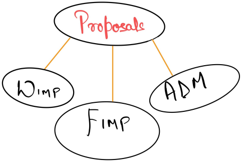
Here we address three of the most important aspects of present day particle physics and cosmology:

- **Dark matter** ⟶ requires beyond the Standard Model fields [*e.g.* Scalar / fermion/ boson].
- **Neutrino mass** ⟶ [most popular one: type-I seesaw: requires additional SM singlet RH neutrinos.]
- **Leptogenesis** ⟶ [most popular one: type-I seesaw]

Explanation of all of these issues requires beyond the Standard Model extensions.

Motivation

Lack of precise information of DM



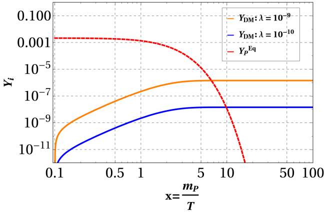
In other words, DM can be:

- Thermal.
- **Non-thermal**.

These DM setups can also **explain**:

- non-zero neutrino masses
- matter-antimatter asymmetry

Non-thermal DM scenario:



Typical behaviour:

- Here, the DM interacts feebly with the bath and hence never thermalise
- P $\rightarrow$ DM, DM
- Its yield saturates once the number density of parent particle becomes Boltzmann suppressed.

Type-I seesaw

Extension: SM + 3 Right handed Neutrinos

$$\mathcal{L}^{\text{Ty-I}} = Y^{\nu}_{\alpha i}\ \bar{\ell}_{L_\alpha}\tilde{H}N_i + \frac{1}{2}M_i\overline{N_i^c}N_i + h.c$$

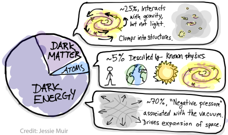
Benifits of Type-I seesaw

- Can explain non-zero neutrino masses and mixing

- Can explain Baryogenesis via *Leptogenesis*

Where is the Antimatter ???

- But can it can explain the existence of DM in the Universe?



Credit: Jessie Muir

DM in Type-I seesaw

Can a RH neutrino play a role of the DM candidate?

Issues associated with RH neutrino DM in Type-I seesaw

- Stability: RH neutrino should not decay

$$Y^{\nu} = \begin{pmatrix} 0 & y_{e2} & y_{e3} \\ 0 & y_{\mu 2} & y_{\mu 3} \\ 0 & y_{\tau 2} & y_{\tau 3} \end{pmatrix}$$

- In such case one of the RH neutrino is **strictly** stable
- DM **cannot be produced** via any interactions
- **Existence** of such DM is **questionable**!!
- Such a scenario also ensures that the lightest active neutrino is **massless** $(m_1 = 0)$

A possible way out: Non-thermal DM

A simplest possible solution of:

- Non-zero neutrino masses
- Matter-antimatter asymmetry of the Universe
- Dark matter

in Type-I seesaw was introduced in ν**MSM** scenario [1]

The νMSM:

- Lightest RH neutrino is a natural **warm DM candidate** with mass $\mathcal{O}$(keV)
- Only possible if the **active-sterile neutrino mixing is very small** guaranteeing the stability over the life time of the Universe.
- Produced non-thermally from **active-sterile neutrino oscillations**.
- The other two RH neutrinos are responsible for the non-zero neutrino masses and matter-anti matter asymmetry of the Universe.

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[1] Phys. Lett. B 620, 17 (2005)

Our Scenario (N_1 as CDM)

If RH neutrino is considered as a **FIMP**, it can play a role of a CDM candidate.

Addressing the Elephant in the room:

How to explain the **Feebly** Interacting Massive Particle **naturally??**

↓

Can it be connected to the **smallness** of the **active neutrino masses**??

Perturbing slightly form **zero in the Y^{ν}** might just provide an **answer**!!

$$Y^{\nu} = \left(\boxed{\begin{matrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{matrix}} \; \boxed{\begin{matrix} y_{e2} & y_{e3} \\ y_{\mu 2} & y_{\mu 2} \\ y_{\tau 2} & y_{\tau 3} \end{matrix}} \right), \epsilon_i << 1.$$

Now, $m_{D_{ij}} = Y^{\nu}_{ij} v/\sqrt{2}$ and $m_1 \neq 0$.

Neutrino mass: $m^{\nu} = -m_D M^{-1} m_D^T$

Active-sterile neutrino mixing: $V_{ij} = m_{D\,ij}/M_j$.

With N_1 as a DM candidate we have,

$$\boxed{V_{i1} = m_{D\,i1}/M_1 = \epsilon_i v/\sqrt{2}M_1}$$

Using the CI parameterization[2] we have,

$$m_D = -i\ U D_{\sqrt{m}} R^T D_{\sqrt{M}},$$

This suggest: $\epsilon_i \propto \sqrt{m_1 M_1}$

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[2] Nucl. Phys. B618, 171 (2001)

Effect of active-sterile mixing

Due to active-sterile mixing, we have,

Gauge interactions:

$$\mathcal{L}_{\mathcal{G}} \subset \frac{g}{\sqrt{2}} W_\mu^+ \sum_{i,j=1}^{3} \left[\bar{N}_i^c (V^\dagger)_{ij} \gamma^\mu P_L \ell_j \right] + \frac{g}{2 C_{\theta_w}} Z_\mu \times \sum_{i,j=1}^{3} \Big[\bar{\nu}_i (U^\dagger V)_{ij} \gamma^\mu P_L N_j^c$$

$$+ \bar{N}_i^c (V^\dagger V)_{ij} \gamma^\mu P_L N_j^c \Big],$$

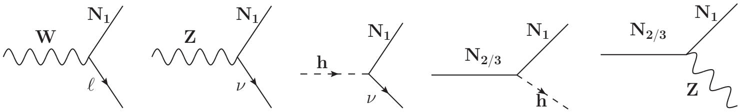
and **Yukawa interactions:**

$$\mathcal{L}_{\mathcal{Y}} \subset \frac{\sqrt{2}}{v} h \sum_{i,j=1}^{3} \left[\bar{\nu}_i (U^\dagger V)_{ij} M_j N_j + \bar{N}_i^c (V^\dagger U)_{ij} m_j \nu_j^c + \bar{N}_i^c (V^\dagger V)_{ij} M_j N_j \right],$$

Production of N_1

Assuming $M_1 < M_W$, N_1 cab be produced from:

Possible production channels:



Decay Widths:

Interaction	Decay width
$W \to N_1 \ell_i$	$\frac{M_W^3}{48\pi v^2 M_1^2}(m_D)_{i1}(m_D)^*_{i1}$
$Z \to N_1 \nu_i$	$\frac{M_Z^3}{96\pi v^2 M_1^2}(U^\dagger m_D)_{i1}(U^\dagger m_D)^*_{i1}$
$h \to N_1 \nu_i$	$\frac{m_H}{32\pi v^2}(U^\dagger m_D)_{i1}(U^\dagger m_D)^*_{i1}$
$N_i \to N_1 h$	$\frac{M_i}{64\pi v^2 M_1^2}(m_D^\dagger m_D)_{1i}(m_D^\dagger m_D)^*_{1i}$
$N_i \to N_1 Z$	$\frac{Mi}{128\pi v^2 M_1^2}(m_D^\dagger m_D)_{1i}(m_D^\dagger m_D)^*_{1i}$

Evolution of the Dark matter

Boltzmann Equations:

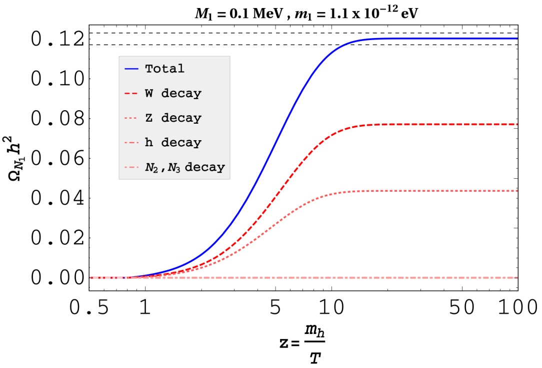
$$\frac{dY_{N_1}}{dz} = \frac{2M_{pl}z}{1.66M_2^2}\frac{g_\rho^{1/2}}{g_s}\Big[\sum_{i=2,3}\Big(Y_{N_i}\sum_{x=Z,W}\Big\langle\Gamma(N_i\to N_1x)\Big\rangle\Big) + \sum_{x=W,Z,h} Y_x^{eq} \times\Big\langle\Gamma(x\to N_1\ell)\Big\rangle\Big],$$

$$\frac{dY_{N_i}}{dz} = -\frac{2M_{pl}z}{1.66M_2^2}\frac{g_\rho^{1/2}}{g_s}\Big[(Y_{N_i}-Y_{N_i}^{eq})\Big\langle\Gamma^D\Big\rangle + Y_{N_i}\sum_{x=h,Z}\Big\langle\Gamma(N_i\to N_1x)\Big\rangle\Big],$$

with $z = m_h/T$ and $\Gamma^D = \Gamma(N_i \to LH) + \Gamma(N_i \to \bar{L}\bar{H}) = \frac{M_i}{8\pi v^2}(m_D^\dagger m_D)_{ii}$.

Relic density

$$\boxed{\Omega_{N_1}h^2 = 2.755\times 10^5\left(\frac{M_1}{\text{MeV}}\right)Y_{N_1}(z_\infty)}$$



Take aways:

- Dominant contribution to the relic density comes from $W^{\pm}$ boson decays and Z boson decays
- DM relic density is independent of M_1: $Y_{N_1} \propto m_1/M_1$
- Relic density only depeds upon the lightest active neutrino mass m_1
- Correct relic density is observed for $m_1 \sim 10^{-12}$ eV

Decay of the DM

Due to the presence of active-sterile mixing the DM can have following decays:

(a) via off shell W/Z: $N_1 \to l_1^- l_2^+ \nu_{l_2}$, $N_1 \to l^- q_1 \bar{q}_2$, $N_1 \to l^- l^+ \nu_l$, $N_1 \to \nu_l \bar{l}' l'$, $N_1 \to \nu_l q \bar{q}$, $N_1 \to \nu_l \nu_{l'} \bar{\nu}_{l'}$, $N_1 \to \nu_l \nu_l \bar{\nu}_l$

(b) via off-shell Higgs: $N_1 \to \nu_\ell \bar{\ell} \ell$

(c) radiative decay of N_1: $N_1 \to \gamma\nu$

The most stringent constraint is obtained from (c).

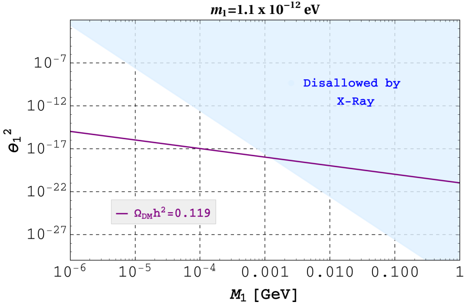
$$\Gamma_{N_1 \to \gamma\nu} = \frac{9\alpha G_F^2}{1024\pi^4} \sin^2 2\theta_1 M_1^5$$

Here, θ_1 is related to the active-sterile neutrino mixing V_{i1} as,

$$\theta_1^2 = \sum_{i=1,2,3} \frac{|(m_D)_{i1}|^2}{M_1^2} \equiv \sum_{i=1,2,3} \frac{|V_{i1}|^2}{M_1}.$$

Non-observance of specific X-ray signal: sets a limit on θ_1^2:

$$\theta_1^2 \quad \leq \quad 2.8 \times 10^{-18} \left(\frac{\text{MeV}}{M_1} \right)^5 .$$



Take away:

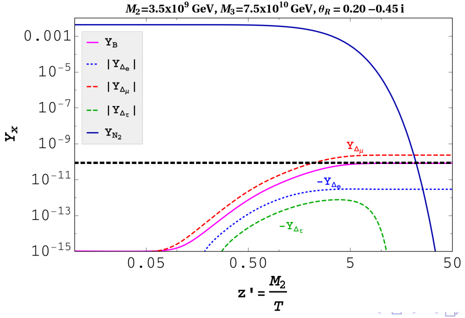
- We find N_1 as a successful FIMP type dark matter within a mass range 1 keV-1 MeV.

Matter-antimatter asymmetry of the Univerese

Role of $N_{2,3}$:

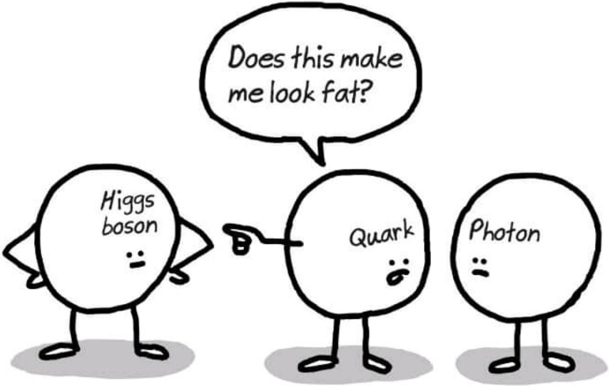
- No significant contribution in the DM phenomenology.
- Responsible for generating non-zero neutrino masses
- Responsible for Baryogenesis via Leptogenesis:

$$\epsilon_{2\alpha}^{cp} = \frac{\Gamma(N_2 \to \ell_\alpha H) - \Gamma(N_2 \to \bar{\ell}_\alpha \bar{H})}{\sum_\alpha [\Gamma(N_2 \to \ell_\alpha H) + \Gamma(N_2 \to \bar{\ell}_\alpha \bar{H})]}$$



Conclusion

- Conventional Type-I seesaw has the potential to offer a FIMP type of dark matter in the form of lightest RH neutrino.
- Relic density is governed by decay of the SM gauge bosons.
- The proposal predicts an upper bound on this lightest neutrino mass as $m_1 \leq \mathcal{O}(10^{-12})$ eV which makes it falsifiable if ongoing (or future) experiments such as KATRIN and PROJECT-8 collaboration succeed to probe it.
- The smallness of couplings involved in a generic FIMP type model, related to dark matter production, can now be connected with the lightness of active neutrino mass m_1 .
- DM mass allowed from the X-ray constraints ranges from 1 kev to 1 MeV
- We also incorporate the flavor leptogenesis scenario to show $M_{2,3} \sim 10^{9-10}$ GeV to explain the baryon asymmetry of the universe.



Thank You