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

Based on
Phys. Rev. Lett. 127, 231801

Rishav Roshan,
CHEP, Kyungpook National University,
Daegu, South Korea

In collaboration with:
Arghyajit Datta and Arunansu Sil
“Hey everybody - we’ve discovered the Higgs boson! It was hidden under this big pile of equations all the time!”

What is next?
Neutrinos:

**What we know** (from Neutrino oscillation):

- 3 mixing angles
- 2 mass-square difference
- CP-violating phase (?)

**What we don’t know**:

- Origin of neutrino mass
- Nature [Dirac/Majorana]
- Absolute neutrino mass

SM Fails to accommodate the tiny neutrino mass
Dark Matter (DM):

What we know (from observations like Galactic rotation/Bullet Clusters/CMB etc.):

- Relic density (~24% of the Universe)
- Massive
- Stable object
- Non or very-weakly interacting

Don’t

\[ \text{What we know:} \]

- Nature of DM
- Interaction with SM fields
- Production mechanism in the early Universe

No such candidate within SM
Baryon Asymmetry of the Universe (BAU):

Why there is solely baryonic matter in the Universe?

\[ Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.70 - 8.73) \times 10^{-11} \]

Possible explanation:

- C and CP violation
- Baryon number violation
- Out-of-equilibrium decay

Not Possible within SM
What can be the simplest/minimal possibility to bring these unknowns together?
Type-I Seesaw
Type-I seesaw and Neutrino mass:

Extension: SM + 3 Right-Handed Neutrinos

\[ \mathcal{L}_{BSM} = Y_{\alpha i} \bar{L}_\alpha \tilde{H} N_i + \frac{M_N}{2} \tilde{N}_i^c N_i + h.c \]

After S.S.B.

\[
\begin{pmatrix}
\bar{\nu}_L \\
(N_R)^c
\end{pmatrix}
\begin{pmatrix}
0_{3 \times 3} & m_{D_{3 \times 3}} \\
m_{D_{3 \times 3}} & M_{N_{3 \times 3}}
\end{pmatrix}
\begin{pmatrix}
(\nu_L)^c \\
N_R
\end{pmatrix}
\]

\[ m_{\nu} = -m_D M_N^{-1} m_D^T \]

Active-sterile mixing

\[ \mathbb{L}^\dagger m_{\text{seesaw}} \mathbb{L}^* = m_{\text{diag}}^{\text{block}} \]

\[ \nu_L = U \nu + V N \]

\[ V = m_D M_N^{-1} \]

\[ D_m = \text{diag}(m_1, m_2, m_3) \]

\[ D_M = \text{diag}(M_1, M_2, M_3) \]
Type-I seesaw and Leptogenesis:

\[ \mathcal{L}_{\text{BSM}} = Y_{\alpha i}^\nu \bar{\ell}_\alpha \hat{H} N_i + \frac{M_R}{2} \bar{N}_i \epsilon^c N_i + h.c \]

- CP Violation
- Lepton number Violation

Out-of equilibrium decay of RHN

Compare decay rate and Hubble

\[ \Delta L \neq 0 \quad \Rightarrow \quad \Delta B \neq 0 \]

Can it also explain the existence of DM in the Universe?
WIMP vs FIMP:

WIMP (production via freezeout)

\[ \frac{\dot{H}_x}{Y_{DM}^{\text{Eq}}} \frac{dY_{DM}}{dx} = -\Gamma \left[ \left( \frac{Y_{DM}}{Y_{DM}^{\text{Eq}}} \right)^2 - 1 \right] \]

- ann. Rate: \( \Gamma(= n_{DM}^{\text{Eq}} (\sigma v)) \gg H \)
- DM in thermal equilibrium

FIMP (Non-thermal production)

\[ \frac{H_x dY_{DM}}{dx} = Y_{DM}^{\text{Eq}} \frac{K_1}{K_2} \Gamma_{P \rightarrow DM,DM} \]

- DM interact feebly with the bath: \( \Gamma_{P \rightarrow DM,DM} \ll H \)
- DM never reach thermal equilibrium

- Direct detection constraints are applicable

- Direct detection is practically impossible (coupling \( \sim 10^{-10} \))
DM in type-I seesaw:

Can one of the RHN play a role of the DM??

• **Issues:**  
  - **Stability:** RHN should not decay

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

One of the RHN is strictly stable.

Existence of such DM is questionable!!

DM cannot be produced via any interaction.
Our Proposal:

If lightest RHN is considered as a FIMP, it can play a role of a CDM candidate.

How to explain Feebly interacting Massive Particle with coupling $\sim 10^{-10}$ naturally?

Can it be connected to smallness of neutrino masses?

\[
Y^\nu = \begin{pmatrix}
0 & y_{e2} & y_{e3} \\
0 & y_{\mu2} & y_{\mu3} \\
0 & y_{\tau2} & y_{\tau3}
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\epsilon_1 & y_{e2} & y_{e3} \\
\epsilon_2 & y_{\mu2} & y_{\mu3} \\
\epsilon_3 & y_{\tau2} & y_{\tau3}
\end{pmatrix}
\epsilon_i \ll 1
\]
Role of active-sterile mixing:

Entries of Yukawa or Dirac mass matrix (using CI parametrisation):

\[ m_D = -i \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_R & \sin \theta_R \\ 0 & -\sin \theta_R & \cos \theta_R \end{pmatrix} \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \]

\[ D_{\sqrt{m}} = \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) \]

\[ D_{\sqrt{M}} = \text{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) \]

\[ \epsilon_i \propto \sqrt{m_1 M_1} \]

Active-sterile mixing relevent to Lightest RHN:

\[ V_{i1} = m_{D_{i1}}/M_1 = \epsilon_i \frac{v}{\sqrt{2M_1}} \propto \sqrt{\frac{m_1}{M_1}} \]
Effects of active-sterile mixing: production of DM

After S.S.B: Neutrinos get mass

In mass diagonal basis

\[ V_{i1} = m_{D,i1}/M_1 \propto \sqrt{m_1/M_1} \]

\[ \nu_L = U\nu + V N \]

\[ \mathcal{L}_G \subset \frac{g}{\sqrt{2}} W^+_{\mu} \sum_{i,j=1}^{3} \left[ \bar{N}_i^c (V^\dagger)_{ij} \gamma^\mu P_L \ell_j \right] \]

\[ + \frac{g}{2 C_{\theta_W}} Z_{\mu} \times \sum_{i,j=1}^{3} \left[ \bar{\nu}_i (U^\dagger V)_{ij} \gamma^\mu P_L N_j^c + \bar{N}_i^c (V^\dagger V)_{ij} \gamma^\mu P_L N_j^c \right], \]

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

(Assuming \( M_1 < M_W \))
**Evolution of DM:**

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

\[ \frac{dY_{N_i}}{dz} = -\frac{2M_{pl} z}{1.66M_2} \left( g_\rho \right)^{1/2} \left[ (Y_{N_i} - Y_{N_i}^{eq}) \left\langle \Gamma^D \right\rangle + Y_{N_i} \sum_{x=h,z} \left\langle \Gamma(N_i \rightarrow N_1 x) \right\rangle \right], \quad i = 2, 3 \]

| Interaction       | Decay Width                                                                 |
|-------------------|-----------------------------------------------------------------------------|
| \( W \rightarrow N_1 \ell_i \) | \( \frac{M_W^3}{48\pi v^2 M_1^2} (m_D)_{i1}(m_D)_{i1}^* \)               |
| \( Z \rightarrow N_1 \nu_i \) | \( \frac{M_Z^3}{96\pi v^2 M_1^2} (U^+ m_D)_{i1}(U^+ m_D)_{i1}^* \)       |
| \( h \rightarrow N_1 \nu_i \)  | \( \frac{m_h}{32\pi v^2} (U^+ m_D)_{i1}(U^+ m_D)_{i1}^* \)               |
| \( N_i \rightarrow N_1 h \)   | \( \frac{M_i}{64\pi v^2 M_1^2} (m_D m_D)_{i1}(m_D m_D)_{i1}^* \)         |
| \( N_i \rightarrow N_1 Z \)   | \( \frac{M_i}{128\pi v^2 M_1^2} (m_D m_D)_{i1}(m_D m_D)_{i1}^* \)         |
**Inferences:**

- Dominant contribution to Relic density
- DM relic is independent of its mass
  \[ \Omega_{N_1} h^2 \propto M_1 Y_{N_1}(z_\infty) \sim M_1 \frac{m_1}{M_1} \]
- DM relic only depends on lightest active neutrino mass \( m_1 \)
- Correct relic observed for \( m_1 \sim 10^{-12} \text{ eV} \)

\[ Y_{N_1}(z_\infty) = 2.755 \times 10^5 \left( \frac{M_1}{\text{MeV}} \right) \]
Constraints from the decay of the DM:

**Active-sterile mixing → Decay of DM**

- **Via offshell W/Z:**
  \[ N_1 \rightarrow l_1^- l_2^+ \nu_2, \; N_1 \rightarrow l^- q_1 \bar{q}_2, \; N_1 \rightarrow l^- l^+ \nu_l, \; N_1 \rightarrow \nu_l \bar{l}' l', \; N_1 \rightarrow \nu_l q \bar{q}, \; N_1 \rightarrow \nu_l \nu_l \bar{\nu}_l, \; N_1 \rightarrow \nu_l \nu_l \nu_l \]

- **Via offshell h:**
  \[ N_1 \rightarrow \nu_\ell \bar{\ell} \ell \]

- **Radiative decay:**

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

Most stringent bound comes from this
Non-observance of specific X-ray signal: Set a limit on $\theta_1^2$:

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

Take away:

- $N_1$ as a successful FIMP type dark matter below 1 MeV.

- The lower limit on $M_1$ is considered as 1 keV to be in consistent with Tremaine–Gunn bound on sterile neutrino mass.

- 1 keV - 1 MeV mass of $N_1$ as FIMP dark matter is allowed.

$\theta_1^2 = m_1/M_1$ dependence with $m_1$ fixed from relic requirement
Matter-Antimatter Asymmetry:

**Aim:**

Utilise remaining two RHNs to generate BAU
Reduce the hierarchy among RHNs as much as possible.

\[ \mathbf{Y}^\nu = \begin{pmatrix} \epsilon_1 & ye_2 & ye_3 \\ \epsilon_2 & y\mu_2 & y\mu_3 \\ \epsilon_3 & y\tau_2 & y\tau_3 \end{pmatrix} \]

Complex Angle $\theta_R$

Involved in CI

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

Attemps in past

- Lightest RHN is **DM**
- DM produced via **Dodelson-Widrow** Mechanism
- BAU can be explained by coherent oscillation of heavy RHNs (**ARS mechanism**)  

Shortfall

- Need **comparatively larger active-sterile mixing** to produce required relic.
- Such **high mixing** is completely **disallowed** by X-ray exp.
- A variant, **Shi-Fuller mechanism**, can be **operative**; however requires **fine tuning**.
- Other attempts require **additional fields and/or enhanced symmetry**...

SM + 3 RHN

- Lightest RHN is **DM**
- DM **non-thermally produced** predominantly from decay of **SM gauge Bosons** and **higgs**.
- BAU can be explained by **Standard Thermal Leptogenesis** from **CP violating decay** of other **two heavy RHNs**.

Our Scenario

Interesting Features

- Required **active-sterile mixing** to produce DM relic is respecting the **X-ray bound**.
- **Relic density** turns out to be independent to **DM mass**.
- The **smallness of the DM coupling** to the SM fields is connected to the **lightness of the lightest active neutrino mass**.
Conclusion:

Type-I seesaw itself (only with SM + 3 RHNs) provides the MOST MINIMAL PLATFORM to explain neutrino mass, DM (lightest RHN), and baryon asymmetry.

- The feeble interaction of the DM with the bath is connected to the lightness of the active neutrino mass $m_1$.
- Correct relic density uniquely determines $m_1 = \mathcal{O}(10^{-12}) \text{eV}$ (remains falsifiable at KATRIN, PROJECT-8 experiments).
- Relic density turns out to be independent to DM mass.
- DM is non-thermally produced predominantly from the decay of the SM gauge bosons, thanks to the active-sterile neutrino mixing.
- The allowed range of DM mass: 1 keV to 1 MeV.
- BAU can be explained via flavor leptogenesis with $M_{2,3} \sim 10^{9-10} \text{GeV}$.
Thank You!