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?

Inadequacies of the Standard Model → Motivation for BSM

Neutrinos :

What we know:
(from Neutrino oscillation)

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

Don't
What we ^ know:

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

SM Fails to accomodate the tiny neutrino mass

Dark Matter (DM) :

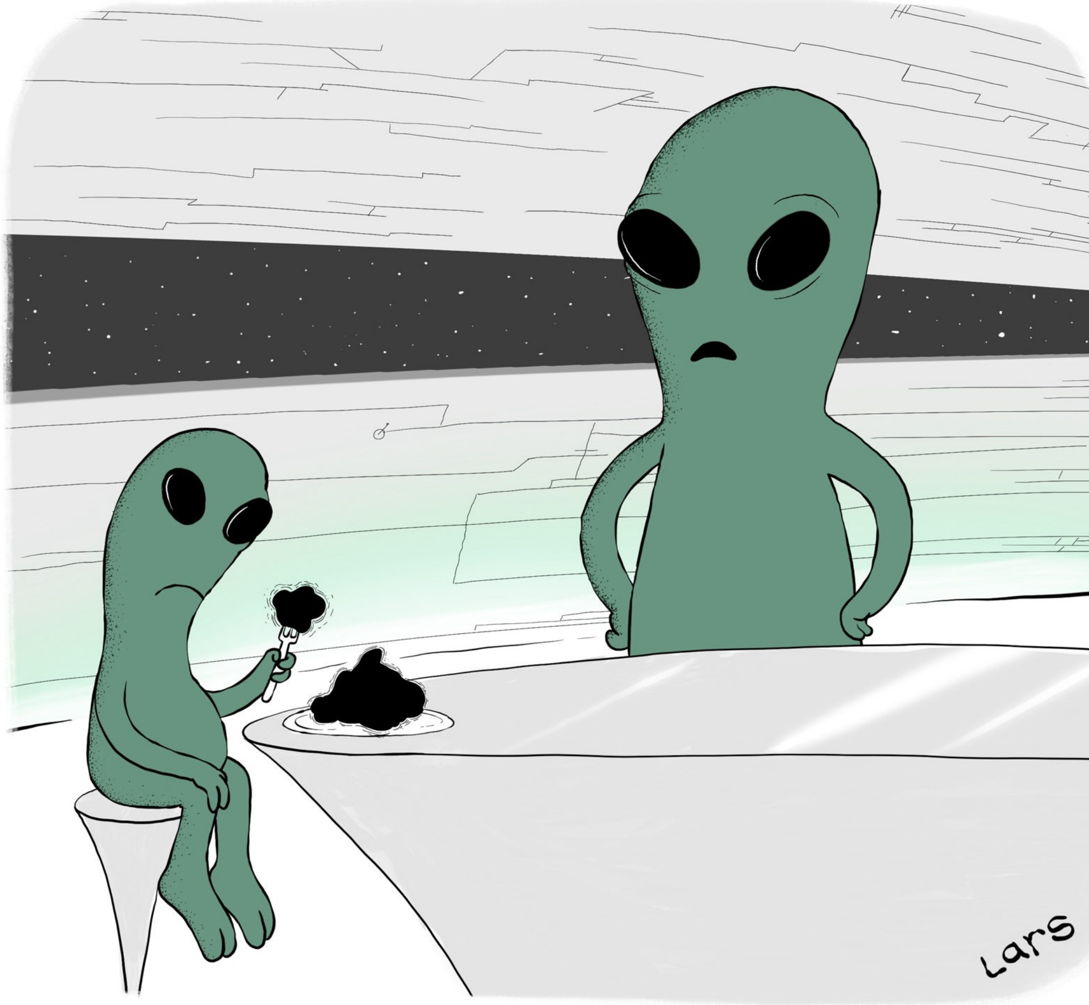
What we know :

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

What we Don't know:

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

No such candidate within SM



"No dessert until you finish your dark matter."

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
(Sakhrov's conditions):

(1) C and CP violation
(2) Baryon number violation
(3) Out-of-equilibrium decay

Not Possible within SM

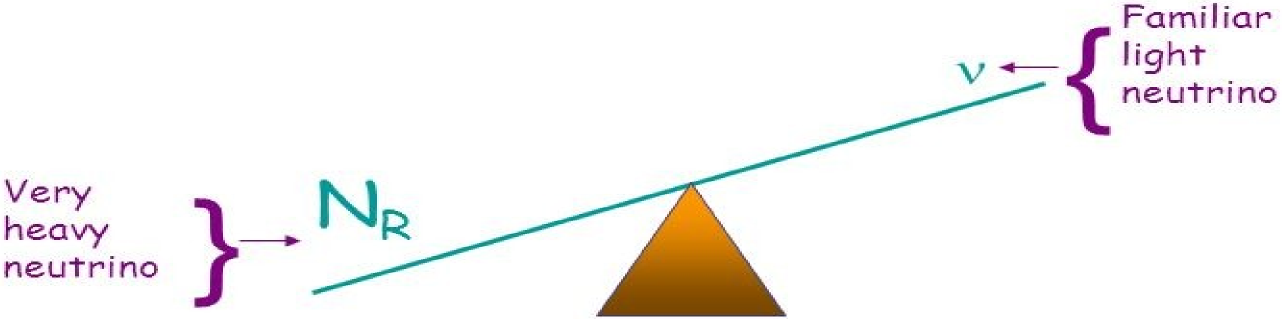
What can be the simplest/minimal possibility to bring these unknowns together?

Type-I Seesaw

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism

(Gell-Mann, Ramond, Slansky (1979), Yanagida(1979), Mohapatra, Senjanovic(1980))



Here are some formulae using the formalism just shown trying to explain what it is all about.

Type-I seesaw and Neutrino mass :

Extension: SM + 3 Right-Handed Neutrinos

$$\mathcal{L}_{\mathbf{BSM}} = \mathbf{Y}^{\nu}_{\alpha \mathbf{i}} \bar{\ell}_{L_\alpha} \tilde{H} N_i + \frac{M_N}{2} \bar{N_i}^c N_i + h.c$$

After S.S.B.

$$\begin{pmatrix} \bar{\nu}_L & \overline{(N_R)^c} \end{pmatrix} \underbrace{\begin{pmatrix} 0_{3\times3} & m^D_{3\times3} \\ m^{D^T}_{3\times3} & M_{N_{3\times3}} \end{pmatrix}}_{m_{seesaw}} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix}$$

$$\mathbb{L}^\dagger m_{seesaw} \mathbb{L}^* = m^{block}_{diag}$$

Active-sterile mixing

$$\begin{pmatrix} m_{\nu_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & M_{N_{3\times3}} \end{pmatrix}$$

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

$$U^\dagger m_\nu U^* = D_m$$

$$\begin{pmatrix} D_{m_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & D_{M_{3\times3}} \end{pmatrix}$$

$$\nu_L = U\nu + VN$$

$$\mathbf{V = m_D M_N^{-1}}$$

$$\mathbf{D_m} = \mathrm{diag}(\mathrm{m_1, m_2, m_3})$$

$$D_M = \mathrm{diag}(\mathrm{M_1, M_2, M_3})$$

Type-I seesaw and Leptogenesis :

$$\mathcal{L}_{\rm BSM} = \mathbf{Y}^{\nu}_{\alpha \mathbf{i}} \bar{\ell}_{L_\alpha} \tilde{H} N_i + \frac{M_R}{2} \bar{N_i}^c N_i + h.c$$

CP Violation

Lepton number Violation

Out-of equilibirum decay of RHN → Compare decay rate and Hubble

$$\Delta \mathrm{L} \neq 0 \xrightarrow{\text{Sphaleron Process}} \Delta \mathrm{B} \neq 0$$

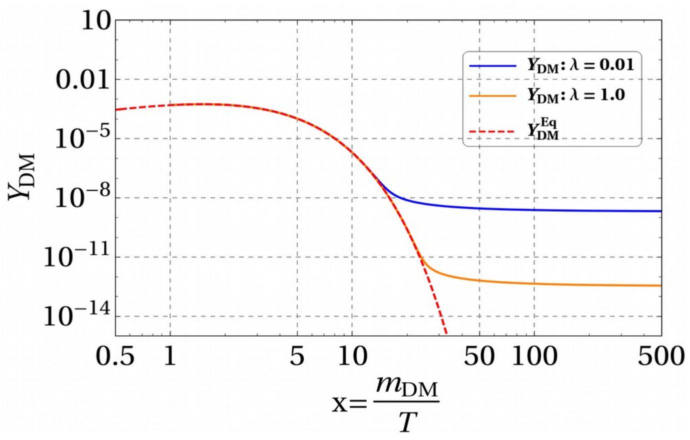
Can it also explain the existence of DM in the Universe?

WIMP vs FIMP :

WIMP (abundance via freeze-out)

$$\frac{Hx}{Y_{DM}^{Eq}}\frac{dY_{DM}}{dx} = -\Gamma\left[\left(\frac{Y_{DM}}{Y_{DM}^{Eq}}\right)^2 - 1\right]$$

- **ann. Rate:** $\Gamma(= n_{DM}^{Eq}\langle\sigma v\rangle) >> H$
- **DM in thermal equilibrium**

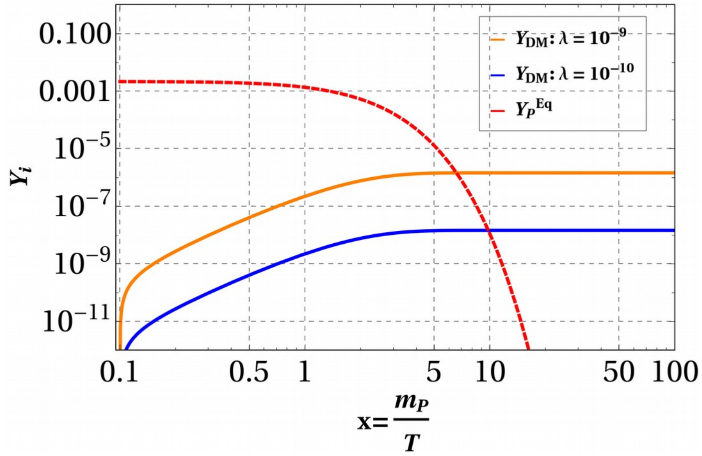


- **Direct detection constraints are applicable**

FIMP (abundance via freeze-in)

$$Hx\frac{dY_{DM}}{dx} = Y_p^{Eq}\frac{K_1}{K_2}\Gamma_{P\to DM,DM}$$

- **DM interact feebly with the bath :** $\Gamma_{P\to DM,DM} << H$
- **DM never reach thermal equilibrium**



- **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 ?

$$Y^{\nu} = \begin{pmatrix} 0 & y_{e2} & y_{e3} \\ 0 & y_{\mu 2} & y_{\mu 3} \\ 0 & y_{\tau 2} & y_{\tau 3} \end{pmatrix} \longrightarrow \begin{pmatrix} \epsilon_1 & y_{e2} & y_{e3} \\ \epsilon_2 & y_{\mu 2} & y_{\mu 3} \\ \epsilon_3 & y_{\tau 2} & y_{\tau 3} \end{pmatrix} \qquad \epsilon_i << 1$$

Role of active-sterile mixing:

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

$$\mathbf{m_D = -i\,U D_{\sqrt{m}} R^T D_{\sqrt{M}}} \longrightarrow \epsilon_i \propto \sqrt{m_1 M_1}$$

$$\mathbf{D}_{\sqrt{\mathbf{m}}} = \mathrm{diag}(\sqrt{\mathrm{m}_1}, \sqrt{\mathrm{m}_2}, \sqrt{\mathrm{m}_3})$$

$$\mathbf{D}_{\sqrt{\mathbf{M}}} = \mathrm{diag}(\sqrt{\mathrm{M}_1}, \sqrt{\mathrm{M}_2}, \sqrt{\mathrm{M}_3})$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_R & \sin\theta_R \\ 0 & -\sin\theta_R & \cos\theta_R \end{pmatrix}$$

θ_R → **Complex Angle**

Active-sterile mixing relevent to Lightest RHN:

$$V_{i1} = m_{D_{i1}}/M_1 = \epsilon_i \frac{v}{\sqrt{2}M_1} \propto \sqrt{\frac{m_1}{M_1}}$$

Effects of active-sterile mixing: production of DM

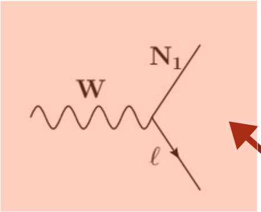
After S.S.B: → Neutrinos get mass

$V_{i1} = m_{D_{i1}}/M_1 \propto \sqrt{\frac{m_1}{M_1}}$

In mass diagonal basis

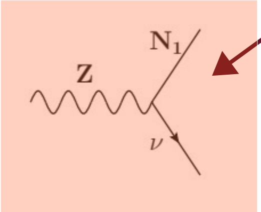
$$\nu_L = U\nu + VN$$

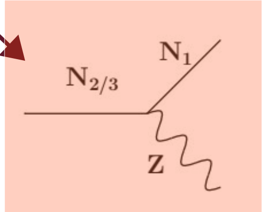
Gauge Interaction



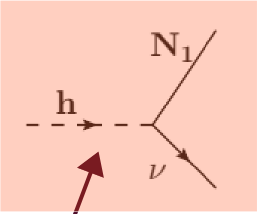
$$\mathcal{L}_{\mathcal{G}} \subset \frac{g}{\sqrt{2}} W_\mu^+ \sum_{i,j=1}^{3} \left[\bar{N}_i^c (V^\dagger)_{ij} \gamma^\mu P_L \ell_j\right]$$

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



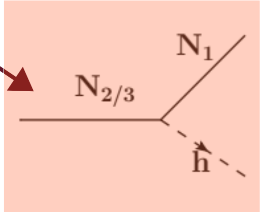


Yukawa Interaction



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

$$\left. + \bar{N}_i^c (V^\dagger V)_{ij} M_j N_j\right],$$



(Assuming $\mathrm{M_1 < M_W}$)

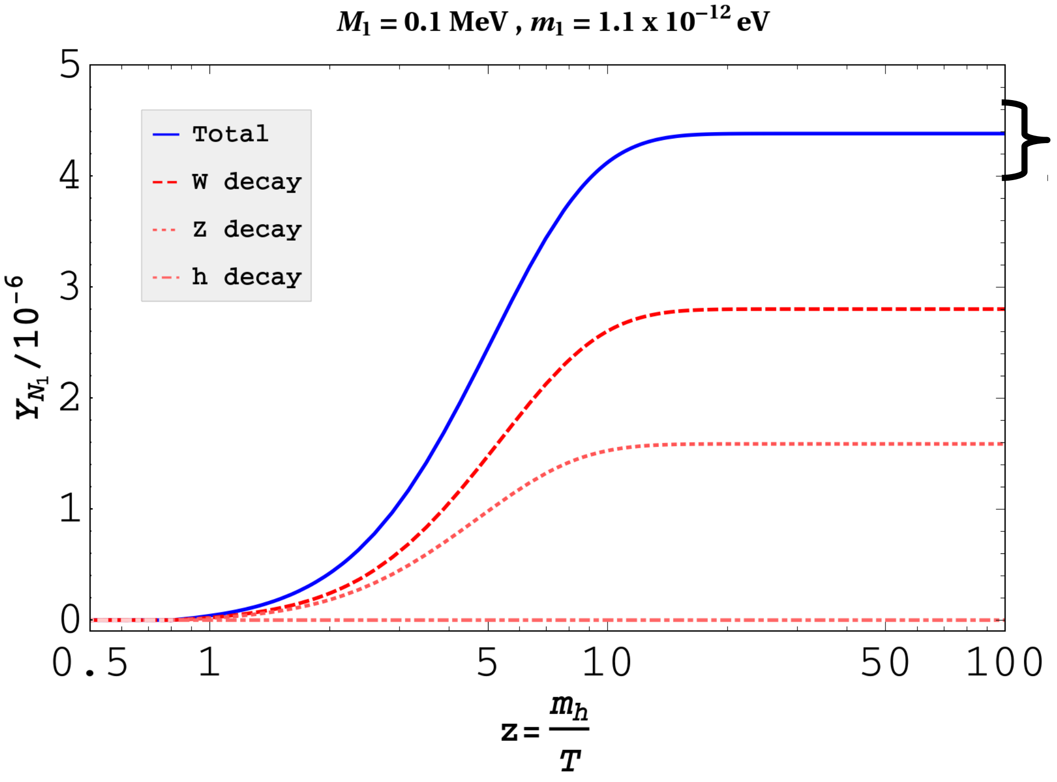
Evolution of DM:

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

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

Interaction	Decay Width
$W\to N_1\ell_i$	$\frac{M_W^3}{48\pi v^2 M_1^2}(m_D)_{i1}(m_D)_{i1}^*$
$Z\to N_1\nu_i$	$\frac{M_Z^3}{96\pi v^2 M_1^2}(U^\dagger m_D)_{i1}(U^\dagger m_D)_{i1}^*$
$h\to N_1\nu_i$	$\frac{m_h}{32\pi v^2}(U^\dagger m_D)_{i1}(U^\dagger m_D)_{i1}^*$
$N_i\to N_1h$	$\frac{M_i}{64\pi v^2 M_1^2}(m_D^\dagger m_D)_{1i}(m_D^\dagger m_D)_{1i}^*$
$N_i\to N_1Z$	$\frac{Mi}{128\pi v^2 M_1^2}(m_D^\dagger m_D)_{1i}(m_D^\dagger m_D)_{1i}^*$

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



$Y_{N_1}(z_\infty)$

Inferences:

- Dominant contribution to Relic density ← $W^{\pm}$ decay, Z decay
- DM relic is independent of its mass

$$\Omega_{N_1} h^2 \propto M_1 Y_{N_1}(Z_\infty) \sim M_1 \Gamma_{W/Z} \sim M_1 \frac{m_1}{M_1}$$

- DM relic only depends on lightest active neutrino mass m_1
- Correct relic observed for $m_1 \sim 10^{-12}$ eV

Constraints from the decay of the DM:

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

- **Via offshell W/Z:**

$$\mathrm{N}_1 \to l_1^- l_2^+ \nu_{l_2},\ N_1 \to l^- q_1 \bar{q}_2,\ N_1 \to l^- l^+ \nu_l,\ N_1 \to \nu_l \bar{l}' l',\ N_1 \to \nu_l q \bar{q},\ N_1 \to \nu_l \nu_{l'} \bar{\nu}_{l'},\ N_1 \to \nu_l \nu_l \bar{\nu}_l$$

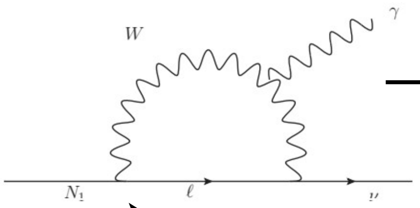
- **Via offshell h:**

$$N_1 \to \nu_\ell \bar{\ell} \ell$$

- **Radiative decay:**

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

$\mathbf{N_1} \to \gamma\nu$ →



V_{i1}

→

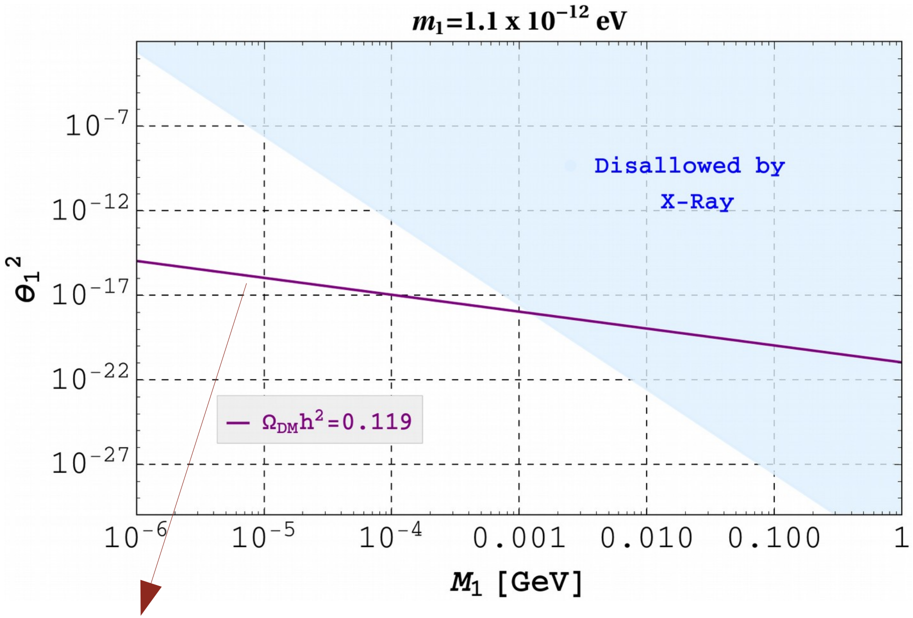
$$\Gamma_{N_1 \to \gamma\nu} = \frac{9\alpha G_F^2}{1024\pi^4} \sin^2 2\theta_1 M_1^5$$

Most stringent bound comes from this

Constraints :

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

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



$\theta_1^2 = m_1/M_1$ **dependence with** m_1 **fixed from relic requirement**

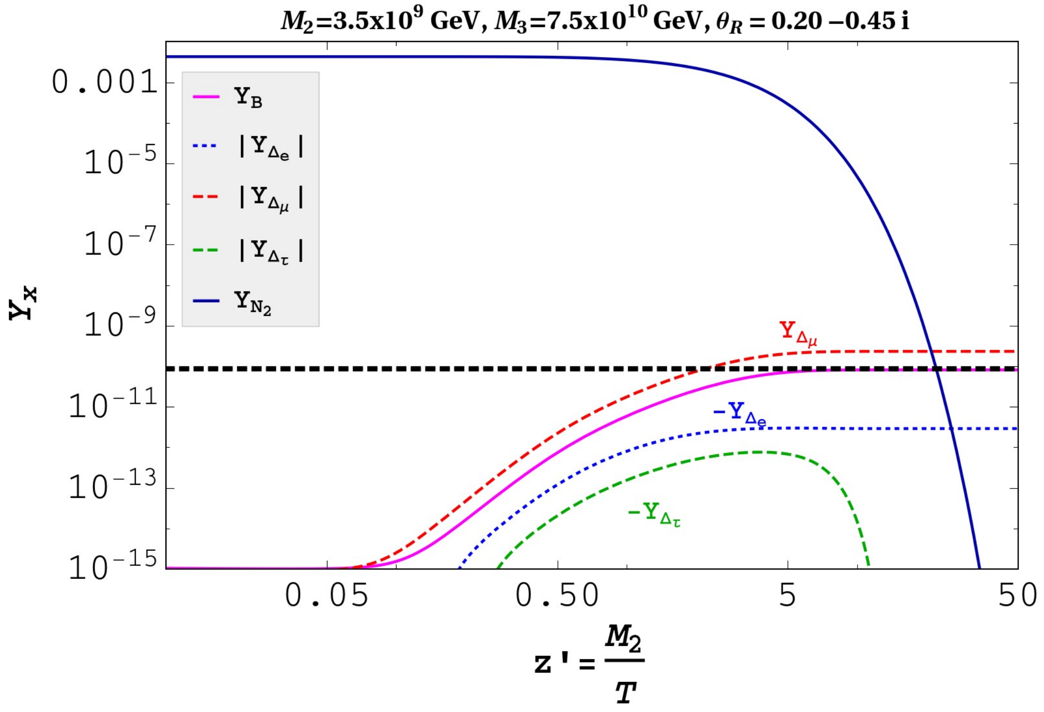
Take away:

- 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.

Matter-Antimatter Asymmetry:

Aim:

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



$$\mathbf{Y}^\nu = \begin{pmatrix} \epsilon_1 & y_{e2} & y_{e3} \\ \epsilon_2 & y_{\mu 2} & y_{\mu 3} \\ \epsilon_3 & y_{\tau 2} & y_{\tau 3} \end{pmatrix}$$

Complex Angle $\theta_{\mathbf{R}}$

Involved in CI

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

Whats new? :

SM + 3 RHN

Attemps in past

νMSM

- 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…**

Our Scenario

- 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.**

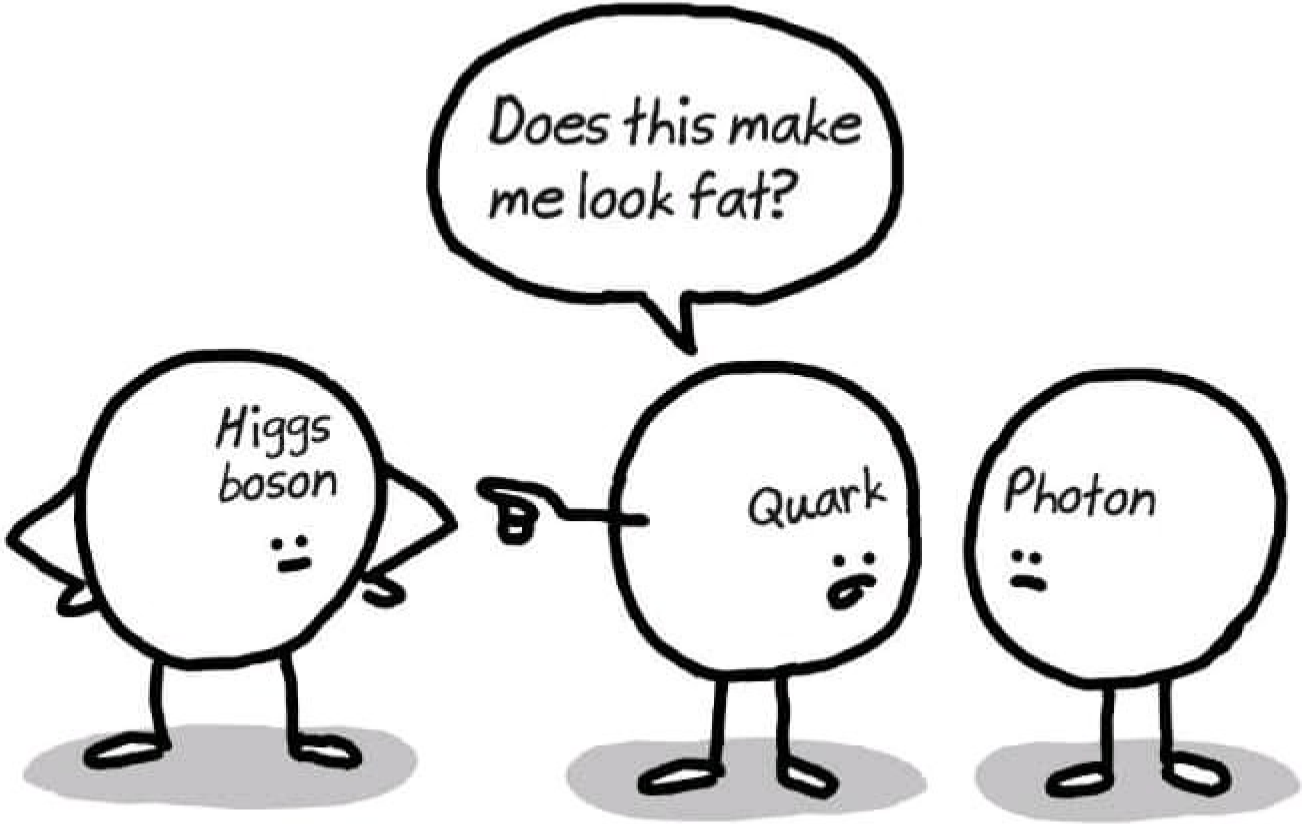
Interesting Features

- 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 $m_1 = \mathcal{O}(10^{-12})$ **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 $M_{2,3} \sim 10^{9-10}$ **GeV**.



Thank You !