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

Based on

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"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 differences**
- **CP-violating phase (?)**

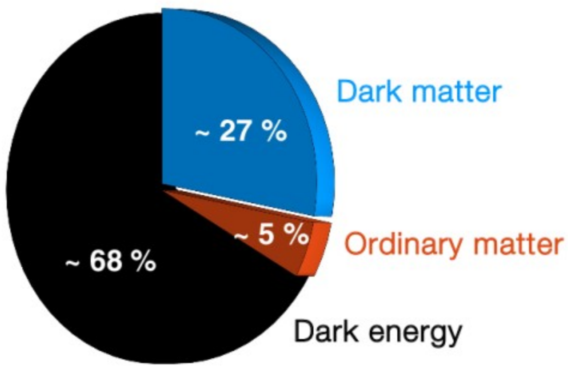
What we Don't know:

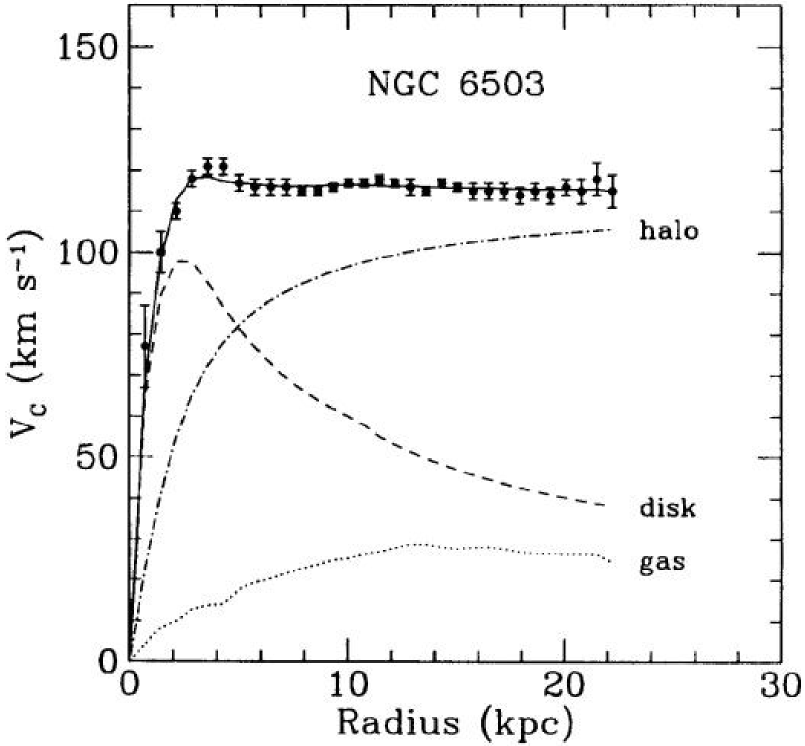
- **Origin of neutrino mass**
- **Nature [Dirac/Majorana]**
- **Absolute neutrino mass**

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 (**~27 % 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

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:

Baryogenesis

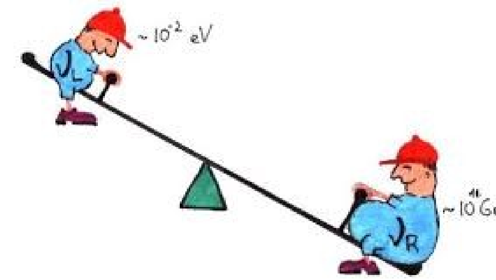
- C and CP violation
- Baryon number violation
- Out-of-equilibrium decay

Not Possible within SM with a Higgs mass 125 GeV

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

Type-I Seesaw

Type-I seesaw and Neutrino mass



[SM + 3 Right-Handed Neutrinos]

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

After S.S.B.

$$\begin{pmatrix} \bar{\nu}_L & \overline{(N_R)^c} \end{pmatrix} \underbrace{\begin{pmatrix} 0_{3\times3} & m^D_{3\times3} \\ m^{D^T}_{3\times3} & M_{N_{3\times3}} \end{pmatrix}}_{m_{seesaw}} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix} \xrightarrow{\mathbb{L}^\dagger m_{seesaw} \mathbb{L}^* = m^{block}_{diag}} \begin{pmatrix} m_{\nu_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & M_{N_{3\times3}} \end{pmatrix}$$

Active-sterile mixing

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

$$\nu_L = U\nu_m + \underbrace{V}_{\mathrm{V = m_D M_N^{-1}}} N_m$$

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

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

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

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

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 equilibrium decay of RHN $\longrightarrow$ **Compare decay rate and Hubble**

Sphaleron Process

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

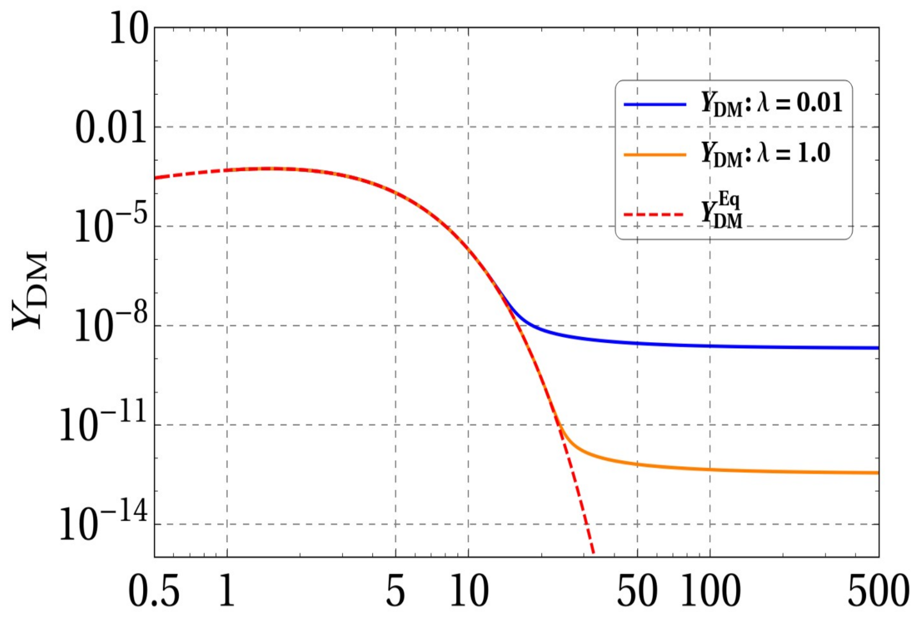
Can it also explain the existence of DM in the Universe?

WIMP (Weakly Interacting) vs FIMP (Feebly Interacting) DM

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**

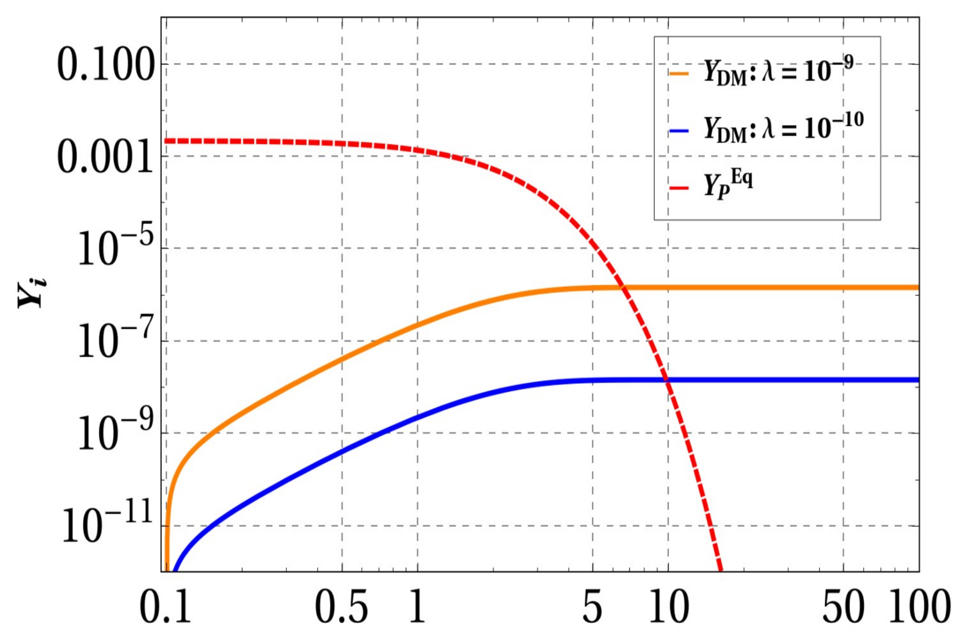


- **Direct detection constraints are applicable**

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 reaches thermal equilibrium**



- **Direct detection is practically impossible (coupling $\simeq 10^{-10}$)**

Earlier Attempt: The νMSM Scenario

[Asaka, Blanchet and Shaposhnikov Phys. Lett. B 631 (2005)]

- The lightest RHN $\mathbf{N_1}$ acts as DM, while other two takes care of BAU and neutrino mass
  [In this minimal case, $\mathbf{N_1}$ can't be WIMP type, decays otherwise!]

- Production of DM proceeds via Dodelson-Widrow (DW) mechanism
  [Dodelson, Widrow PRL 72 (1994)]

Sterile neutrino mass eigenstate has a small active neutrino component due to tiny active-sterile mixing:

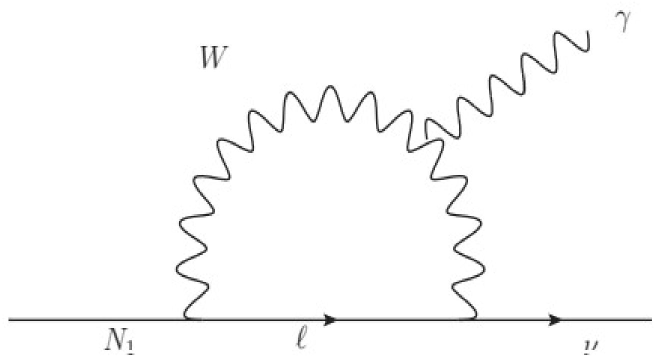
$$N_m = \cos\theta_s N_\alpha + \sin\theta_s \nu_{L\alpha}$$

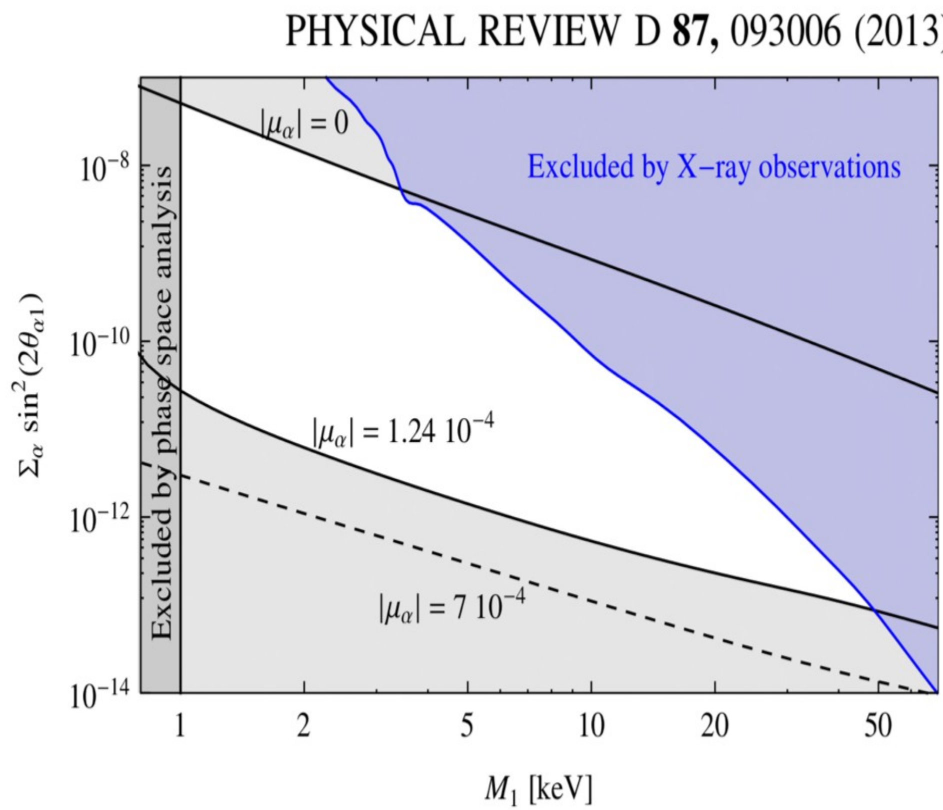
- Sterile neutrinos cannot be in thermal equilibrium before BBN
- DM generated via active to sterile neutrino oscillation (non-resonant)

$$\Omega_{N_1} h^2 \sim 0.1 \left(\frac{\theta}{10^{-4}}\right)^2 \left(\frac{M_1}{\text{keV}}\right)^2$$

DW in νMSM Continued..

But, it would decay to X-rays





Decay rate:

$$\Gamma_{N_1 \to \gamma\nu} = \frac{9\,\alpha\,G_F^2}{1024\pi^4}\sin^2(2\theta_1)\,M_1^5 \simeq 5.5\times 10^{-22}\ \theta_1^2\left[\frac{M_1}{\mathrm{keV}}\right]^5\ \mathrm{s}^{-1}$$

This possibility is ruled out by X-ray limits.

Shi-Fuller Mechanism: may save it by producing N_1 through resonantly enhanced Active-sterile mixing induced by a precise (fine tuned) pre-existing lepton asymmetry.

DM in Type-I seesaw

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

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

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

One of the RHN is strictly Stable

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

Existence of such DM is questionable!!

Lightest neutrino mass: m_1=0

DM cannot be produced via any interaction

Our Attempt to the problem

If **lightest RHN (N_1)** is considered as a **FIMP**, it can play the role of a CDM candidate.

Feebly interacting Massive Particle requires a coupling $\sim 10^{-10}$ **. Can such small coupling be explained naturally ?**

Can it be connected to the smallness of neutrino masses ?

With $L_B = 0$, N1 is absolutely stable;
With $L_B \neq 0$, N1 may have feeble interaction

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

L_B R_B

$\epsilon_i \propto \sqrt{m_1 M_1}$ Followed from CI parametrization of Y^{ν} : $Y_{\nu} = -i\frac{\sqrt{2}}{v} U D_{\sqrt{m}} R D_{\sqrt{M}}$

[JA Casas, 2001]

Active-sterile mixing associated to M₁

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

$$\mathrm{m_D} = -\mathrm{i}\ \mathrm{U} \mathrm{D}_{\sqrt{\mathrm{m}}} \mathrm{R}^{\mathrm{T}} \mathrm{D}_{\sqrt{\mathrm{M}}} \longrightarrow$$

Entries of L_B

$$\epsilon_i \propto \sqrt{m_1 M_1}$$

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

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

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

Complex Angle

Active-sterile mixing relevant to Lightest RHN:

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

As in the limit: $m_1 \to 0$, the entire column $L_B \to 0$, the smallness of m_1 is connected with smallness of the active-sterile mixing V_{i1}.

Neutral and Charged Current Interaction

$$\mathcal{L}^{l}_{CC} = \frac{g}{\sqrt{2}} W^{+}_{\mu} \sum_{\alpha=1}^{3} \bar{\nu}_{L\alpha} \gamma^{\mu} e_{L\alpha}$$

$$\mathcal{L}^{\nu}_{CC} = \frac{g}{2\cos\theta_w} Z_{\mu} \sum_{\alpha=1}^{3} \bar{\nu}_{L_\alpha} \gamma^{\mu} \nu_{L_\alpha}$$

$$\nu_L = U\nu_m + VN_m$$

Let us consider N_1 to be lighter than SM gauge bosons, while $N_{2,3}$ are much heavier

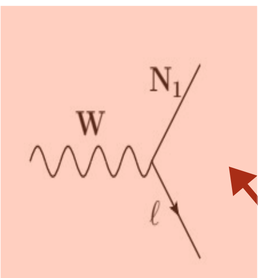
Effects of active-sterile mixing V_{i1}: production of DM

After S.S.B: → **Neutrinos get mass**

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

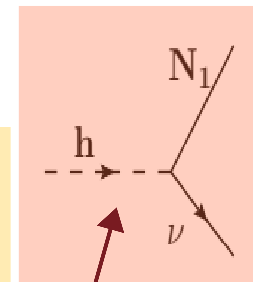
In mass diagonal basis

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



Gauge Interaction

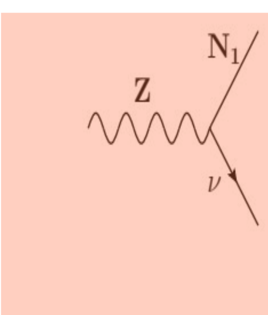
Yukawa Interaction

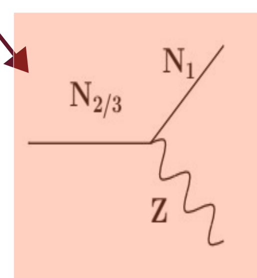


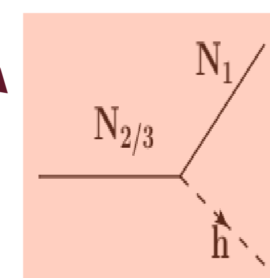
$$\mathcal{L}_{\mathcal{G}} \subset \frac{g}{\sqrt{2}} W_\mu^+ \sum_{i,j=1}^{3} \left[\bar{N}_i^c (V^\dagger)_{ij} \gamma^\mu P_L \ell_j\right]$$

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

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







Assuming $\mathrm{M_1 < M_W}$

Evolution of DM:

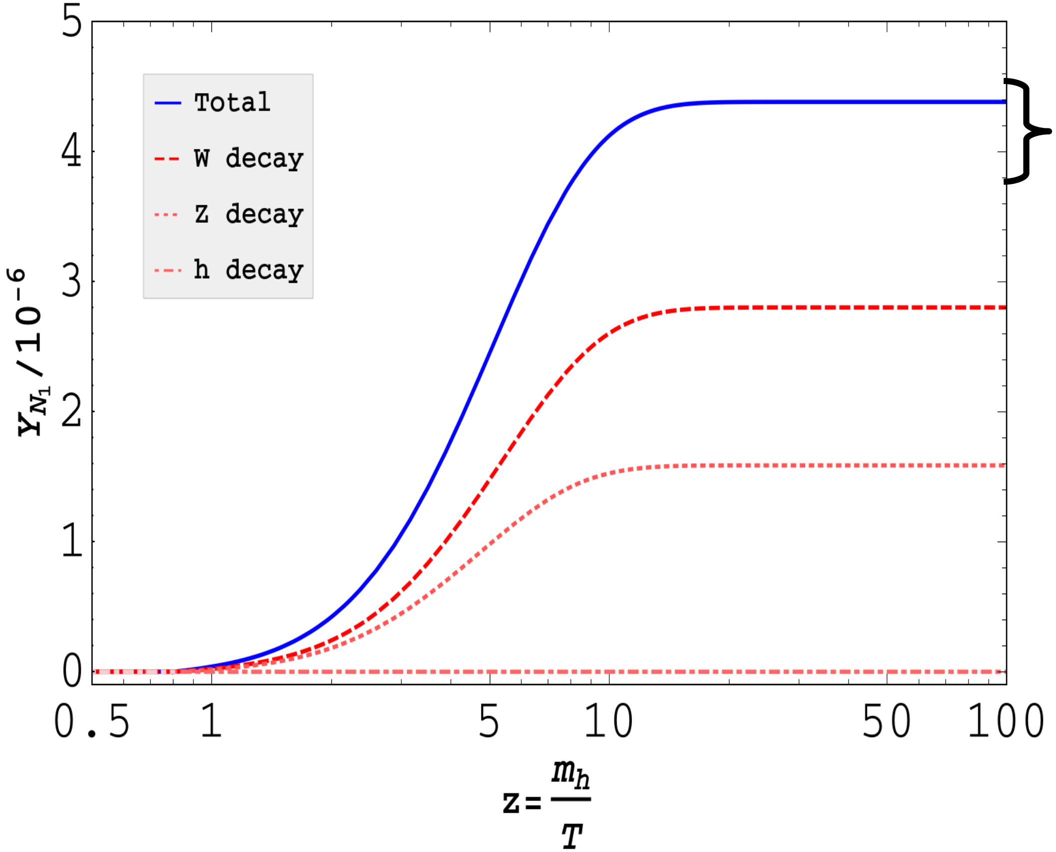
$$\frac{dY_{N_1}}{dz} = \frac{2M_{pl}z}{1.66m_h^2}\frac{g_\rho^{1/2}}{g_s}\left[\sum_{i=2,3}\left(Y_{N_i}\sum_{x=Z,W}\left\langle\Gamma(N_i\to N_1 x)\right\rangle\right)+\sum_{x=W,Z,h}Y_x^{eq}\times\left\langle\Gamma(x\to N_1\ell)\right\rangle\right],$$

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

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

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

$M_1 = 0.1$ MeV , $m_1 = 1.1 \times 10^{-12}$ eV



$Y_{N_1}(z_\infty)$

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**

- **Correct relic observed for** $m_1 \sim 10^{-12}$ eV

Recall that $\Gamma_{W/Z} \propto |V_{i1}|^2 \simeq |\sqrt{m_1/M_1}|^2$

Constraints from the decay of the DM

Active-sterile mixing $\longrightarrow$ **Decay of DM**

- **Via off-shell W/Z**

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

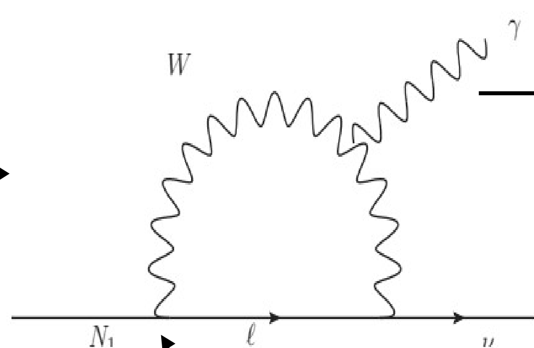
- **Via off-shell higgs**

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

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

- **Radiative decay:**

$\mathrm{N}_1 \to \gamma\nu$ $\longrightarrow$



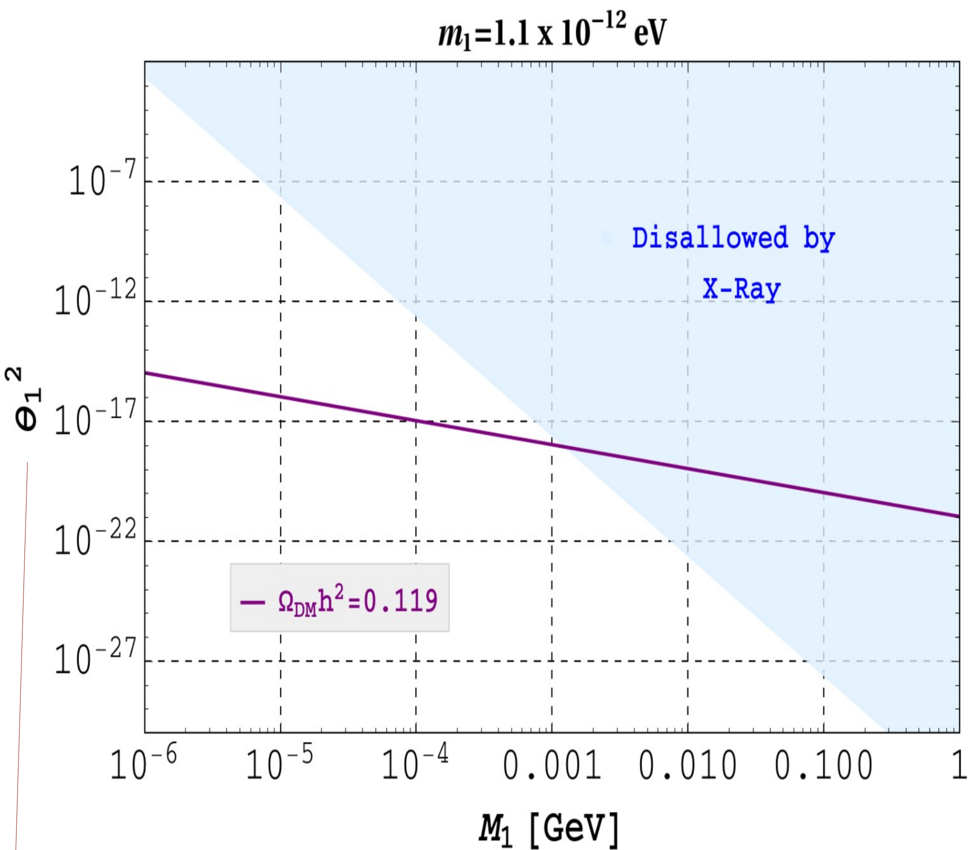
V_{i1}

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

Most stringent bound comes from this

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

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



$\theta_1^2 = \mathrm{m}_1/\mathrm{M}_1$ **dependence with m_1 fixed from relic requirement**

Inferences:

→ **N1** as a successful FIMP type dark matter below **1 MeV**

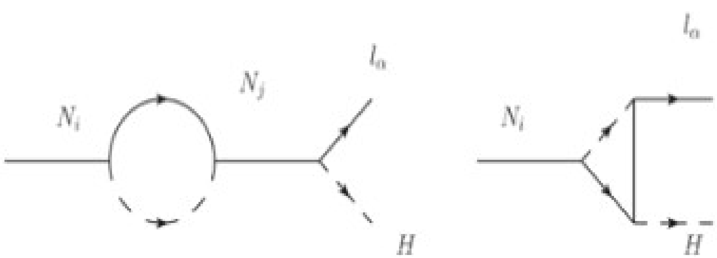
→ The lower limit on M_1 is considered as **1 keV** (to be in consistent with **Tremaine–Gunn bound)**.

→ **Hence 1 keV - 1 MeV** mass of N_1 as **FIMP dark matter** is allowed.

Matter-Antimatter Asymmetry:

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**)

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

Matter-Antimatter Asymmetry:

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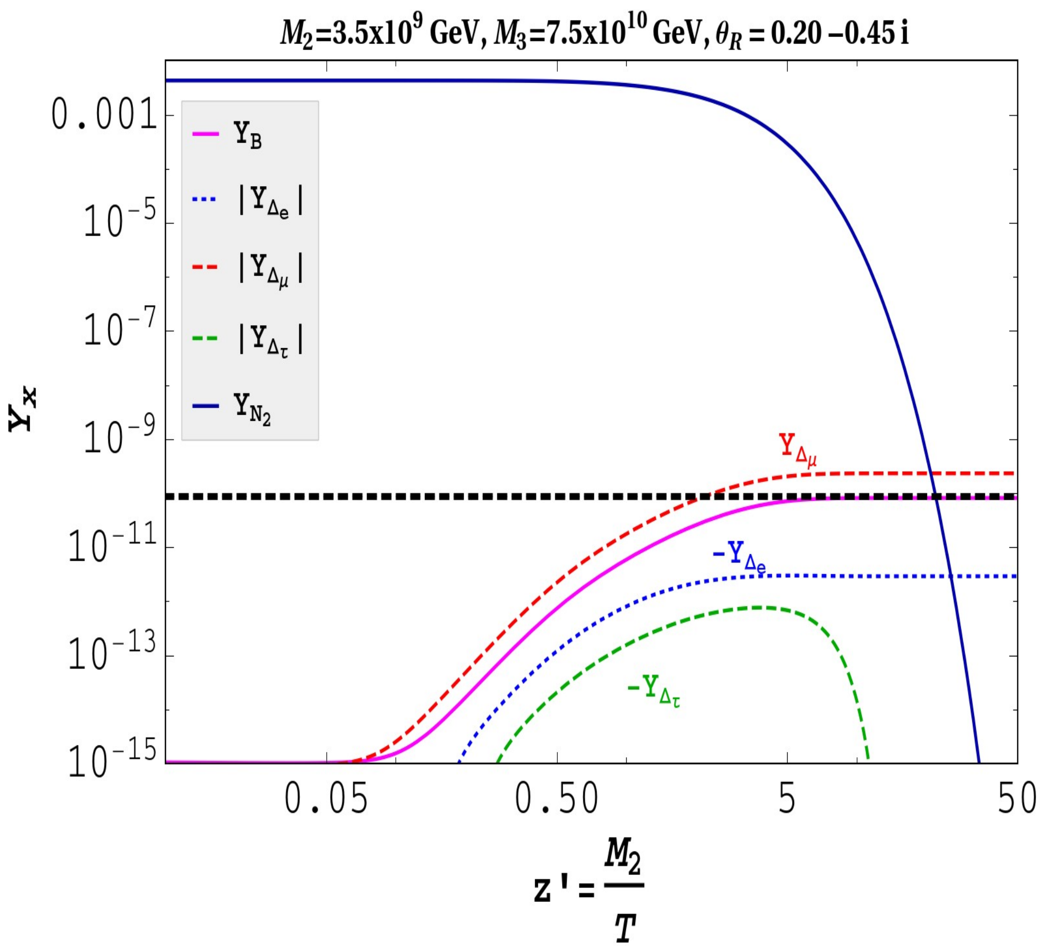
Complex angle $\theta_{\mathbf{R}}$

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

Attempts 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.**

Thank You !