Baryon Asymmetry, Dark Matter & Neutrino Mass via Exotic Multiplets

Sandy S. C. Law

National Cheng Kung University
Tainan, TAIWAN

It is clear that some kind of extension to the standard model (SM) is required in order to solve the problems of cosmic **baryon asymmetry**, **dark matter** (DM) or **neutrino mass**.

Motivation & Overview

It is clear that some kind of extension to the standard model (SM) is required in order to solve the problems of cosmic **baryon asymmetry**, **dark matter** (DM) or **neutrino mass**.

Among the numerous ways to extend the SM, in this work, we have explored the possibility of solving **all** these issues via the introduction of **exotic multiplets**.

Ref: C.-H. Chen and S. S. C. Law, *Phys. Rev.* D85 055012 (2012) [arXiv:1111.5462 [hep-ph]]

Motivation & Overview

It is clear that some kind of extension to the standard model (SM) is required in order to solve the problems of cosmic **baryon asymmetry**, **dark matter** (DM) or **neutrino mass**.

Among the numerous ways to extend the SM, in this work, we have explored the possibility of solving **all** these issues via the introduction of **exotic multiplets**.

Ref: C.-H. Chen and S. S. C. Law, *Phys. Rev.* D85 055012 (2012) [arXiv:1111.5462 [hep-ph]]

Originally, the investigation of these multiplets was motivated by the idea of "*minimal dark matter*" where their stability is guaranteed by the SM gauge symmetry alone [Cirelli et al., Nucl. Phys. B753,178 (06); B787,152 (07); New J. Phys.11,105005 (09)] .

Motivation & Overview

It is clear that some kind of extension to the standard model (SM) is required in order to solve the problems of cosmic **baryon asymmetry**, **dark matter** (DM) or **neutrino mass**.

Among the numerous ways to extend the SM, in this work, we have explored the possibility of solving **all** these issues via the introduction of **exotic multiplets**.

Ref: C.-H. Chen and S. S. C. Law, *Phys. Rev.* D85 055012 (2012) [arXiv:1111.5462 [hep-ph]]

Originally, the investigation of these multiplets was motivated by the idea of "*minimal dark matter*" where their stability is guaranteed by the SM gauge symmetry alone [Cirelli et al., Nucl. Phys. B753,178 (06); B787,152 (07); New J. Phys.11,105005 (09)] .

Since it is well-known that neutrino mass (i.e. lepton number violation) may be linked to WIMP-like DM when it is generated by loop diagrams [Krauss et al., Phys. Rev. D67 085002 (03); Ma, Phys. Rev. D73 077301 (06)], it is sensible to ask if a model with these multiplets can simultaneously provide a solution to the three problems above.

Motivation & Overview

It is clear that some kind of extension to the standard model (SM) is required in order to solve the problems of cosmic **baryon asymmetry**, **dark matter** (DM) or **neutrino mass**.

Among the numerous ways to extend the SM, in this work, we have explored the possibility of solving **all** these issues via the introduction of **exotic multiplets**.

<u>Ref</u>: C.-H. Chen and S. S. C. Law, *Phys. Rev.* D85 055012 (2012) [arXiv:1111.5462 [hep-ph]]

Originally, the investigation of these multiplets was motivated by the idea of "*minimal dark matter*" where their stability is guaranteed by the SM gauge symmetry alone [Cirelli et al., Nucl. Phys. B753,178 (06); B787,152 (07); New J. Phys.11,105005 (09)] .

Since it is well-known that neutrino mass (i.e. lepton number violation) may be linked to WIMP-like DM when it is generated by <u>loop diagrams</u> [Krauss et al., Phys. Rev. D67 085002 (03); Ma, Phys. Rev. D73 077301 (06)], it is sensible to ask if a model with these multiplets can simultaneously provide a solution to the three problems above.

Some related references: Cai et al., JHEP 1112 054 (2011) [arXiv:1108.0969 [hep-ph]]
Kumericki et al., arXiv:1204.6597 [hep-ph]
Kumericki et al., arXiv:1204.6599 [hep-ph]

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets	N_k $\sim$ $(1, 5, 0)$	$\times$ **3** generations $(k = 1, 2, 3.)$
scalar 6-plets	χ $\sim$ $(1, 6, -1/2)$	$\times$ **1** only

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets $N_k \sim (1, 5, 0)$ × **3** generations (k = 1, 2, 3.)

scalar 6-plets $\chi \sim (1, 6, -1/2)$ × **1** only

Why 5-plet N?   Suppose we want the lightest N_k as dark matter, then

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets $\qquad N_k \sim (1, 5, 0) \qquad \times\, 3$ generations ($k = 1, 2, 3.$)
scalar 6-plets $\qquad \chi \sim (1, 6, -1/2) \qquad \times\, 1$ only

Why 5-plet N? $\qquad$ Suppose we want the lightest N_k as dark matter, then

$$(1,1,0) \quad \text{or} \quad (1,3,0) \qquad \text{couples to}\ \ L\phi \qquad\qquad \textcolor{red}{\times}$$

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets $\qquad\qquad$ Sandy S. C. Law, NCKU, Taiwan

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets $\qquad N_k \sim (1, 5, 0) \qquad \times$ **3** generations ($k = 1, 2, 3.$)

scalar 6-plets $\qquad \chi \sim (1, 6, -1/2) \qquad \times$ **1** only

Why 5-plet N? Suppose we want the lightest N_k as dark matter, then

$(1,1,0)$ or $(1, 3, 0)$ $\qquad$ couples to $L\phi$ $\qquad$ ✘

$(1, 2, 0)$ or $(1, 4, 0)$ $\qquad$ has fractional charges $\qquad$ ✘

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets	N_k ~ (1, 5, 0)	× **3** generations	(k = 1, 2, 3.)
scalar 6-plets	χ ~ (1, 6, −1/2)	× **1** only	

Why 5-plet N?   Suppose we want the lightest N_k as dark matter, then

(1, 1, 0) or (1, 3, 0)	couples to $L\phi$	✘
(1, 2, 0) or (1, 4, 0)	has fractional charges	✘
(1, 5, 0)	ok	✓

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets	$N_k \sim (1, 5, 0)$	$\times$ **3** generations ($k = 1, 2, 3.$)
scalar 6-plets	$\chi \sim (1, 6, -1/2)$	$\times$ **1** only

Why 5-plet N?   Suppose we want the lightest N_k as dark matter, then

$(1,1,0)$ or $(1, 3, 0)$	couples to $L\phi$	✘
$(1, 2, 0)$ or $(1, 4, 0)$	has fractional charges	✘
$(1, 5, 0)$	ok	✓

Why 6-plet χ?   **After** 5-plet N_k has been chosen, we need a new Yukawa term in the model to connect it to SM leptons, **$L\,\chi\,N$**. SU(2) group theory then implies

$$\underline{2} \times \underline{5} = \underline{4} + \underline{6}$$

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

    fermion 5-plets $N_k \sim (1, 5, 0)$ $\times$ **3** generations ($k = 1, 2, 3.$)

    scalar 6-plets $\chi \sim (1, 6, -1/2)$ $\times$ **1** only

<u>Why 5-plet *N*?</u>   Suppose we want the lightest N_k as dark matter, then

        $(1,1,0)$ or $(1,3,0)$ couples to $L\phi$ ✘

        $(1,2,0)$ or $(1,4,0)$ has fractional charges   ✘

            $(1,5,0)$ ok   ✔

<u>Why 6-plet χ?</u>   **After** 5-plet N_k has been chosen, we need a new Yukawa term in the model to connect it to SM leptons, $L\chi N$. SU(2) group theory then implies

$$\underline{2} \times \underline{5} = \underline{4} + \underline{6}$$

    4-plet χ ok if $\phi^\dagger\phi\phi\chi$ and $\chi^\dagger\chi\chi\phi \ll 1$

    6-plet χ ok if $\chi^\dagger\chi\chi\phi \ll 1$

A Model with Exotic Multiplets

We add to the SM the following **exotic SU(2)$_L$ multiplet** fields:-

| fermion 5-plets | $N_k \sim (1, 5, 0)$ | $\times$ **3** generations $(k = 1, 2, 3.)$ |
| scalar 6-plets | $\chi \sim (1, 6, -1/2)$ | $\times$ **1** only |

<u>Why 5-plet N?</u>   Suppose we want the lightest N_k as dark matter, then

$(1,1,0)$ or $(1,3,0)$	couples to $L\phi$	✘
$(1,2,0)$ or $(1,4,0)$	has fractional charges	✘
$(1,5,0)$	ok	✔

<u>Why 6-plet χ?</u>   **After** 5-plet N_k has been chosen, we need a new Yukawa term in the model to connect it to SM leptons, **$L\chi N$**. SU(2) group theory then implies

$$\underline{2} \times \underline{5} = \underline{4} + \underline{6}$$

4-plet χ ok if $\phi^\dagger\phi\phi\chi$ and $\chi^\dagger\chi\chi\phi \ll 1$

6-plet χ ok if $\chi^\dagger\chi\chi\phi \ll 1$ ✔ our model building choice

A Model with Exotic Multiplets [2]

With these **exotic $SU(2)_L$ multiplet** fields:-

fermion 5-plets $\quad N_k \sim (1, 5, 0) \quad \times$ **3** generations $(k = 1, 2, 3.)$

scalar 6-plets $\quad \chi \sim (1, 6, -1/2) \quad \times$ **1** only

A Model with Exotic Multiplets [2]

With these **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets	$N_k \sim (1, 5, 0)$	$\times$ **3** generations ($k = 1, 2, 3.$)
scalar 6-plets	$\chi \sim (1, 6, -1/2)$	$\times$ **1** only

the SM gauge invariant interaction Lagrangian is given by (when $\chi^\dagger \chi \chi \phi \ll \mathbf{1}$)

$$\mathcal{L}_{\text{int}} = i\overline{N}_k \not{D} N_k + (D^\mu \chi)^\dagger (D_\mu \chi) - \left[h_{jk} \overline{L}_j \chi N_k + \frac{1}{2}\overline{(N_k)^c} M_k N_k + h.c. \right] - V_S \,,$$

$$V_S = \mu_\phi^2 \phi^\dagger \phi + \mu_\chi^2 \chi^\dagger \chi + \frac{\lambda_\phi}{2}\left(\phi^\dagger \phi\right)^2 + \frac{\lambda_{\chi\alpha}}{2}\left(\chi^\dagger \chi\right)_\alpha^2 + \lambda_{\phi\chi\beta}\left(\phi^\dagger \phi \chi^\dagger \chi\right)_\beta + \frac{1}{2}\left[\lambda'_{\phi\chi}(\phi\chi)^2 + h.c.\right]$$

L_j = SM lepton doublet ; ϕ = SM Higgs ; D_μ = covariant derivative.

With these **exotic SU(2)$_L$ multiplet** fields:-

$\quad$ fermion 5-plets $\qquad$ $N_k \sim (1, 5, 0)$ $\qquad$ $\times$ **3** generations ($k = 1, 2, 3.$)

$\quad$ scalar 6-plets $\qquad$ $\chi \sim (1, 6, -1/2)$ $\qquad$ $\times$ **1** only

the SM gauge invariant interaction Lagrangian is given by (when $\chi^\dagger \chi \chi \phi \ll 1$)

$$\mathcal{L}_{\text{int}} = i\overline{N}_k \slashed{D} N_k + (D^\mu \chi)^\dagger (D_\mu \chi) - \left[h_{jk} \overline{L}_j \chi N_k + \frac{1}{2}\overline{(N_k)^c} M_k N_k + h.c. \right] - V_S ,$$

$$V_S = \mu_\phi^2 \phi^\dagger \phi + \mu_\chi^2 \chi^\dagger \chi + \frac{\lambda_\phi}{2}\left(\phi^\dagger \phi\right)^2 + \frac{\lambda_{\chi\alpha}}{2}\left(\chi^\dagger \chi\right)_\alpha^2 + \lambda_{\phi\chi\beta}\left(\phi^\dagger \phi \chi^\dagger \chi\right)_\beta + \frac{1}{2}\left[\lambda'_{\phi\chi}(\phi\chi)^2 + h.c.\right]$$

L_j = SM lepton doublet ; ϕ = SM Higgs ; D_μ = covariant derivative.

Required fine-tunings of the scalar potential, V_S, to ensure stability of the lightest N_k

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets $\qquad$ Sandy S. C. Law, NCKU, Taiwan

A Model with Exotic Multiplets [2]

With these **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets	N_k ~ (1, 5, 0)	× **3** generations (k = 1, 2, 3.)
scalar 6-plets	χ ~ (1, 6, −1/2)	× **1** only

the SM gauge invariant interaction Lagrangian is given by (when $\chi^\dagger\chi\chi\phi \ll 1$)

$$\mathcal{L}_{\text{int}} = i\overline{N}_k\not{D}N_k + (D^\mu\chi)^\dagger(D_\mu\chi) - \left[h_{jk}\,\overline{L}_j\,\chi\,N_k + \frac{1}{2}\overline{(N_k)^c}\,M_k\,N_k + h.c. \right] - V_S\ ,$$

$$V_S = \mu_\phi^2\phi^\dagger\phi + \mu_\chi^2\chi^\dagger\chi + \frac{\lambda_\phi}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_{\chi\alpha}}{2}\left(\chi^\dagger\chi\right)_\alpha^2 + \lambda_{\phi\chi\beta}\left(\phi^\dagger\phi\chi^\dagger\chi\right)_\beta + \frac{1}{2}\left[\lambda'_{\phi\chi}(\phi\chi)^2 + h.c.\right]$$

L_j = SM lepton doublet ; ϕ = SM Higgs ; D_μ = covariant derivative.

Required fine-tunings of the scalar potential, V_S , to ensure stability of the lightest N_k

- $\chi^\dagger\chi\chi\phi \ll 1$ (a technically natural limit) [Kumericki et al., arXiv:1204.6597]

With these **exotic SU(2)$_L$ multiplet** fields:-

fermion 5-plets $N_k \sim (1, 5, 0)$ × **3** generations (k = 1, 2, 3.)

scalar 6-plets $\chi \sim (1, 6, -1/2)$ × **1** only

the SM gauge invariant interaction Lagrangian is given by (when $\chi^\dagger \chi \chi \phi \ll 1$)

$$\mathcal{L}_{\text{int}} = i\overline{N}_k \slashed{D} N_k + (D^\mu \chi)^\dagger (D_\mu \chi) - \left[h_{jk} \overline{L}_j \chi N_k + \frac{1}{2} \overline{(N_k)^c} M_k N_k + h.c. \right] - V_S \,,$$

$$V_S = \mu_\phi^2 \phi^\dagger \phi + \mu_\chi^2 \chi^\dagger \chi + \frac{\lambda_\phi}{2} \left(\phi^\dagger \phi \right)^2 + \frac{\lambda_{\chi\alpha}}{2} \left(\chi^\dagger \chi \right)_\alpha^2 + \lambda_{\phi\chi\beta} \left(\phi^\dagger \phi \chi^\dagger \chi \right)_\beta + \frac{1}{2} \left[\lambda'_{\phi\chi} (\phi\chi)^2 + h.c. \right]$$

L_j = SM lepton doublet ; ϕ = SM Higgs ; D_μ = covariant derivative.

Required fine-tunings of the scalar potential, V_S, to ensure stability of the lightest N_k

- $\chi^\dagger \chi \chi \phi \ll 1$ (a technically natural limit)   [Kumericki et al., arXiv:1204.6597]

- μ_ϕ, μ_χ, λ_ϕ, $\lambda_{\chi\alpha}$, … must be such that VEV $\langle \chi \rangle = 0$

Some important observations & consequences:

A Model with Exotic Multiplets [3]

Some important observations & consequences:

- When $\chi^\dagger \chi \chi \phi \ll 1$ and $\langle \chi \rangle = 0$, the Lagrangian is also invariant under

$$\Psi_{SM} \rightarrow \Psi_{SM} \; ; \; N_k \rightarrow -N_k \; ; \; \chi \rightarrow -\chi$$

which ensures the lightest fermion 5-plet N_k (e.g. N_1) be absolutely stable if $M_\chi > M_1$.

A Model with Exotic Multiplets [3]

Some important observations & consequences:

- When $\chi^\dagger\chi\chi\phi \ll 1$ and $\langle\chi\rangle = 0$, the Lagrangian is also invariant under

$$\Psi_{SM} \rightarrow \Psi_{SM} \; ; \; N_k \rightarrow -N_k \; ; \; \chi \rightarrow -\chi$$

which ensures the lightest fermion 5-plet N_k (e.g. N_1) be absolutely stable if $M_\chi > M_1$.

dark matter candidate

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

A Model with Exotic Multiplets [3]

Some important observations & consequences:

- When $\chi^{\dagger}\chi\chi\phi \ll 1$ and $\langle\chi\rangle = 0$, the Lagrangian is also invariant under

$$\Psi_{SM} \rightarrow \Psi_{SM} \; ; \; N_k \rightarrow -N_k \; ; \; \chi \rightarrow -\chi$$

which ensures the lightest fermion 5-plet N_k (e.g. N_1) be absolutely stable if $M_\chi > M_1$.

dark matter candidate

- The Yukawa coupling $h_{jk}\, \overline{L}_j\, \chi\, N_k$ provides the link to the LH neutrinos

A Model with Exotic Multiplets [3]

Some important observations & consequences:

- When $\chi^\dagger \chi \chi \phi \ll 1$ and $\langle \chi \rangle = 0$, the Lagrangian is also invariant under

$$\Psi_{SM} \rightarrow \Psi_{SM} \; ; \; N_k \rightarrow -N_k \; ; \; \chi \rightarrow -\chi$$

which ensures the lightest fermion 5-plet N_k (e.g. N_1) be absolutely stable if $M_\chi > M_1$.

> dark matter candidate

- The Yukawa coupling $h_{jk} \overline{L}_j \chi N_k$ provides the link to the LH neutrinos

  ❖ but no neutrino Dirac mass term as $\langle \chi \rangle = 0$;

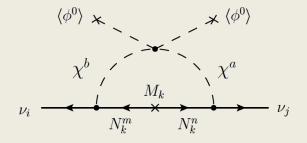Some important observations & consequences:

- When $\chi^\dagger \chi \chi \phi \ll 1$ and $\langle \chi \rangle = 0$, the Lagrangian is also invariant under

$$\Psi_{SM} \rightarrow \Psi_{SM} \; ; \; N_k \rightarrow -N_k \; ; \; \chi \rightarrow -\chi$$

  which ensures the lightest fermion 5-plet N_k (e.g. N_1) be absolutely stable if $M_\chi > M_1$.

  > dark matter candidate

- The Yukawa coupling $h_{jk} \overline{L}_j \chi N_k$ provides the link to the LH neutrinos

  - ❖ but no neutrino Dirac mass term as $\langle \chi \rangle = 0$;
  - ❖ yet, because of the $\lambda'_{\phi\chi}(\phi\chi)^2$ term in V_S, one gets at **one-loop**
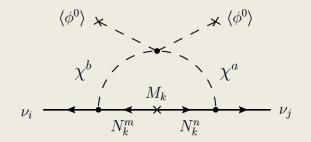
A Model with Exotic Multiplets [3]

Some important observations & consequences:

- When $\chi^\dagger \chi \chi \phi \ll 1$ and $\langle \chi \rangle = 0$, the Lagrangian is also invariant under

$$\Psi_{SM} \to \Psi_{SM} \; ; \; N_k \to -N_k \; ; \; \chi \to -\chi$$

which ensures the lightest fermion 5-plet N_k (e.g. N_1) be absolutely stable if $M_\chi > M_1$.

> dark matter candidate

- The Yukawa coupling $h_{jk} \, \overline{L}_j \, \chi \, N_k$ provides the link to the LH neutrinos

  - ❖ but no neutrino Dirac mass term as $\langle \chi \rangle = 0$;
  - ❖ yet, because of the $\lambda'_{\phi\chi}(\phi\chi)^2$ term in V_S, one gets at **one-loop**

> neutrino masses

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Some important observations & consequences (*continued*):

Sandy S. C. Law, NCKU, Taiwan

A Model with Exotic Multiplets [4]

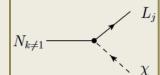Some important observations & consequences (*continued*):

- Although the lightest N_1 is stable, the **heavier 5-plet fermion N_2** (or N_3) may decay via the Yukawa term

$$h_{jk}\,\overline{L}_j\,\chi\,N_k$$

  if mass $M_{2,3} > M_\chi$.

A Model with Exotic Multiplets [4]

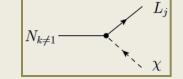Some important observations & consequences (*continued*):

- Although the lightest N_1 is stable, the **heavier 5-plet fermion N_2** (or N_3) may decay via the Yukawa term

$$h_{jk}\,\overline{L}_j\,\chi\,N_k$$

if mass $M_{2,3} > M_\chi$.

Suppose couplings $\boldsymbol{h_{jk}}$ contains CP violating phases, then (in principle) a **lepton asymmetry** can be generated in the early universe. As a result, the cosmic baryon asymmetry can be explained via leptogenesis.

A Model with Exotic Multiplets [4]

Some important observations & consequences (*continued*):

- Although the lightest N_1 is stable, the **heavier 5-plet fermion N_2** (or N_3) may decay via the Yukawa term

$$h_{jk} \, \overline{L}_j \, \chi \, N_k$$

if mass $M_{2,3} > M_\chi$.

Suppose couplings h_{jk} contains CP violating phases, then (in principle) a **lepton asymmetry** can be generated in the early universe. As a result, the cosmic baryon asymmetry can be explained via leptogenesis.
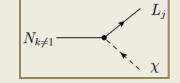
baryon asymmetry

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

A Model with Exotic Multiplets [4]

Some important observations & consequences (*continued*):

- Although the lightest N_1 is stable, the **heavier 5-plet fermion N_2** (or N_3) may decay via the Yukawa term

$$h_{jk}\,\overline{L}_j\,\chi\,N_k$$

if mass $M_{2,3} > M_\chi$.

Suppose couplings $\boldsymbol{h_{jk}}$ contains CP violating phases, then (in principle) a **lepton asymmetry** can be generated in the early universe. As a result, the cosmic baryon asymmetry can be explained via leptogenesis.
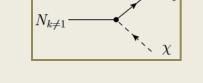
baryon asymmetry

- So, the challenge is to demonstrate that there exists a **parameter space** where all three problems can be addressed consistently.

The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

5-plet N_k masses   6-plet χ mass

The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

$\underbrace{}$ **5-plet N_k masses**

$\underbrace{}$ **6-plet χ mass**

$\underbrace{\phantom{h_{jk}}}$ **Yukawas (L_j, χ, N_k)**

A Model with Exotic Multiplets [5]

The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

5-plet N_k masses   **6-plet χ mass**   **Yukawas (L_j , χ , N_k)**   **$\phi\phi\chi\chi$ coupling**

A Model with Exotic Multiplets [5]

The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

5-plet N_k masses   **6-plet χ mass**   **Yukawas** (L_j, χ, N_k) $\phi\phi\chi\chi$ **coupling**

suppose: N_1 is the dark matter
                 N_2 for leptogenesis

then: $\boxed{M_1 \; < \; M_\chi \; < \; M_2 \; < \; M_3}$

A Model with Exotic Multiplets [5]

The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

5-plet N_k masses   **6-plet χ mass**   **Yukawas (L_j , χ , N_k)**   **$\phi\phi\chi\chi$ coupling**

<u>suppose</u>: N_1 is the dark matter
               N_2 for leptogenesis

<u>then</u>: $M_1 < M_\chi < M_2 < M_3$
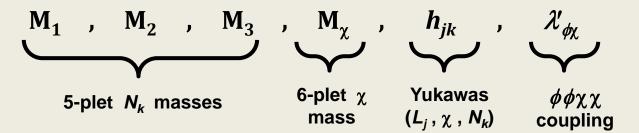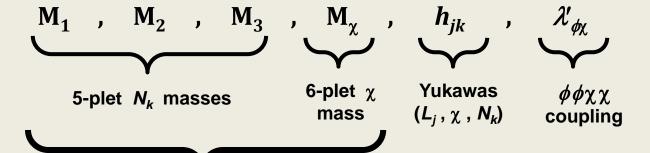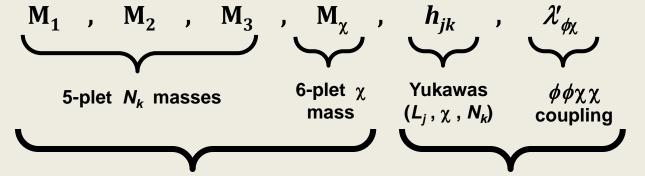
Once the masses $M_{1,2,3}$ and M_χ are fixed, these determine the masses for the **light neutrinos**.
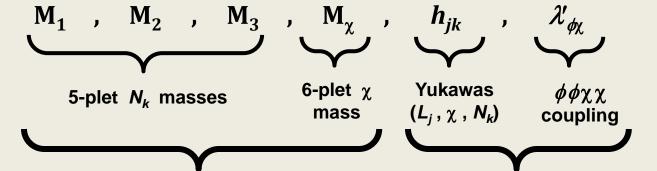
The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

5-plet N_k masses   **6-plet χ mass**   **Yukawas (L_j , χ , N_k)**   **$\phi\phi\chi\chi$ coupling**

suppose: N_1 is the dark matter
          N_2 for leptogenesis

then: $M_1 < M_\chi < M_2 < M_3$

Once the masses $M_{1,2,3}$ and M_χ are fixed, these determine the masses for the **light neutrinos.**

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

The **key parameters** in the model at a glance:

$$M_1 \quad , \quad M_2 \quad , \quad M_3 \quad , \quad M_\chi \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

5-plet N_k masses   **6-plet χ mass**   **Yukawas (L_j, χ, N_k)**   **$\phi\phi\chi\chi$ coupling**

<u>suppose</u>: N_1 is the dark matter
           N_2 for leptogenesis

<u>then</u>: $M_1 < M_\chi < M_2 < M_3$
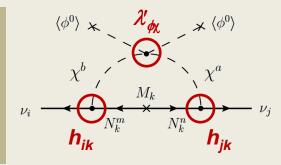
Once the masses $M_{1,2,3}$ and M_χ are fixed, these determine the masses for the **light neutrinos**.

The M_1 scale is dictated by the constraints from DM (e.g. **relic density**):

$$M_1 \gtrsim 10 \text{ TeV}$$

(co)annihilation of N_k's mediated by SM gauge bosons assumed [Cirelli et al., New J. Phys. 11,105005 (09)]

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryogenesis via N_2-Leptogenesis

Conventionally, in seesaw models with RH neutrinos, " $N_{1,2,3}$ ", leptogenesis is done via the decays of the **lightest** Majorana fermion " N_1 ".

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

LHC

Conventionally, in seesaw models with RH neutrinos, "$N_{1,2,3}$", leptogenesis is done via the decays of the **lightest** Majorana fermion "$\boldsymbol{N_1}$".

➡ because the asymmetry from N_2 (and N_3) decays is usually <u>suppressed</u> due to the washout processes mediated by N_1 ;

Baryogenesis via N_2-Leptogenesis

LHC

Conventionally, in seesaw models with RH neutrinos, "$N_{1,2,3}$", leptogenesis is done via the decays of the **lightest** Majorana fermion "N_1".

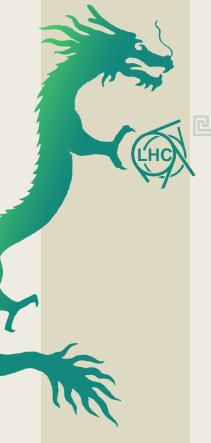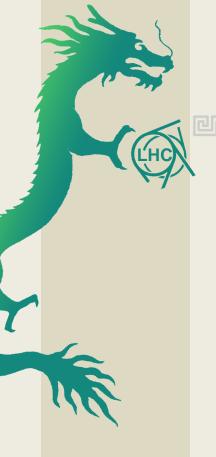➡ because the asymmetry from N_2 (and N_3) decays is usually <u>suppressed</u> due to the washout processes mediated by N_1 ;

➡ and one can only get successful N_2-leptogenesis by fully incorporating **flavor effects** in the analysis [Barbieri et al., 00; Abada et al., Nardi et al., 06; Josse-Michaux et al., 07; Bertuzzo et al., 11; Antusch et al.,12].

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryogenesis via N_2-Leptogenesis

Conventionally, in seesaw models with RH neutrinos, " $N_{1,2,3}$ ", leptogenesis is done via the decays of the **lightest** Majorana fermion " N_1 ".

➡ because the asymmetry from N_2 (and N_3) decays is usually <u>suppressed</u> due to the washout processes mediated by N_1 ;

➡ and one can only get successful N_2-leptogenesis by fully incorporating **flavor effects** in the analysis [Barbieri et al., 00; Abada et al., Nardi et al., 06; Josse-Michaux et al., 07; Bertuzzo et al., 11; Antusch et al.,12].

In N_2-leptogenesis, the evolution of the lepton asymmetry is divided into **two** main stages:

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryogenesis via N_2-Leptogenesis

Conventionally, in seesaw models with RH neutrinos, "$N_{1,2,3}$", leptogenesis is done via the decays of the **lightest** Majorana fermion "N_1".

→ because the asymmetry from N_2 (and N_3) decays is usually <u>suppressed</u> due to the washout processes mediated by N_1 ;

→ and one can only get successful N_2-leptogenesis by fully incorporating **flavor effects** in the analysis [Barbieri et al., 00; Abada et al., Nardi et al., 06; Josse-Michaux et al., 07; Bertuzzo et al., 11; Antusch et al.,12].

In N_2-leptogenesis, the evolution of the lepton asymmetry is divided into **two** main stages:
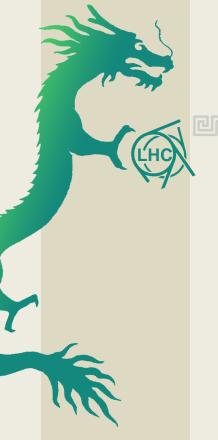
1. asymmetry production at $T \simeq M_2$ ($N_2 \to L_j \, \chi$ is out-of-equilibrium)

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryogenesis via N_2-Leptogenesis

LHC

Conventionally, in seesaw models with RH neutrinos, "$N_{1,2,3}$", leptogenesis is done via the decays of the **lightest** Majorana fermion "N_1".

➤ because the asymmetry from N_2 (and N_3) decays is usually <u>suppressed</u> due to the washout processes mediated by N_1 ;

➤ and one can only get successful N_2-leptogenesis by fully incorporating **flavor effects** in the analysis [Barbieri et al., 00; Abada et al., Nardi et al., 06; Josse-Michaux et al., 07; Bertuzzo et al., 11; Antusch et al.,12].

In N_2-leptogenesis, the evolution of the lepton asymmetry is divided into **two** main stages:

1. asymmetry production at $T \simeq M_2$ ($N_2 \rightarrow L_j\,\chi$ is out-of-equilibrium)

2. (additional) washout stage at $T \simeq M_1$ ($N_1 \rightarrow L_j\chi$ is out-of-equilibrium)

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryogenesis via N_2-Leptogenesis

Conventionally, in seesaw models with RH neutrinos, "$N_{1,2,3}$", leptogenesis is done via the decays of the **lightest** Majorana fermion "N_1".

➡ because the asymmetry from N_2 (and N_3) decays is usually <u>suppressed</u> due to the washout processes mediated by N_1 ;

➡ and one can only get successful N_2-leptogenesis by fully incorporating **flavor effects** in the analysis [Barbieri et al., 00; Abada et al., Nardi et al., 06; Josse-Michaux et al., 07; Bertuzzo et al., 11; Antusch et al.,12].

In N_2-leptogenesis, the evolution of the lepton asymmetry is divided into **two** main stages:

1. asymmetry production at $T \simeq M_2$ ($N_2 \to L_j\,\chi$ is out-of-equilibrium)

2. (additional) washout stage ~~at $T \simeq M_1$~~   ~~($N_1 \to L_j\chi$ is out-of-equilibrium)~~
   For our case with $M_\chi > M_1$, $T \simeq M_\chi$ and $\chi \to L_j\,N_1$ is out-of-equilibrium.

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryogenesis via N_2-Leptogenesis

Conventionally, in seesaw models with RH neutrinos, " $N_{1,2,3}$ ", leptogenesis is done via the decays of the **lightest** Majorana fermion " N_1 ".

→ because the asymmetry from N_2 (and N_3) decays is usually <u>suppressed</u> due to the washout processes mediated by N_1 ;

→ and one can only get successful N_2-leptogenesis by fully incorporating **flavor effects** in the analysis [Barbieri et al., 00; Abada et al., Nardi et al., 06; Josse-Michaux et al., 07; Bertuzzo et al., 11; Antusch et al.,12].

In N_2-leptogenesis, the evolution of the lepton asymmetry is divided into **two** main stages:

1. asymmetry production at T $\simeq$ M$_2$ ($N_2 \to L_j \chi$ is out-of-equilibrium)

2. (additional) washout stage ~~at T $\simeq$ M$_1$~~ ~~($N_1 \to L_j \chi$ is out-of-equilibrium)~~
   For our case with **M$_\chi$ > M$_1$, T $\simeq$ M$_\chi$** and $\chi \to L_j N_1$ is out-of-equilibrium.

<u>NB</u>: the decay of χ will NOT generate any lepton asymmetry since there is only **one** type of 6-plet scalar in the model $\Rightarrow$ vanishing absorptive part for the interference term with one-loop correction graphs.

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} ,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} ,$$

where $z = M_2 / T$.

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} ,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} ,$$

where $z = M_2 / T$.

CP asymmetry
from N_2 decays

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\mathrm{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} ,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\mathrm{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} ,$$

where $z = M_2 / T$.

decay term   washout term

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\mathrm{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} ,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\mathrm{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} ,$$

where $z = M_2 / T$.

tree-level flavor projector

$$P_{2j}^0 = \frac{h_{j2}^* h_{j2}}{(h^\dagger h)_{22}}$$

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} \,,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} \,,$$

where $z = M_2 / T$.

non-diagonal flavor coupling matrix

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays
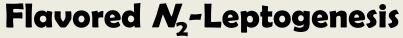
$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} \,,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} \,,$$

where $z = M_2 / T$.

It turns out that for successful N_2-leptogenesis, the total lepton asymmetry should originate mainly from decays in the **tau** flavor [Bertuzzo et al., 11; Antusch et al.,12].

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} ,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\text{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} ,$$

where $z = M_2/T$.

It turns out that for successful N_2-leptogenesis, the total lepton asymmetry should originate mainly from decays in the **tau** flavor [Bertuzzo et al., 11; Antusch et al.,12].

This then implies that the flavored **decay parameters** K_{2j} and $K_{\chi j}$, which are functions of the flavor projectors,

$$P_{2j}^0 = \frac{h_{j2}^* h_{j2}}{(h^\dagger h)_{22}} \quad \text{and} \quad P_{\chi j}^0 = \frac{h_{j1}^* h_{j1}}{(h^\dagger h)_{11}} \quad \text{respectively}$$

are constrained.

Flavored N_2-Leptogenesis

With **flavor effects**, the Boltzmann equations that govern the evolution of the lepton asymmetry in each flavor are **coupled**. For example, in the two-flavor regime, one has from N_2 decays

$$\frac{d\mathcal{N}_{\Delta_\perp}}{dz} = -\varepsilon_{2\perp} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\mathrm{eq}}\right) - P_{2\perp}^0 W_2 \sum_{j=\perp,\tau} C_{\perp j}^{f=2} \mathcal{N}_{\Delta_\perp} ,$$

$$\frac{d\mathcal{N}_{\Delta_\tau}}{dz} = -\varepsilon_{2\tau} D_2 \left(\mathcal{N}_{N_2} - \mathcal{N}_{N_2}^{\mathrm{eq}}\right) - P_{2\tau}^0 W_2 \sum_{j=\perp,\tau} C_{\tau j}^{f=2} \mathcal{N}_{\Delta_\tau} ,$$

where $z = M_2 / T$.

It turns out that for successful N_2-leptogenesis, the total lepton asymmetry should originate mainly from decays in the **tau** flavor [Bertuzzo et al., 11; Antusch et al.,12].

This then implies that the flavored **decay parameters** K_{2j} and $K_{\chi j}$, which are functions of the flavor projectors,

$$P_{2j}^0 = \frac{h_{j2}^* h_{j2}}{(h^\dagger h)_{22}} \quad \text{and} \quad P_{\chi j}^0 = \frac{h_{j1}^* h_{j1}}{(h^\dagger h)_{11}} \quad \text{respectively}$$

are constrained.

To ensure enough asymmetry is produced, we typically need $K_{2\tau} \gtrsim 1$ and $K_{\chi\tau} \ll 1$.

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

An example of a viable setup

Recalling the key parameters in the theory:

$$M_1 \quad , \quad M_\chi \quad , \quad M_2 \quad , \quad M_3 \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

O(10^4) GeV

fixed by DM
constraints

Sandy S. C. Law, NCKU, Taiwan

An example of a viable setup

Recalling the key parameters in the theory:

$$M_1 \quad , \quad M_\chi \quad , \quad M_2 \quad , \quad M_3 \quad , \quad h_{jk} \quad , \quad \lambda'_{\phi\chi}$$

$O(10^4)\,\text{GeV} \qquad 10^7 \qquad 10^{10} \qquad 10^{13}$

fixed by DM constraints

GeV
(hierarchical spectrum)

An example of a viable setup

Recalling the key parameters in the theory:

$$M_1 \quad , \quad M_\chi \quad , \quad M_2 \quad , \quad M_3 \quad , \quad \boxed{h_{jk}} \quad , \quad \lambda'_{\phi\chi}$$

$O(10^4)\,$GeV $\qquad 10^7 \qquad\quad 10^{10} \qquad\quad 10^{13}$

fixed by DM
constraints

GeV
(hierarchical spectrum)

The requirement for $K_{2\tau} \gtrsim 1$ and $K_{\chi\tau} \ll 1$ will constrain the Yukawa $\boldsymbol{h_{\tau k}}$ for all k.

For illustration, we use $\boldsymbol{K_{2\tau} \simeq 65}$ and $\boldsymbol{K_{\chi\tau} \simeq 0.1}$

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

An example of a viable setup

Recalling the key parameters in the theory:

$$M_1 \quad , \quad M_\chi \quad , \quad M_2 \quad , \quad M_3 \quad , \quad \boxed{h_{jk}} \quad , \quad \lambda'_{\phi\chi}$$

$O(10^4)\,\text{GeV}$ 10^7 10^{10} 10^{13} 0.1

fixed by DM   **GeV**
constraints   **(hierarchical spectrum)**

The requirement for $K_{2\tau} \gtrsim 1$ and $K_{\chi\tau} \ll 1$ will constrain the Yukawa $h_{\tau k}$ for all k.

For illustration, we use $K_{2\tau} \simeq 65$ and $K_{\chi\tau} \simeq 0.1$

May tune this to control the size of the Yukawa couplings given a light neutrino mass scale

An example of a viable setup

Recalling the key parameters in the theory:

$$M_1 \quad , \quad M_\chi \quad , \quad M_2 \quad , \quad M_3 \quad , \quad \boxed{h_{jk}} \quad , \quad \lambda'_{\phi\chi}$$

$\mathcal{O}(10^4)\,\text{GeV}$ 10^7 10^{10} 10^{13} 0.1

fixed by DM   **GeV**
constraints   **(hierarchical spectrum)**

The requirement for $K_{2\tau} \gtrsim 1$ and $K_{\chi\tau} \ll 1$ will constrain the Yukawa $\boldsymbol{h_{\tau k}}$ for all k.

For illustration, we use $K_{2\tau} \simeq 65$ and $K_{\chi\tau} \simeq 0.1$

May tune this to control the size of the Yukawa couplings given a light neutrino mass scale

With these parameters and assuming a **normal hierarchy** of light neutrinos (with $m_1 \simeq 0.002$ eV), a possible set of h_{jk} that is consistent with oscillation data is

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

An example of a viable setup

Recalling the key parameters in the theory:

$$\mathbf{M_1} \quad , \quad \mathbf{M_\chi} \quad , \quad \mathbf{M_2} \quad , \quad \mathbf{M_3} \quad , \quad \boxed{h_{jk}} \quad , \quad \lambda'_{\phi\chi}$$

| $\mathbf{O(10^4)\,GeV}$ | $\mathbf{10^7}$ | $\mathbf{10^{10}}$ | $\mathbf{10^{13}}$ | | $\mathbf{0.1}$ |

fixed by DM constraints

GeV
(hierarchical spectrum)

The requirement for $K_{2\tau} \gtrsim 1$ and $K_{\chi\tau} \ll 1$ will constrain the Yukawa $\boldsymbol{h_{\tau k}}$ for all k.

For illustration, we use $K_{2\tau} \simeq 65$ and $K_{\chi\tau} \simeq 0.1$

May tune this to control the size of the Yukawa couplings given a light neutrino mass scale

With these parameters and assuming a **normal hierarchy** of light neutrinos (with $m_1 \simeq 0.002$ eV), a possible set of h_{jk} that is consistent with oscillation data is

$$h_{e1} = 1.23 + 0.359i \,, \quad h_{e2} = 0.104 - 0.329i \,, \quad h_{e3} = -0.344 + 0.263i \,,$$
$$h_{\mu 1} = 1.71 - 1.02i \,, \quad h_{\mu 2} = -0.304 - 0.468i \,, \quad h_{\mu 3} = -3.76 + 0.367i \,,$$
$$h_{\tau 1} = 1.07 \times 10^{-5} \,, \quad h_{\tau 2} = 8.88 \times 10^{-3} \,, \quad h_{\tau 3} = 5.34 \,.$$

An example of a viable setup

Recalling the key parameters in the theory:

$$M_1 \quad , \quad M_\chi \quad , \quad M_2 \quad , \quad M_3 \quad , \quad \boxed{h_{jk}} \quad , \quad \lambda'_{\phi\chi}$$

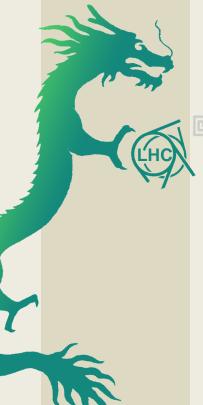| $O(10^4)$ GeV | 10^7 | 10^{10} | 10^{13} | | 0.1 |

fixed by DM constraints

GeV
(hierarchical spectrum)

The requirement for $K_{2\tau} \gtrsim 1$ and $K_{\chi\tau} \ll 1$ will constrain the Yukawa $\boldsymbol{h_{\tau k}}$ for all k.

For illustration, we use $K_{2\tau} \simeq 65$ and $K_{\chi\tau} \simeq 0.1$

May tune this to control the size of the Yukawa couplings given a light neutrino mass scale

With these parameters and assuming a **normal hierarchy** of light neutrinos (with $m_1 \simeq 0.002$ eV), a possible set of h_{jk} that is consistent with oscillation data is

$$h_{e1} = 1.23 + 0.359i \,, \quad h_{e2} = 0.104 - 0.329i \,, \quad h_{e3} = -0.344 + 0.263i \,,$$
$$h_{\mu 1} = 1.71 - 1.02i \,, \quad h_{\mu 2} = -0.304 - 0.468i \,, \quad h_{\mu 3} = -3.76 + 0.367i \,,$$
$$h_{\tau 1} = 1.07 \times 10^{-5} \,, \quad h_{\tau 2} = 8.88 \times 10^{-3} \,, \quad h_{\tau 3} = 5.34 \,.$$

$$\eta_B \simeq 6 \times 10^{-10}$$

Summary

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan

Summary

- In this work, we attempt to solve the problems of **baryon asymmetry**, **dark matter** and **neutrino mass** simultaneously by adding to the SM

    $3 \times$ SU(2)$_L$ 5-plet fermions N_k ($k = 1, 2, 3$) ;

    $1 \times$ SU(2)$_L$ 6-plet scalar χ .

- In this work, we attempt to solve the problems of **baryon asymmetry**, **dark matter** and **neutrino mass** simultaneously by adding to the SM

  $3 \times$ SU(2)$_L$ 5-plet fermions N_k $(k = 1, 2, 3)$;

  $1 \times$ SU(2)$_L$ 6-plet scalar χ .

- When the scalar potential is suitably fine-tuned ($\langle \chi \rangle = 0$ and $\chi^\dagger \chi \chi \phi \ll 1$), the **lightest** 5-plet fermion **N_1 can be a dark matter** candidate if $M_1 < M_\chi$.

Summary

- In this work, we attempt to solve the problems of **baryon asymmetry**, **dark matter** and **neutrino mass** simultaneously by adding to the SM

    $3 \times$ SU(2)$_L$ 5-plet fermions N_k ($k = 1, 2, 3$) ;

    $1 \times$ SU(2)$_L$ 6-plet scalar χ .

- When the scalar potential is suitably fine-tuned ($\langle \chi \rangle = 0$ and $\chi^\dagger \chi \chi \phi \ll 1$), the **lightest** 5-plet fermion N_1 **can be a dark matter** candidate if $M_1 < M_\chi$.

- A baryon asymmetry can be produced via **flavored N_2-leptogenesis** when the next-to-lightest 5-plet fermion decay in the early universe.

Summary

- In this work, we attempt to solve the problems of **baryon asymmetry**, **dark matter** and **neutrino mass** simultaneously by adding to the SM

  $3 \times$ SU(2)$_L$ 5-plet fermions N_k ($k = 1, 2, 3$) ;

  $1 \times$ SU(2)$_L$ 6-plet scalar χ .

- When the scalar potential is suitably fine-tuned ($\langle\chi\rangle = \mathbf{0}$ and $\chi^\dagger\chi\chi\phi \ll 1$), the **lightest** 5-plet fermion N_1 **can be a dark matter** candidate if $M_1 < M_\chi$.

- A baryon asymmetry can be produced via **flavored N_2-leptogenesis** when the next-to-lightest 5-plet fermion decay in the early universe.

- Light **neutrino mass** is generated at **one-loop** with the gauge invariant term $\phi\phi\chi\chi$ in the scalar potential providing the vital link.

Summary

- In this work, we attempt to solve the problems of **baryon asymmetry**, **dark matter** and **neutrino mass** simultaneously by adding to the SM

  $3 \times$ SU(2)$_L$ 5-plet fermions N_k ($k = 1, 2, 3$) ;

  $1 \times$ SU(2)$_L$ 6-plet scalar χ .

- When the scalar potential is suitably fine-tuned ($\langle\chi\rangle = 0$ and $\chi^\dagger\chi\chi\phi \ll 1$), the **lightest** 5-plet fermion **N_1 can be a dark matter** candidate if M$_1 <$ M$_\chi$.

- A baryon asymmetry can be produced via **flavored N_2-leptogenesis** when the next-to-lightest 5-plet fermion decay in the early universe.

- Light **neutrino mass** is generated at **one-loop** with the gauge invariant term $\phi\phi\chi\chi$ in the scalar potential providing the vital link.

- We have demonstrated that there is a parameter space in this model where a consistent solution to all three problems can be obtained.

Baryon asymmetry, dark matter and neutrino mass via exotic multiplets   Sandy S. C. Law, NCKU, Taiwan