Baryogenesis in an extended νMSM

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Introducing sterile neutrinos

- Active (left-handed) neutrino oscillations give

$$
\begin{aligned}
m_2^2 - m_1^2 &= \Delta m_{\text{sol}}^2 &= (7.59 \pm 0.21) \times 10^{-5}\text{eV}^2 \\
\left|m_3^2 - m_2^2\right| &= \left|\Delta m_{\text{atm}}^2\right| &= (2.43 \pm 0.13) \times 10^{-3}\text{eV}^2
\end{aligned}
$$

  At least two active neutrinos are massive!
- To give neutrinos mass, need sterile (right-handed) neutrinos; singlets under SU(3)×SU(2)×U(1)
- At least two sterile neutrinos are needed to explain active neutrino masses, but including more may explain other BSM physics

Sterile neutrino Lagrangian

- The most general renormalizable Lagrangian with n sterile neutrinos N_i $(i = 1, \ldots, n)$ is

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\overline{N_i}\gamma^\mu\partial_\mu N_i - \left(F_{\alpha i}\overline{L_\alpha}\Phi N_i + \frac{M_i}{2}\overline{N_i^c}N_i + \mathrm{h.c.}\right)$$

  where the Majorana mass matrix M_i has been diagonalized by a unitary transformation of the N_i
- At high temperatures, the N_i are mass eigenstates; at low temperatures, they will be mixed with the active neutrinos to form mass eigenstates

The νMSM

- Add minimum number of sterile neutrinos needed to explain neutrino masses, dark matter, and baryon asymmetry: 3

Dark matter

- N_1 with mass M_1 in the $1 - 10$ keV range
- Yukawa couplings $F_{\alpha 1} \sim 10^{-12}$

Baryon asymmetry

- $N_{2,3}$ with masses $M_{2,3}$ in the $1 - 17$ GeV range
- Yukawa couplings $F_{\alpha 2}, F_{\alpha 3} > 10^{-8}$
- Mass degeneracy $M_3 - M_2 \sim M_1$

- Mass degeneracy may suggest underlying physics

Is there a way to generate the νMSM mass degeneracy?

- Idea: Have two mass scales (GeV and keV) and choose N_i couplings to give desired pattern
- Add new global symmetry and scalar particle θ with charges

	Q
N_1	1
N_2	-1
N_3	-1
θ	2

- At high temperatures, relevant mass terms in the Lagrangian are

$$-\mathcal{L}_{\text{mass}} = \frac{M_{ij}}{2}\overline{N_i^c}N_j + \lambda_{ij}\langle\theta\rangle\overline{N_i^c}N_j + \text{h.c.}$$

where the global symmetry restricts M_{ij} and λ_{ij}

Mass degeneracy

- The global symmetry requires

$$M_{ij} = \begin{pmatrix} 0 & * & * \\ * & 0 & 0 \\ * & 0 & 0 \end{pmatrix}, \quad \lambda_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & * & * \\ 0 & * & * \end{pmatrix}$$

- Assume Majorana masses M_{ij} originate at the GeV scale
- Assume $\lambda_{ij} \langle \theta \rangle$ is at the keV scale
- Diagonalize mass matrix $\implies$ $M_1 \sim$ keV, $M_{2,3} \sim$ GeV, and $M_3 - M_2 \sim M_1$ ✔

Active neutrino masses

- At low temperatures, the seesaw mechanism gives active neutrino mass matrix

$$(m_\nu)_{\alpha\beta} = -\sum_i F_{\alpha i} \frac{\langle \Phi \rangle^2}{M_i} F_{\beta i}$$

- Choosing $\overline{L_\alpha}\Phi = -1$, the symmetry requires

$$F_{\alpha i} = \begin{pmatrix} * & 0 & 0 \\ * & 0 & 0 \\ * & 0 & 0 \end{pmatrix}$$

Diagonalizing $(m_\nu)_{\alpha\beta} \implies$ only one massive active neutrino ✗

Active neutrino masses

- Choosing $\overline{L_\alpha}\Phi = 1$, the symmetry requires

$$F_{\alpha i} = \begin{pmatrix} 0 & * & * \\ 0 & * & * \\ 0 & * & * \end{pmatrix}$$

Diagonalizing $(m_\nu)_{\alpha\beta} \implies$ only one massive active neutrino ✗

Way out?

- Choose $\overline{L_\alpha}\Phi = -1$ and add two more sterile neutrinos N_1', N_2' with charges matching N_1, N_2 5 sterile neutrinos
- Two pairs of degenerate sterile neutrinos in the GeV range and one in the keV range
- Two massive active neutrinos at correct scale if $F_{\alpha i} \sim 10^{-5}$

Important question

Does extending the νMSM in this way destroy its predictions of baryogenesis or dark matter?

Baryogenesis via leptogenesis

- Qualitatively, baryogenesis in the extended νMSM proceeds as in νMSM – via leptogenesis
  1. At high temperatures, sterile neutrino oscillations and CP violation in the neutrino mass matrix produce lepton asymmetry in the active neutrinos
  2. Electroweak sphalerons transfer active neutrino lepton asymmetry into baryon asymmetry for $T \gtrsim 100$ GeV
- Major difference in extended νMSM is coupling to new particle θ – how does this affect baryogenesis quantitatively?

Kinetic equation

- To describe neutrinos in early universe, need to use density matrices $\rho_L, \rho_{\bar{L}}, \rho_N, \rho_{\bar{N}}$
- Evolution of density matrices given by kinetic equation

$$i\frac{d\rho_L}{dt} = \left[H_L^0 + V_L, \rho_L\right] - \frac{i}{2}\left\{\Gamma_L, \rho_L - \rho_L^{\text{eq}}\right\} + \frac{i\sin\phi}{4}TF\left(\rho_N - \rho_N^{\text{eq}}\right)F^\dagger$$

$$i\frac{d\rho_N}{dt} = \left[H_N^0 + V_N, \rho_N\right] - \frac{i}{2}\left\{\Gamma_N, \rho_N - \rho_N^{\text{eq}}\right\} + \frac{i\sin\phi}{8}TF^\dagger\left(\rho_L - \rho_L^{\text{eq}}\right)F + \frac{i\sin\phi}{4}T\lambda^*\left(\rho_{\bar{N}} - \rho_{\bar{N}}^{\text{eq}}\right)\lambda$$

where

$$V_L = \frac{1}{16}TFF^\dagger \qquad \Gamma_L = 2\sin\phi V_L$$

$$V_N = \frac{1}{8}TF^\dagger F + \frac{1}{16}T\left\{\lambda, \lambda^*\right\} \qquad \Gamma_N = 2\sin\phi V_N$$

- Equations for $\rho_{\bar{L}}$ and $\rho_{\bar{N}}$ by taking $F \to F^*$ and $\lambda \to \lambda^*$

Solving the kinetic equation

1. Sterile neutrinos created without asymmetry at $O\left(F^2 + \lambda^2\right)$

$$\rho_N(T)_{ij} = \frac{\sin\phi}{4e}\frac{M_0}{T_L}\left(F^\dagger F + \frac{1}{2}\left[\lambda, \lambda^*\right]\right)_{ij}\int_0^{T_L/T} e^{ik\left(x^3-y^3\right)}dy$$

where $k \in \{-1, 0, 1\}$ and $T_L \gg 100$ GeV

2. Active neutrinos created with asymmetry at $O\left(F^4 + F^2\lambda^2\right)$

$$\Delta L_\alpha\left(T\right) \equiv \left(\rho_L - \rho_{\bar{L}}\right)_{\alpha\alpha} = \frac{\sin^2\phi}{4e}\frac{M_L^2}{T_L^2}\sum_{i>j} A_{ij}^{\alpha} J\left(T_L/T\right)$$

where $A_{ij}^{\alpha} = \text{Im}\left[F_{\alpha i}\left(F^\dagger F + \frac{1}{2}\left[\lambda, \lambda^*\right]\right)_{ij}F_{\alpha j}^*\right]$ and $J\left(\infty\right) \approx 0.69$
Asymmetry in each flavour and total asymmetry!

Solving the kinetic equation

❸ Sphalerons transfer total lepton asymmetry to baryon asymmetry until $T_W \sim 100$ GeV

$$\Delta B(T) = -\frac{28}{79}\sum_{\alpha} \Delta L_{\alpha}(T)$$

and then the baryon asymmetry is frozen at $\Delta B(T_W)$

Summary

- Baryogenesis at $O(F^2\lambda^2)$ instead of $O(F^6)$ – does this reduce the need for a large mass degeneracy?
- Need to investigate other cosmological constraints on λ_{ij}

Conclusions

- Sterile (right-handed) neutrinos are needed to explain active neutrino masses
- With 3 sterile neutrinos and a 10^{-6} mass degeneracy, it is also possible to explain dark matter and the baryon asymmetry – νMSM
- We have attempted to explain the mass degeneracy in a natural way with 5 sterile neutrinos, scalar θ, and global symmetry – extended νMSM
- Initial results indicate the baryon asymmetry in the extended νMSM may be much larger than in the νMSM, but we need to further investigate cosmological constraints on this model

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