Symmetries, the νMSM and cosmology

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Outline

1. Introduction to the νMSM
    - Standard Model plus three right-handed neutrinos
    - Dark matter and baryon asymmetry constraints
2. Model building with symmetries and scalars
    - Explaining masses and Yukawa couplings
    - Primordial dark matter production and inflation
3. Summary

The νMSM

- The goal of the νMSM is to see how many of the experimental shortcomings of the Standard Model (rather than fine-tuning problems) can be explained with right-handed neutrinos
- There is little doubt that the Standard Model is an incomplete theory. Physical phenomena that cannot be explained include neutrino oscillations, dark matter, and the baryon asymmetry
- Idea: add the fewest number of right-handed neutrinos needed to explain these phenomena → 3 right-handed neutrinos

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \overline{N_I} i \partial\!\!\!/ N_I - F_{\alpha I} \overline{L_\alpha} N_I H + \frac{M_{IJ}}{2} \overline{N_I^c} N_J + \text{h.c.}$$

- What pattern of masses M_{IJ} and Yukawa couplings $F_{\alpha I}$ is needed to explain dark matter and the baryon asymmetry?

Dark matter

- In the νMSM, the sterile neutrino N_1 is the dark matter

Lyman-α bound

- Free streaming N_1 would wipe out small scale density fluctuations unless its velocity is small enough

$$M_1 \gtrsim 8 \text{ keV}$$

X-ray constraint

- N_1 mixing with active neutrinos allows the decay $N_1 \to \nu + \gamma$, which has not been observed

$$F_1 \lesssim 4 \times 10^{-12} \left(\frac{\text{keV}}{M_1}\right)^{1.2}$$

Dark matter

- N_1 mixing with active neutrinos is also responsible for N_1 production via active-sterile neutrino oscillations
- Demanding that 100% of dark matter be produced in this way fixes a relation between M_1 and the mixing angle θ_1

Dark matter production bound

- Assuming a large lepton asymmetry (Shi-Fuller scenario), dark matter production and the X-ray constraint give

$$M_1 \lesssim 50 \text{ keV}$$

Baryon asymmetry

- Baryogenesis proceeds via leptogenesis: N_2, N_3 oscillations produce an asymmetry in active neutrinos that is converted into a baryon asymmetry by sphalerons ($B - L$ conserved)

Baryon asymmetry

- Requiring no lepton number violating processes above T_{EW} (or else lepton asymmetry is wiped out) and N_2, N_3 decaying before Big Bang Nucleosynthesis gives

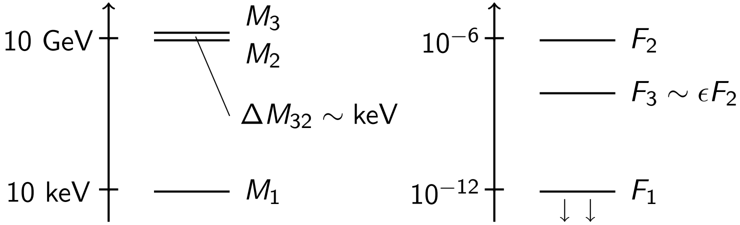
$$F_2, F_3 \lesssim 10^{-6}, \qquad M_2, M_3 \sim 1 - 20 \text{ GeV}$$

- Effective baryon asymmetry production then requires

$$F_2 \sim 10^{-6}, \qquad F_3 \sim 10^{-6}\epsilon, \qquad \Delta M_{32} \sim \text{keV}$$

Summary of masses and couplings

- Thus the νMSM requires a specific pattern of Majorana masses and Yukawa couplings



- We would like to explain this pattern in a natural way (otherwise there is some level of fine-tuning)
- Can flavour symmetries be used to give this pattern?

Explaining masses and couplings

- The approach we take is a combination of continuous/discrete symmetries and the Froggatt-Nielsen mechanism
- First we suppose that Majorana masses are given by the VEV of a new scalar ϕ and regular Yukawa couplings are allowed

$$\Delta\mathcal{L} = \frac{1}{2}\underbrace{\lambda_{IJ}\phi}_{M_{IJ} = \lambda_{IJ}\langle\phi\rangle} N_I N_J - F_I \nu H N_I + \text{h.c.}$$

A simple U(1) symmetry and charge assignment that can give these terms is

	N_1	N_2	N_3	ϕ	νH
$\mathrm{U}(1)_\phi$	1	1	1	-2	-1

- Note that we have a new interaction $\phi N_I N_J$ compared with the νMSM

Explaining masses and couplings

- Next we impose a Z_2 symmetry to prevent $N_1 N_2$ and $N_1 N_3$ mass terms that tend to produce large F_1

	N_1	N_2	N_3	ϕ	νH
Z_2	1	0	0	0	0

- Under this symmetry, $F_1 = 0$ and hence there is no N_1 production from active-sterile neutrino oscillations → primordial N_1 production from new interaction $\phi N_1 N_1$
- A hierarchical mass matrix and Yukawa couplings that produce the rest of the desired pattern is

$$M_{IJ} \sim \begin{pmatrix} \text{keV} & 0 & 0 \\ 0 & \text{keV} & \text{GeV} \\ 0 & \text{GeV} & * \end{pmatrix}, \qquad F_{\alpha I} \sim \begin{pmatrix} 0 & 10^{-6} & 10^{-6}\epsilon \\ \vdots & \vdots & \vdots \end{pmatrix}$$

Explaining masses and couplings

- To generate heirarchies, use the Froggatt-Nielsen mechanism
  - Introduce a $\mathrm{U}(1)_{FN}$ symmetry and scalar field ϑ
  - Charge particles under the $\mathrm{U}(1)_{FN}$ symmetry
  - Once ϑ acquires a VEV, powers of $\langle\vartheta\rangle / M_{\mathrm{Pl}}$ suppress terms. For example,

$$\underbrace{\phi N_1 N_1}_{+5} \underbrace{\vartheta^5}_{\text{-5}} \longrightarrow \left(\frac{\langle\vartheta\rangle}{M_{\mathrm{Pl}}}\right)^5 \phi N_1 N_1$$

- Take $\frac{\langle\vartheta\rangle}{M_{\mathrm{Pl}}} \approx 10^{-2}$ and assign charges

	N_1	N_2	N_3	ϕ	νH	ϑ
$\mathrm{U}(1)_{FN}$	2	-3	4	1	0	-1

- With $\langle\phi\rangle \sim 10^5$ GeV, this gives the parameters

$$M_1 \sim 10 \text{ keV}, \quad M_2, M_3 \sim 10 \text{ GeV}, \quad \Delta M_{32} \sim 10 \text{ keV}$$

$$F_1 = 0, \quad F_2 \sim 10^{-6}, \quad F_3 \sim 10^{-8}$$

Primordial N_1 production and inflation

- With $F_1 = 0$, the only source of N_1 production is through the decays $\phi \to N_1 N_1$ (if $m_\phi > 2M_1$)
- Assuming ϕ is in thermal equilibrium for $T \approx m_\phi$ (due to its mixing with the Higgs), the amount of N_1 produced is

$$\Omega_{N_1} \sim \left(\frac{\lambda_{11}}{10^{-8}}\right)^3 \left(\frac{\langle\phi\rangle}{m_\phi}\right) \overset{\text{100\% DM}}{\Longrightarrow} \lambda_{11} \sim 10^{-8} \left(\frac{m_\phi}{\langle\phi\rangle}\right)^{1/3}$$

- Check that ϕ can be the inflaton in a particular model of inflation: chaotic inflation with a quartic potential (Shaposhnikov & Tkachev, Phys. Lett. B 639 (2006) 414–417)

$$V(H,\phi) = \lambda \left(H^\dagger H - \frac{\alpha}{\lambda}\phi^2\right)^2 + \frac{\beta}{4}\phi^4 - \frac{1}{2}m_\phi^2\phi^2$$

Primordial N_1 production and inflation

- For a quartic potential, the COBE measurement of temperature fluctuations in the CMB fixes $\beta \sim 10^{-13}$. Expanding $V(H, \phi)$ about its minima gives the relations

$$\frac{m_\phi}{\langle\phi\rangle} = \sqrt{2\beta} \sim 10^{-6}, \qquad m_\phi = m_h\sqrt{\frac{\beta}{2\alpha}} \sim 100 \text{ MeV}$$

- Dark matter production then requires

$$\lambda_{11} \sim 10^{-8}\left(\frac{m_\phi}{\langle\phi\rangle}\right)^{1/3} \sim 10^{-10} \implies M_1 \sim 10 \text{ keV} \quad ✓$$

- Remark
  - For this primordial production, ϕ doesn't need to be the inflaton – it only needs to be in thermal equilibrium

Phenomenological consequences

- Phenomenology is generally similar to the νMSM but with some differences due to vanishing F_1 and light inflaton ϕ
- Neutrino experiments
  - One massless active neutrino and other two fixed at 9 and 50 meV (47 and 48 meV) for normal (inverted) hierarchy
  - N_2, N_3 mixing with active neutrinos of the order $\theta_{2,3} \sim 10^{-5.5}$
  - Conflict with LSND and MiniBooNE hints of an eV sterile neutrino with large mixing ($\theta \sim 0.1$)
- Astrophysics
  - Negative result for x-ray searches of decaying N_1 ($\theta_1 = 0$)
  - Light inflaton may be visible in meson decays
- LHC
  - Without an intermediate energy scale between the weak and Planck scales, only the Higgs (mixed with ϕ) will be found

Summary

- The νMSM is a model that can explain neutrino oscillations, dark matter, and the baryon asymmetry with right-handed neutrinos a specific pattern of masses and couplings
- We have investigated how a $\mathrm{U}(1)_\phi \times Z_2 \times \mathrm{U}(1)_{FN}$ symmetry and additional scalars ϕ, ϑ can produce such a pattern
- In this extension, dark matter is produced through the decays $\phi \to N_1 N_1$ and ϕ may be the inflaton

Thanks for your attention!

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