Dark matter, singlet extensions of the νMSM, and symmetries

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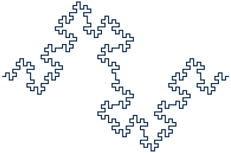

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OUTLINE

A SINGLET EXTENSION OF THE νMSM
- Introduction: the νMSM
- DM production from a Higgs singlet
- Hierarchical parameters

THE νNMSM AND SYMMETRIES
- Flavour symmetries
- The νNMSM + vacuum stabilization

CONCLUSIONS

INTRODUCTION: THE νMSM

- Standard Model plus three right-handed neutrinos N_1, N_2, N_3 with masses below the electroweak scale

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I H - \frac{M_{IJ}}{2} \bar{N}_I^c N_J + \text{h.c.}$$

- Experimental evidence for beyond the SM physics:
    - Dark matter → N_1 is warm dark matter ($\sim$ keV) produced through left-right neutrino mixing (Asaka, Blanchet, and Shaposhnikov, 2005)
    - Baryon asymmetry → Lepton asymmetry from oscillations of N_2, N_3 ($\sim$ GeV) converted to a baryon asymmetry through EW sphalerons (Asaka and Shaposhnikov, 2005)
    - Inflation → Higgs boson with a large non-minimal coupling to gravity is the inflaton (Bezrukov and Shaposhnikov, 2008)
- An economical, highly predictive, and tightly constrained model

A SINGLET EXTENSION: THE νNMSM

- An extension of the νMSM by a Higgs singlet can address a serious issue with the model

Dark matter production

- The simplest, non-resonant production of DM in the νMSM is disfavoured by X-ray limits + small scale structure bounds

$M_1^{\text{NRP}} \lesssim 2.2$ keV X-ray limits: $N_1 \to \nu\gamma$ (Watson, Li, and Polley, 2012)

$M_1^{\text{NRP}} \gtrsim 13$ keV Lyman-α forest bound (Boyarsky et al., 2009)

- Alternatively, DM production through the decays of a Higgs singlet $\phi \to N_1 N_1$ can satisfy the Lyman-α bound (Shaposhnikov and Tkachev, 2006)
- We refer to this extension as the νNMSM

$$\Delta\mathcal{L} = -F_{\alpha I}\bar{L}_\alpha N_I H - \frac{\lambda_{IJ}}{2}\phi \bar{N}_I^c N_J + \text{h.c.}, \qquad \lambda_{11} \sim 4 \times 10^{-9}\left(\frac{m_\phi}{\langle\phi\rangle}\right)^{1/3}$$

- Bonus: Singlet provides an origin for Majorana masses $M_{IJ} = \lambda_{IJ}\langle\phi\rangle$!

A SINGLET EXTENSION: THE νNMSM

- We are free to choose a scalar potential for ϕ that can solve other possible issues with the νMSM

Vacuum stability

- For $m_h \simeq 125$–126 GeV, the SM potential develops an instability below $M_{\rm Pl}$ unless the top quark mass is 2σ below its central value (Elias-Miro et al., 2012)
- A Higgs singlet can stabilize the EW vacuum by changing the running of λ or through a threshold effect (Lebedev, 2012; Elias-Miro et al., 2012)

Inflation

- For Higgs inflation, tree-level unitarity breaks down below the inflationary scale; it is unclear if this model can be realized
- Alternatively, the Higgs singlet of the νNMSM can be the inflaton (Shaposhnikov and Tkachev, 2006)

HIERARCHICAL PARAMETERS

- The νNMSM, with a particular choice of scalar sector, is therefore a well-motivated model
- Like the νMSM, it requires a specific hierarchy of Yukawa couplings $F_{\alpha I}$ and Majorana masses $M_{IJ} = \lambda_{IJ} \langle \phi \rangle$ without an obvious origin

$$\begin{aligned} F_{\alpha 1} \lesssim 10^{-13}, \qquad & F_{\alpha 2} \sim 10^{-7}, \qquad & F_{\alpha 3} \sim 10^{-(7\ldots 10)}, \\ \lambda_{11} \sim 4 \times 10^{-9} \left(\frac{m_\phi}{\langle \phi \rangle} \right)^{1/3}, \qquad & \lambda_{23} \sim \frac{\mathrm{GeV}}{\langle \phi \rangle}, \qquad & \lambda_{22}, \lambda_{33} \sim \frac{\mathrm{meV–MeV}}{\langle \phi \rangle} \end{aligned}$$

- An important question is whether this pattern of couplings can be realized from an underlying symmetry — and if so, what implications does it have
- We argue that such a symmetry can be found, but it requires a complex ϕ with some experimental signatures that are distinct from the νMSM

FLAVOUR SYMMETRIES

- First consider how the structure of the νNMSM Lagrangian can arise without regard to the size of the couplings $F_{\alpha I}$ and λ_{IJ}

$$\Delta\mathcal{L} = -F_{\alpha I}\bar{L}_\alpha N_I H - \frac{\lambda_{IJ}}{2}\phi\bar{N}_I^c N_J + \text{h.c.}$$

- Global U(1) symmetry:
  - Can arise from a global U(1) under which ϕ is charged (complex)
  - Low-scale global symmetries can come from a local U(1) that becomes massive via the Stueckelberg mechanism (Burgess et al., 2008)
  - Local U(1) must satisfy anomaly cancellation conditions

	N_1	N_2	N_3	L_α	E_α	Q_i	U_i	D_i	H	ϕ
U(1)	-1	-1	-1	-1	-1	1/3	1/3	1/3	0	2

- Discrete Z_N symmetry:
  - Lagrangian can similarly arise from a Z_N symmetry, but spontaneous breaking of Z_N can lead to problematic domain walls (Casini and Sarkar, 2002)

FLAVOUR SYMMETRIES

- Now consider how we can produce the hierarchies in $F_{\alpha I}$ and λ_{IJ} for a complex $\phi = \phi + i\chi$
- To explain the small Yukawa couplings $F_{\alpha 1} \lesssim 10^{-13}$ and prevent the fast DM decay $N_1 \to \nu\chi$, introduce a Z_2 symmetry under which only N_1 is charged

$$F_{\alpha I} = \begin{pmatrix} 0 & F_{e2} & F_{e3} \\ 0 & F_{\mu 2} & F_{\mu 3} \\ 0 & F_{\tau 2} & F_{\tau 3} \end{pmatrix}, \quad \lambda_{IJ} = \begin{pmatrix} \lambda_{11} & 0 & 0 \\ 0 & \lambda_{22} & \lambda_{23} \\ 0 & \lambda_{23} & \lambda_{33} \end{pmatrix}$$

- The Z_2 symmetry implies N_1 is completely stable (no X-rays) and one left-handed neutrino is exactly massless!
- To generate hierarchies in the remaining $F_{\alpha I}$ and λ_{IJ}, can use the Froggatt-Nielsen mechanism:

$$f_{\alpha 2} \left(\underbrace{\frac{\langle \vartheta \rangle^2}{M_{\rm Pl}^2}}_{-2} \right) \underbrace{\bar{L}_\alpha N_2 H}_{+2} \;\to\; F_{\alpha 2} \bar{L}_\alpha N_2 H, \qquad \vartheta = \text{scalar “flavon” field}$$

THE νNMSM + VACUUM STABILIZATION

- To give a definite example of the Froggatt-Nielsen symmetry, consider a potential that can stabilize the EW vacuum via a scalar threshold effect (Elias-Miro et al., 2012)

  $$V = \lambda_h(H^\dagger H - \tfrac{v^2}{2})^2 + \lambda_\phi(\phi^\dagger\phi - \tfrac{w^2}{2})^2 + 2\lambda_{h\phi}(H^\dagger H - \tfrac{v^2}{2})(\phi^\dagger\phi - \tfrac{w^2}{2}),$$

  where $\delta\lambda \equiv \lambda_{h\phi}^2/\lambda_\phi \simeq 0.01$
- Choose $\lambda_{h\phi}, \lambda_\phi \sim 0.01$ and $w \equiv \langle\phi\rangle \simeq 10^8$ GeV (*Note: no attempt is made to explain scalar sector parameters*)
- For the large $\lambda_{h\phi} \sim 0.01$, this model has
  - a $\Delta N_{\text{eff}} \simeq 4/7$ contribution to the effective number of neutrino species from the Goldstone mode χ
  - an invisible Higgs branching ratio of $\sim$ 20–30%

THE νNMSM + VACUUM STABILIZATION

- The required pattern of masses and couplings of the νNMSM can then be achieved for two flavon fields ϑ_1, ϑ_2 with

$$\frac{\langle\vartheta_1\rangle}{M_{\rm Pl}} \simeq 10^{-8}, \qquad \frac{\langle\vartheta_2\rangle}{M_{\rm Pl}} \simeq 10^{-7}$$

and a U(1) × $Z_3 \times Z_2$ symmetry

	N_1	N_2	N_3	L_α	E_α	Q_i	U_i	D_i	H	ϕ	ϑ_1	ϑ_2
U(1)	-1	-1	-1	-1	-1	1/3	1/3	1/3	0	-1	3	0
Z_3	0	1	-1	0	0	0	0	0	0	0	0	1
Z_2	1	0	0	0	0	0	0	0	0	0	0	0

- This is the simplest anomaly-free example we could find, though other charge assignments are possible

THE νNMSM + VACUUM STABILIZATION

- After the spontaneous symmetry breaking for ϑ_1, ϑ_2, the parameters of the low-energy νNMSM are

$$F_{\alpha 1} = 0, \qquad F_{\alpha 2} \sim 1 \times 10^{-7}, \qquad F_{\alpha 3} \sim 1 \times 10^{-7},$$

$$M_1 \sim 1\,\mathrm{GeV}, \quad M_2 \simeq M_3 \sim 1\,\mathrm{GeV}, \quad \Delta M_{23} \sim 100\,\mathrm{eV}$$

- N_1 can be much heavier than the keV scale in the νNMSM to avoid the Lyman-α forest bound
- This model demonstrates that it is possible to use an underlying symmetry to produce the hierarchical pattern of masses and couplings of the νNMSM, though the hierarchy problem in the scalar sector remains

CONCLUSIONS

- The νNMSM allows for DM production from the decays of a singlet ϕ that is consistent with experimental bounds and provides an origin for the Majorana masses
- We have shown how the hierarchical parameters of the νNMSM (excluding the scalar sector) can arise from an underlying symmetry for a complex ϕ
- Such a symmetry generically predicts completely stable N_1 (no X-ray signature) and one exactly massless left-handed neutrino
- For the specific $\mathrm{U}(1) \times Z_3 \times Z_2$ example considered, the model can help stabilize the EW vacuum, has a contribution of $\Delta N_{\mathrm{eff}} \simeq 4/7$, and has a large invisible branching ratio of the Higgs

Thank you for your attention!