

Common Origin of Neutrino Mass and Dark Matter

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Introduction

Physics Beyond the Standard Model (**SM**) should include neutrino mass and dark matter (**DM**).

Are they related?

In this talk, I propose that neutrino mass is due to the existence of dark matter. I will discuss some recent models and their phenomenological consequences.

A candidate for dark matter should be neutral and stable, the latter implying at least an exactly conserved odd-even symmetry (Z_2).

In the **MSSM**, the lightest neutral particle having odd R parity is a candidate. It is usually assumed to be a fermion, i.e. the lightest neutralino. [The lightest neutral boson, presumably a scalar neutrino, is ruled out phenomenologically.]

If all we want is **DM**, the simplest way is to add a second Higgs doublet (η^+, η^0) [**Barbieri/Hall/Rychkov(2006)**] which is odd under Z_2 with all **SM** particles even. This differs from the scalar **MSSM** $(\tilde{\nu}, \tilde{l})$ doublet, because η_R^0 and η_I^0 are split in mass by the Z_2 conserving term $(\lambda_5/2)(\Phi^\dagger \eta)^2 + H.c.$ which is absent in the **MSSM**.

Neutrino Mass: Six Generic Mechanisms

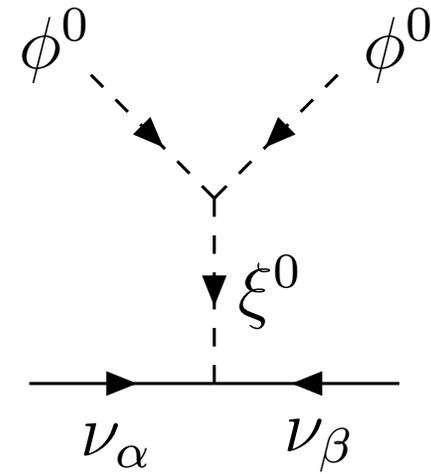
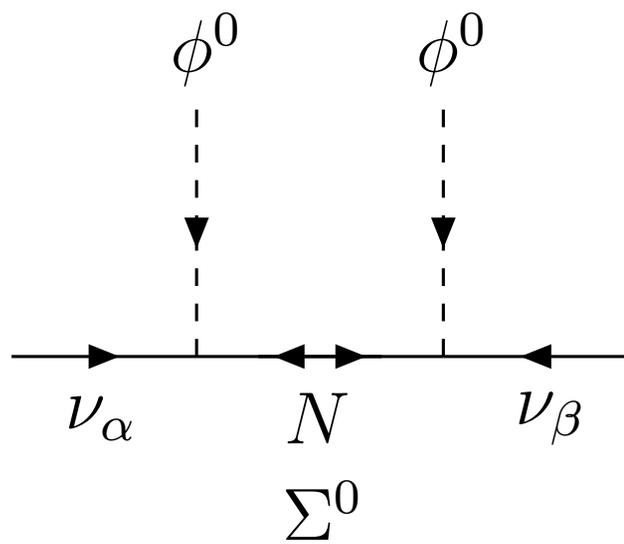
Weinberg(1979):

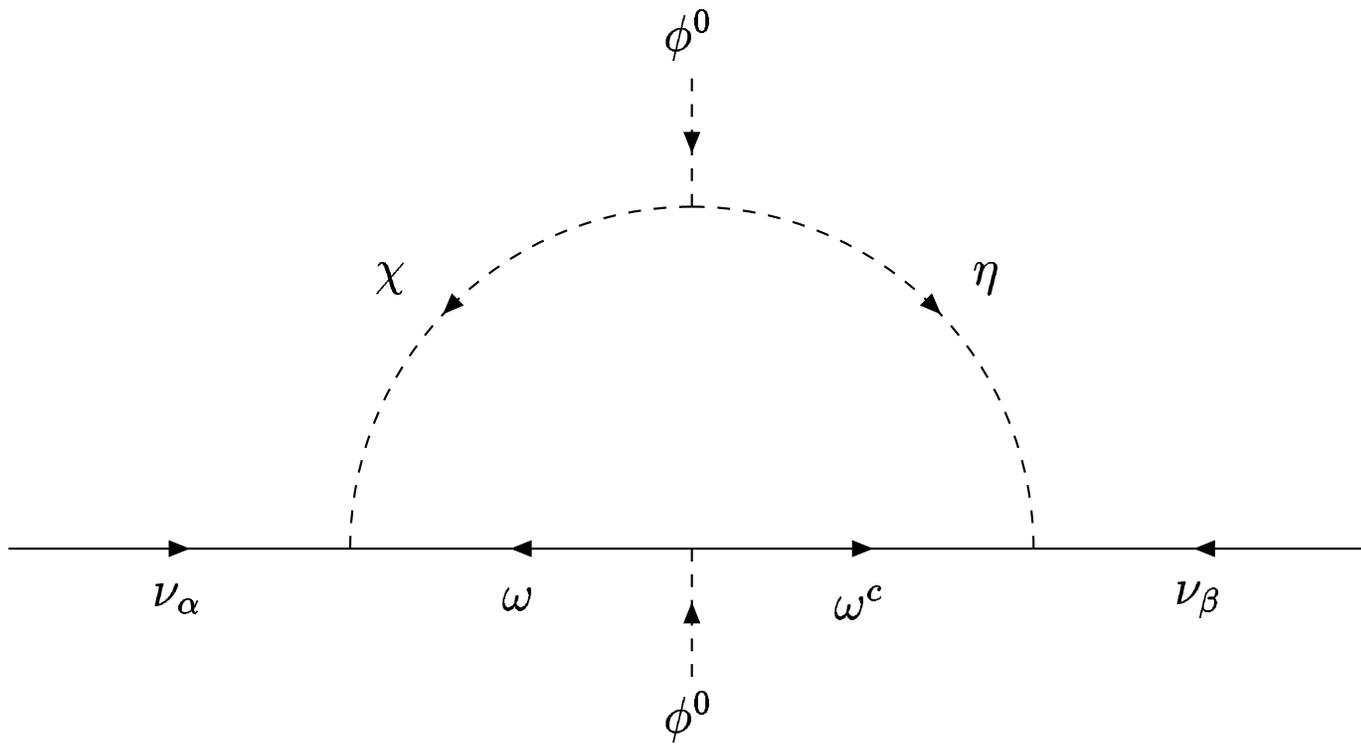
Unique dimension-five operator for Majorana neutrino mass in SM:

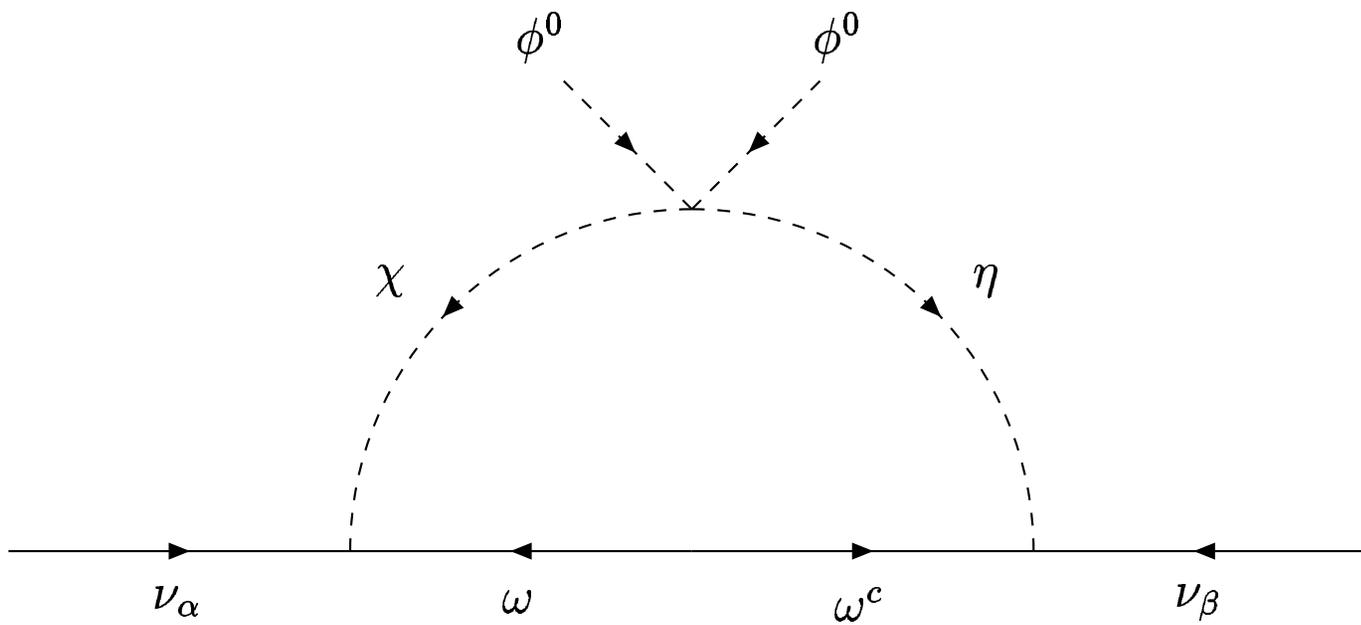
$$\frac{f_{\alpha\beta}}{2\Lambda}(\nu_{\alpha}\phi^0 - l_{\alpha}\phi^+)(\nu_{\beta}\phi^0 - l_{\beta}\phi^+).$$

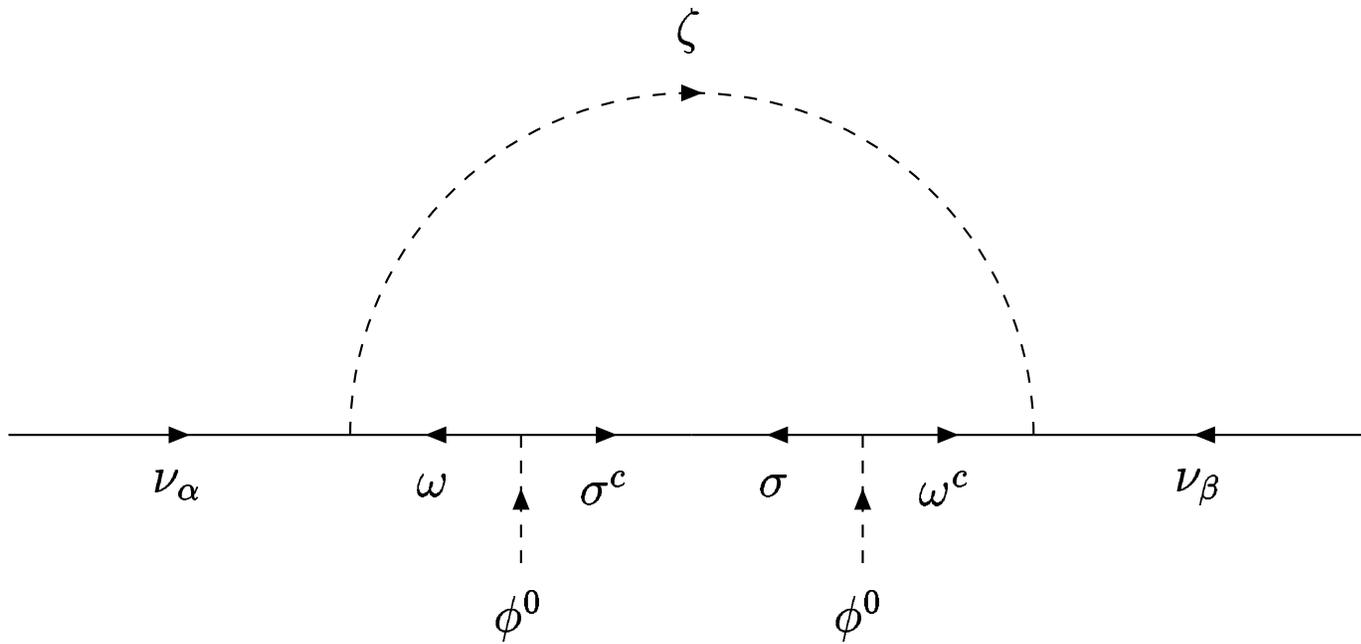
Ma(1998):

Three tree-level realizations: (I) N , (II) (ξ^{++}, ξ^+, ξ^0) , (III) $(\Sigma^+, \Sigma^0, \Sigma^-)$; and three generic one-loop realizations: (IV), (V), (VI).









Dark Scalar Doublet

Deshpande/Ma(1978): Add to the **SM** a second scalar doublet (η^+, η^0) which is odd under a new exactly conserved Z_2 discrete symmetry, then η_R^0 or η_I^0 is absolutely stable. [**Ma/Pakvasa/Tuan(1977)**: This doublet may even have a new conserved $U(1)$ quantum number, i.e. η^0 is one particle.] This simple idea lay dormant for almost thirty years until [**Ma, Phys. Rev. D 73, 077301 (2006)**]. It was then studied seriously in **Barbieri et al., Phys. Rev. D 74, 015007 (2006)** and **Lopez Honorez et al., JCAP 0702, 028 (2007)**.

Generically, the **dark scalar doublet** has the gauge interactions

$$\eta^+ \eta_R^0 W^-, \eta^+ \eta_I^0 W^-, \eta^+ \eta^- Z, \eta^+ \eta^- \gamma, \eta_R^0 \eta_I^0 Z,$$

and the scalar interactions

$$h(\eta_R^0)^2, h(\eta_I^0)^2, h\eta^+ \eta^-, h^2(\eta_R^0)^2, h^2(\eta_I^0)^2, h^2\eta^+ \eta^-, (\eta^\dagger \eta)^2.$$

They are easily pair produced at the LHC through $q\bar{q} \rightarrow W^\pm, Z, \gamma$.

The decays $\eta^+ \rightarrow W^+ \eta_R^0$ and $\eta_I^0 \rightarrow Z \eta_R^0$ will carry distinct signatures. [**Cao/Ma/Rajasekaran**, in preparation.]

Detailed study of the relic abundance of η_R^0 has been given by **Lopez Honorez/Nezri/Oliver/Tytgat(2007)**.

Radiative Neutrino Mass and Dark Matter

Ma(2006): (V) $\omega = \omega^c = N$, $\chi = \eta = (\eta^+, \eta^0)$, $\langle \eta^0 \rangle = 0$.
Here N interacts with ν , but they are not Dirac mass partners. This is due to the exactly conserved Z_2 symmetry, under which N and (η^+, η^0) are odd, and all SM particles are even.

Result: (A) η_R^0 or η_I^0 is dark matter with mass 60 to 80 GeV [BHR06];

or (B) N is dark matter, with all masses of order 350 GeV or less. [Kubo/Ma/Suematsu(2006)]

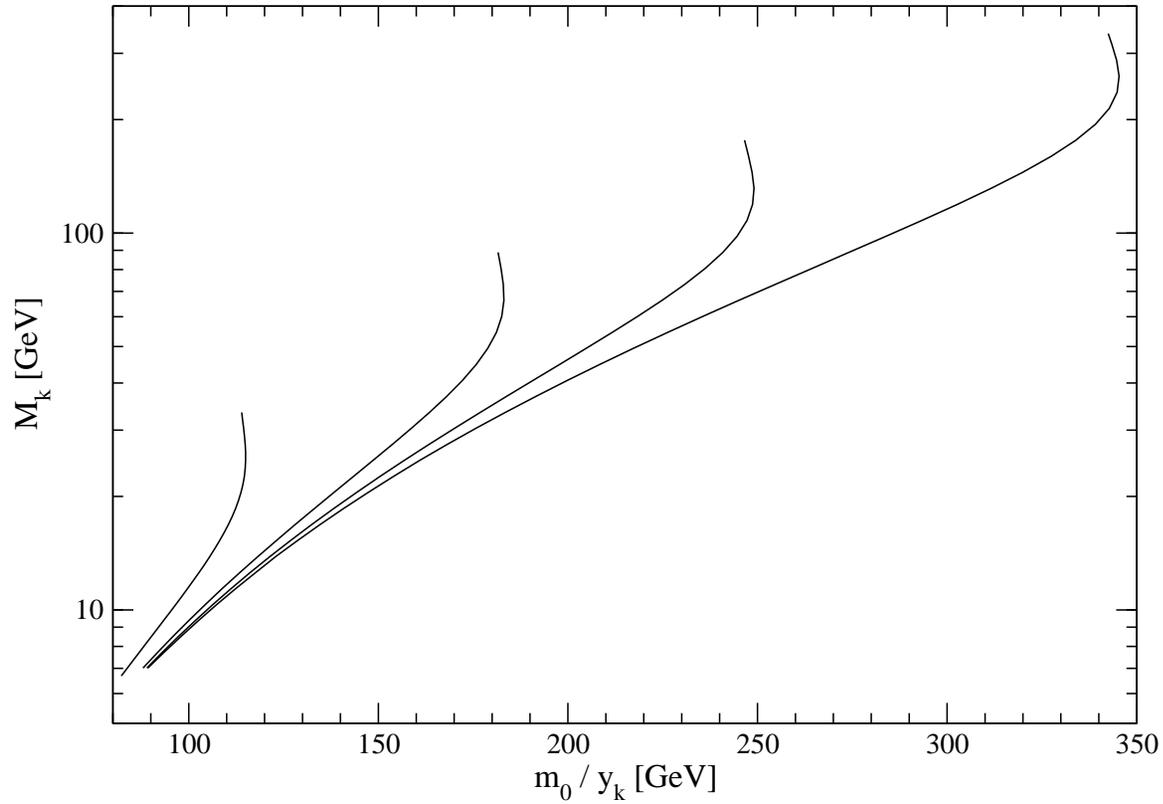


Figure 1: M_k versus m_0/y_k for $y_k = 0.3, 0.5, 0.7, 1.0$ (left to right) for $\Omega_d h^2 = 0.12$, where y_k is an effective Yukawa coupling.

Supersymmetric $E_6/U(1)_N$ Model

Ma(1996): Under $E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$,
 $Q_N = 6Y_L + T_{3R} - 9Y_R$ defines $U(1)_N$:

superfield	$SU(5)$	Q_N
$(u, d), u^c, e^c$	10	1
$d^c, (\nu, e)$	5^*	2
$h, (E^c, N_E^c)$	5	-2
$h^c, (\nu_E, E)$	5^*	-3
S	1	5
N^c	1	0

Ma/Sarkar(2007): Impose exact $Z_2 \times Z_2$ symmetry:

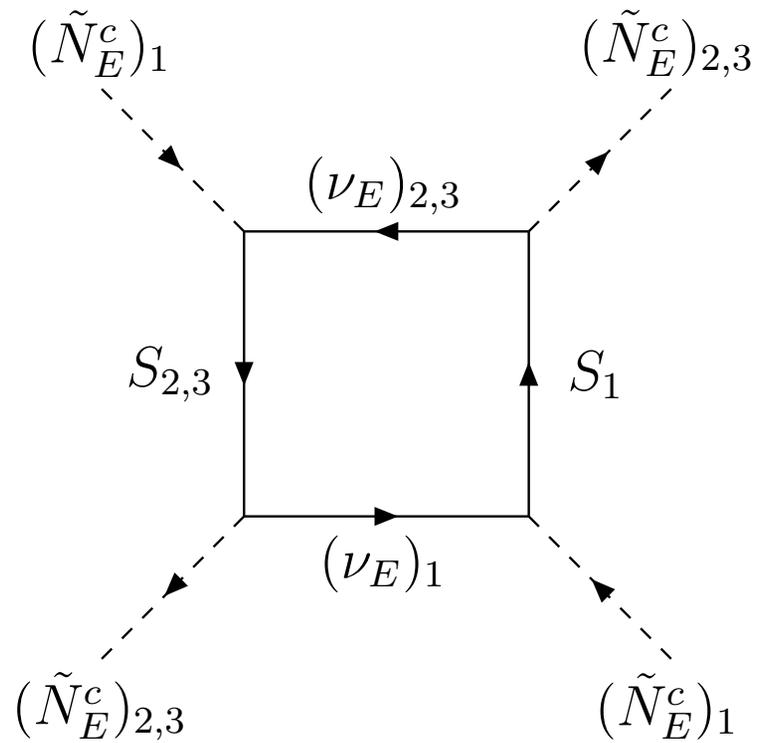
superfield	M	N
$(u, d), u^c, d^c$	+	+
$(\nu, e), e^c$	-	+
h, h^c	-	+
$[(\nu_E, E), (E^c, N_E^c), S]_1$	+	+
$[(\nu_E, E), (E^c, N_E^c), S]_{2,3}$	+	-
N^c	-	-

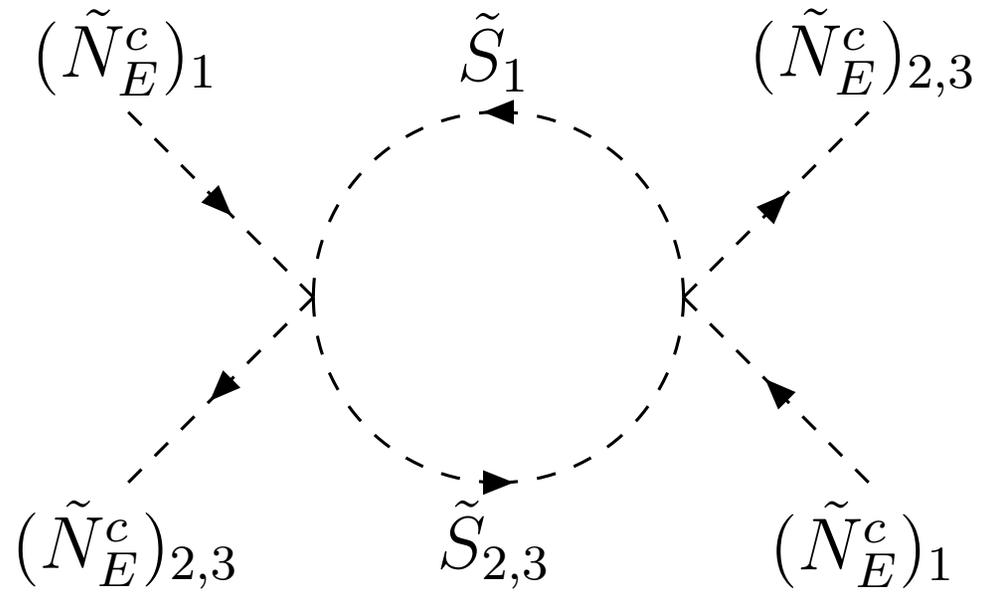
M parity implies the usual R parity with $B = 1/3$ and $L = 1$ for h .

The only terms involving N^c are the allowed Majorana mass terms $N^c N^c$ and the Yukawa terms $[\nu(N_E^c)_{2,3} - e(E^c)_{2,3}]N^c$, i.e. exactly as required for the seesaw mechanism.

However, N parity forbids m_ν at tree level, and the necessary λ_5 quartic scalar term for a one-loop mass, i.e. $[(\tilde{N}_E^c)_{2,3}^\dagger (\tilde{N}_E^c)_1]^2$, is not available in exact supersymmetry.

Fortunately, as the supersymmetry is broken by soft terms, an effective λ_5 term itself can be generated in one loop. Thus m_ν is a two-loop effect in this model.





At least **two** out of the following **three** particles are dark-matter candidates:

- (1) the usual lightest neutralino of the **MSSM** with $(R, N) = (-, +)$,
- (2) the lightest exotic neutral particle with $(+, -)$,
- (3) and that with $(-, -)$.

The dark matter of the Universe may not be all the same, as most people have taken for granted!

Conclusion

The evidence of **dark matter** signals a new class of particles at the **TeV** scale, which may manifest themselves indirectly through **loop** effects. They may be responsible for **neutrino mass**, and perhaps also **muon anomalous magnetic moment**, as well as **leptogenesis**. **Observable bosonic dark matter** at the **electroweak** scale are possible, as well as neutral singlet fermions at the **TeV** scale.