Common Origin of Neutrino Mass and Dark Matter

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Contents

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.]

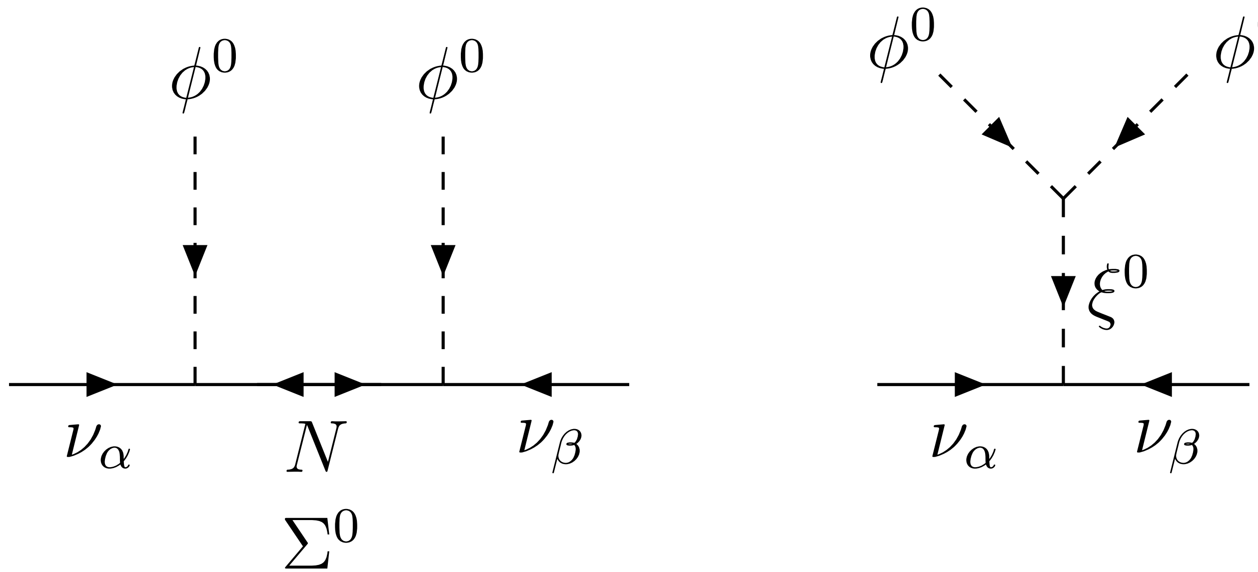
If all we want is DM, the simplest way is to add a second Higgs doublet (η^+, η^0) [Barbieri/Hall/Rychkov(2006)] which is odd under Z_2 with all SM particles even. This differs from the scalar MSSM $(\tilde{\nu}, \tilde{l})$ doublet, because η^0_R and η^0_I are split in mass by the Z_2 conserving term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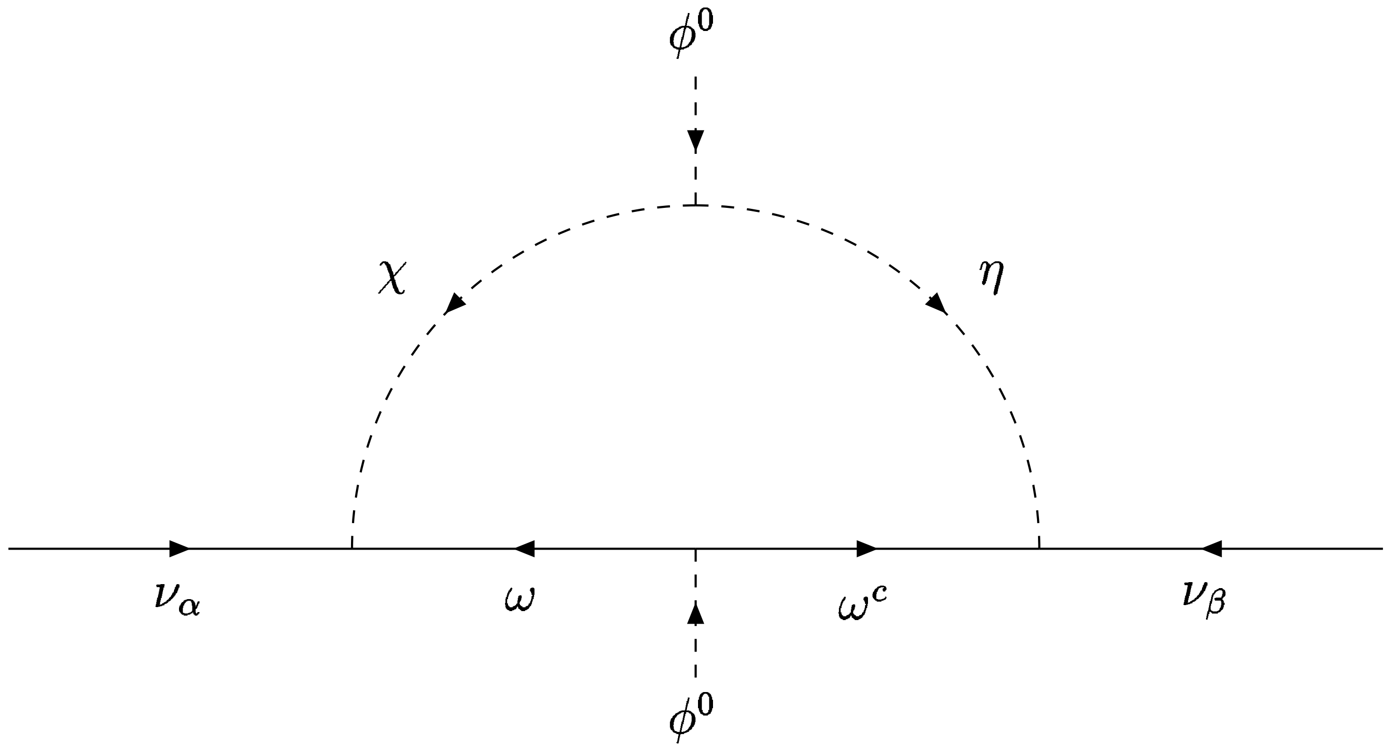
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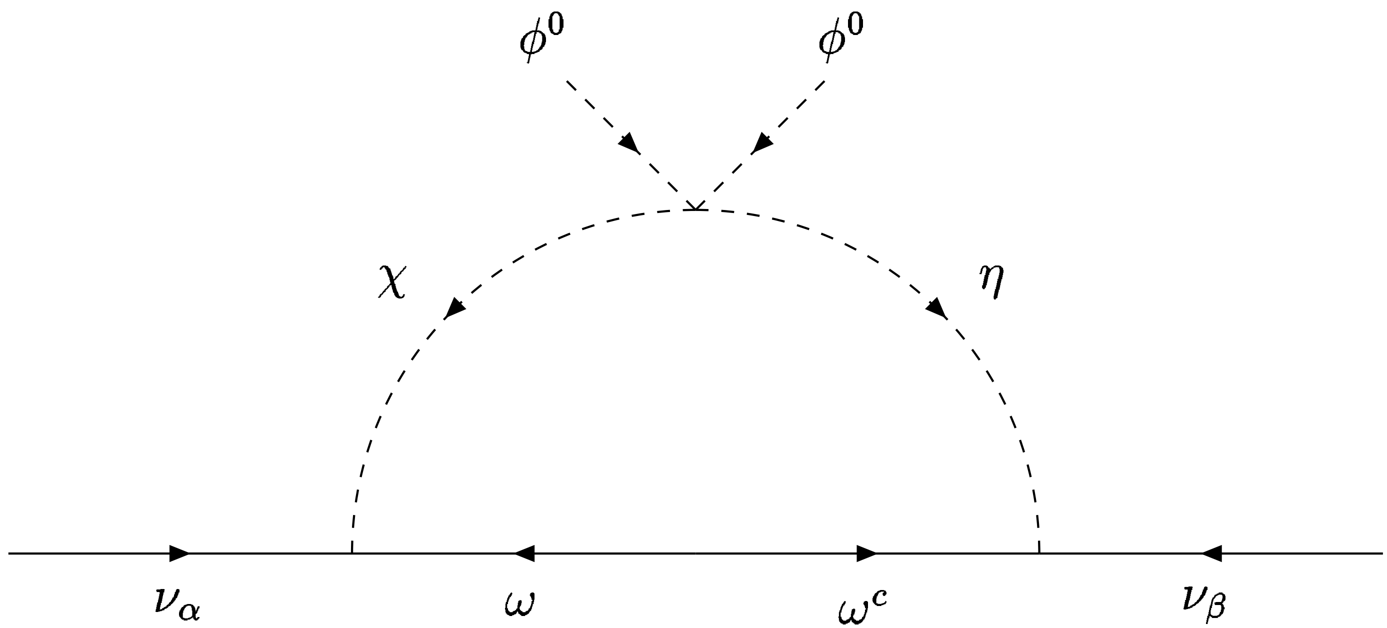

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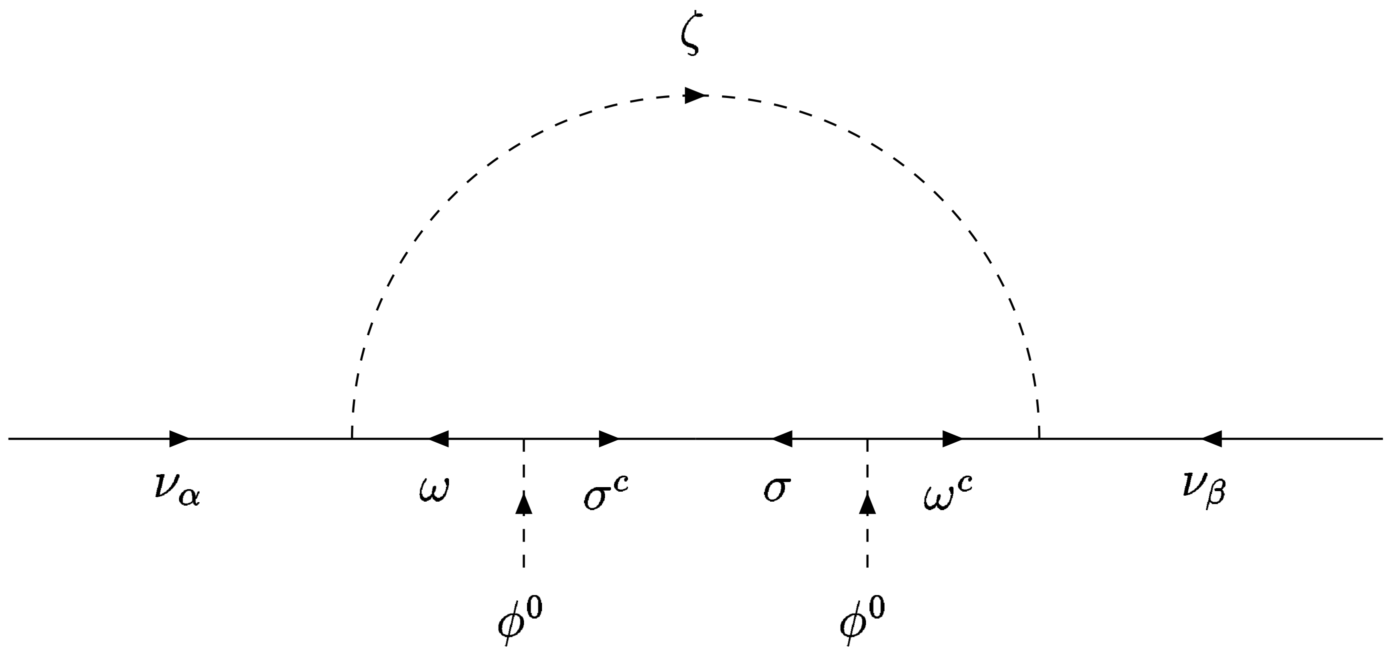


ζ
ν_α
ω
σ^c
σ
ω^c
ν_β
ϕ^0
ϕ^0

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)]

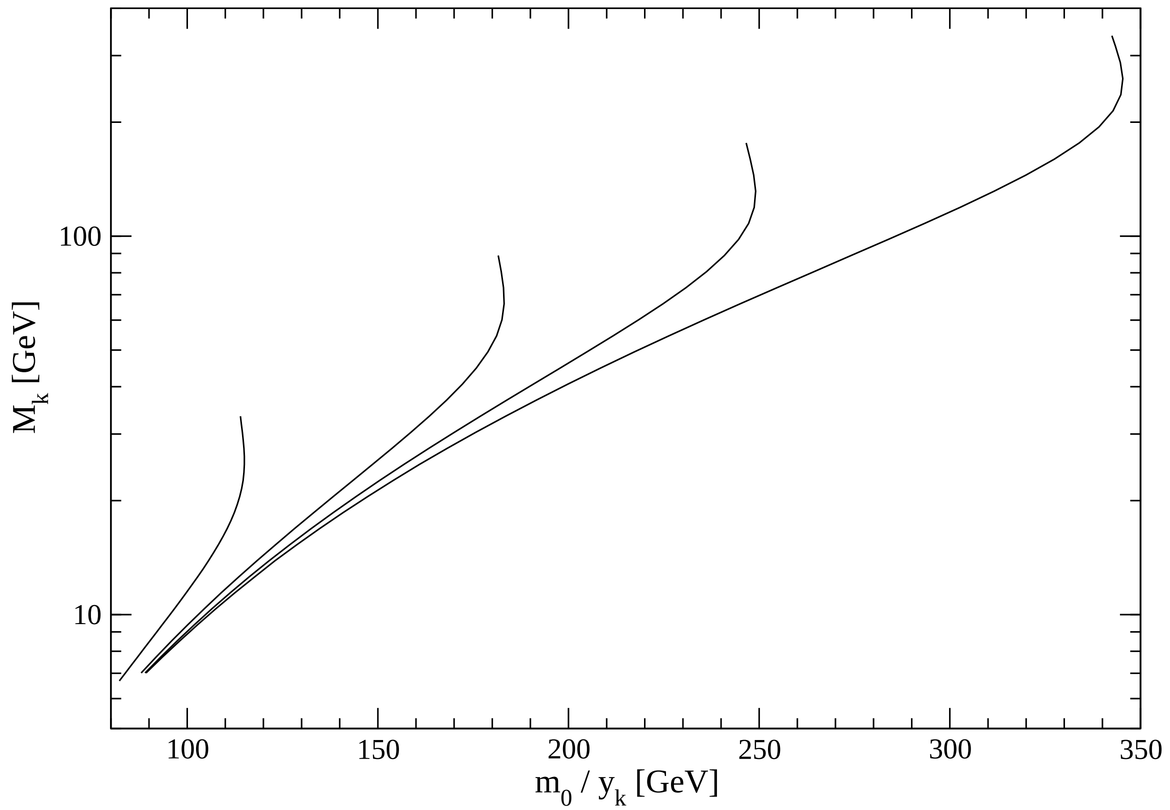


Figure 1: M_k versus m_0/y_k for $y_k = 0.3, 0.5, 0.7, 1.0$ (left to right) for $\Omega_d h^2 = 0.12$, where y_k is an effective Yukawa coupling.

Supersymmetric $E_6/U(1)_N$ Model

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

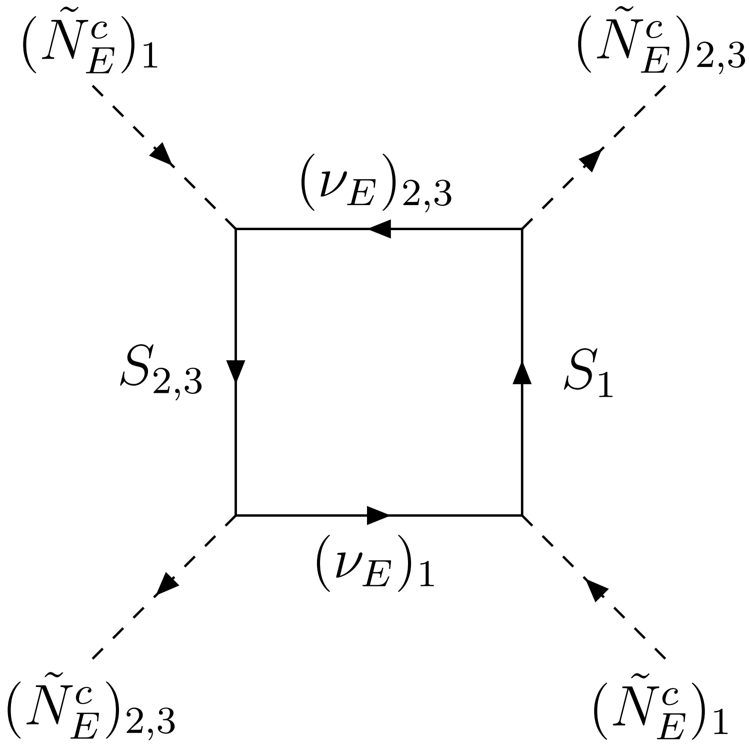
superfield	M	N
$(u, d), u^c, d^c$	$+$	$+$
$(\nu, e), e^c$	$-$	$+$
h, h^c	$-$	$+$
$[(\nu_E, E), (E^c, N_E^c), S]_1$	$+$	$+$
$[(\nu_E, E), (E^c, N_E^c), S]_{2,3}$	$+$	$-$
N^c	$-$	$-$

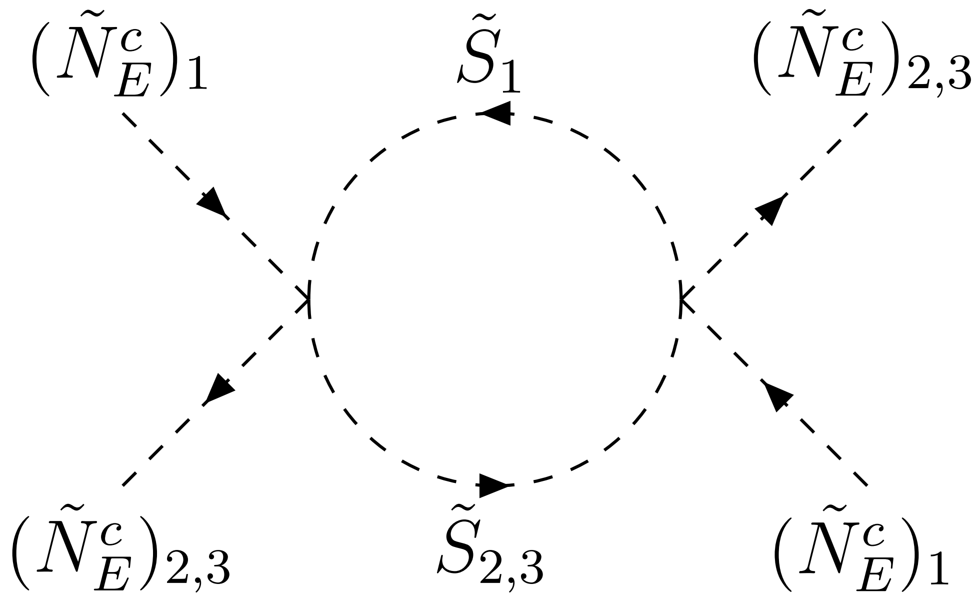
M parity implies the usual R parity with $B = 1/3$ and $L = 1$ for h.

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. $[(\tilde{N}_E^c)^\dagger_{2,3}(\tilde{N}_E^c)_1]^2$, 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.


$(\tilde{N}_E^c)_1$
$(\tilde{N}_E^c)_{2,3}$
$(\nu_E)_{2,3}$
$S_{2,3}$
S_1
$(\nu_E)_1$
$(\tilde{N}_E^c)_{2,3}$
$(\tilde{N}_E^c)_1$


$(\tilde{N}_E^c)_1$
$\tilde{S}_1$
$(\tilde{N}_E^c)_{2,3}$
$(\tilde{N}_E^c)_{2,3}$
$\tilde{S}_{2,3}$
$(\tilde{N}_E^c)_1$

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.