Neutrino Mass, Dark Matter, and Leptogenesis

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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.]

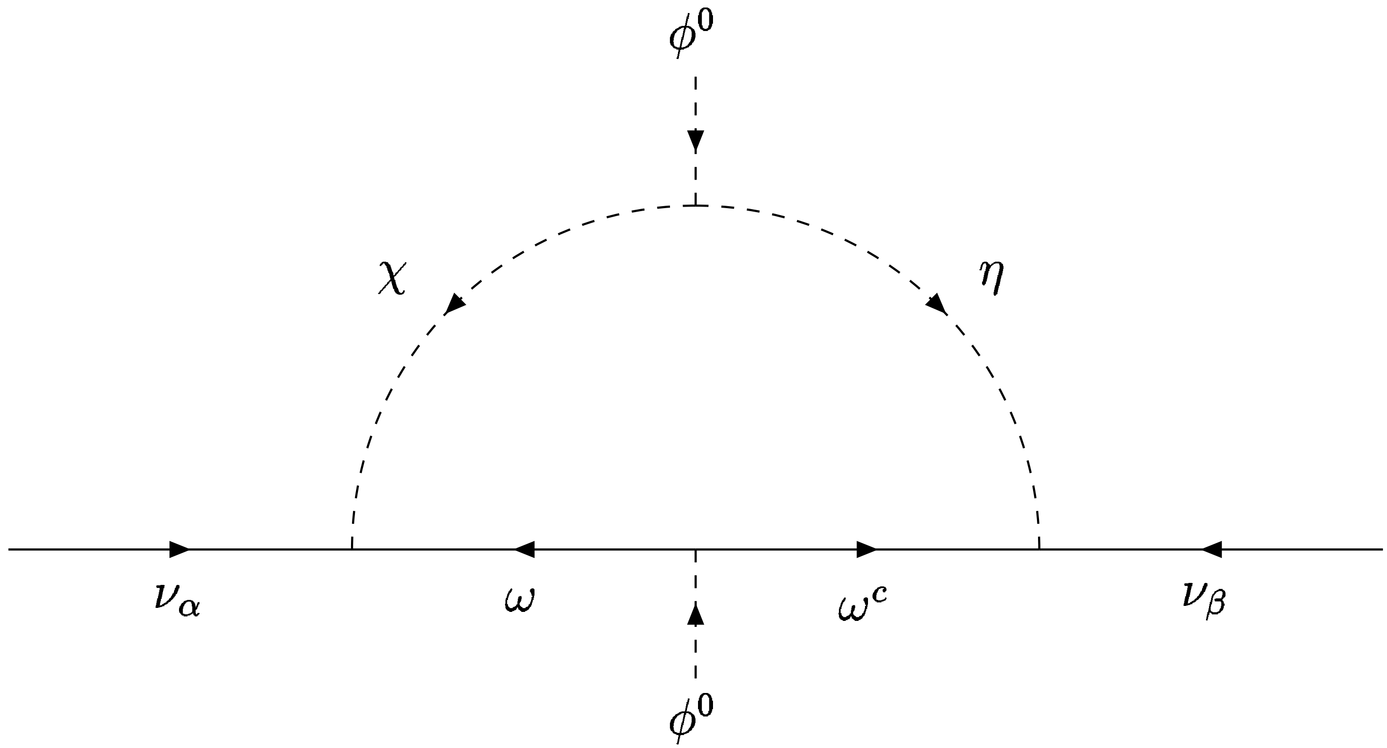
If all we want is DM, the simplest way is to add a second Higgs doublet (η^+, η^0) [Barbieri/Hall/Rychkov(2006)] which is odd under Z_2 with all SM particles even. This differs from the scalar MSSM $(\tilde{\nu}, \tilde{l})$ doublet, because η_R^0 and η_I^0 are split in mass by the Z_2 conserving term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

Neutrino Mass and Dark Matter

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).


ϕ^0
χ
η
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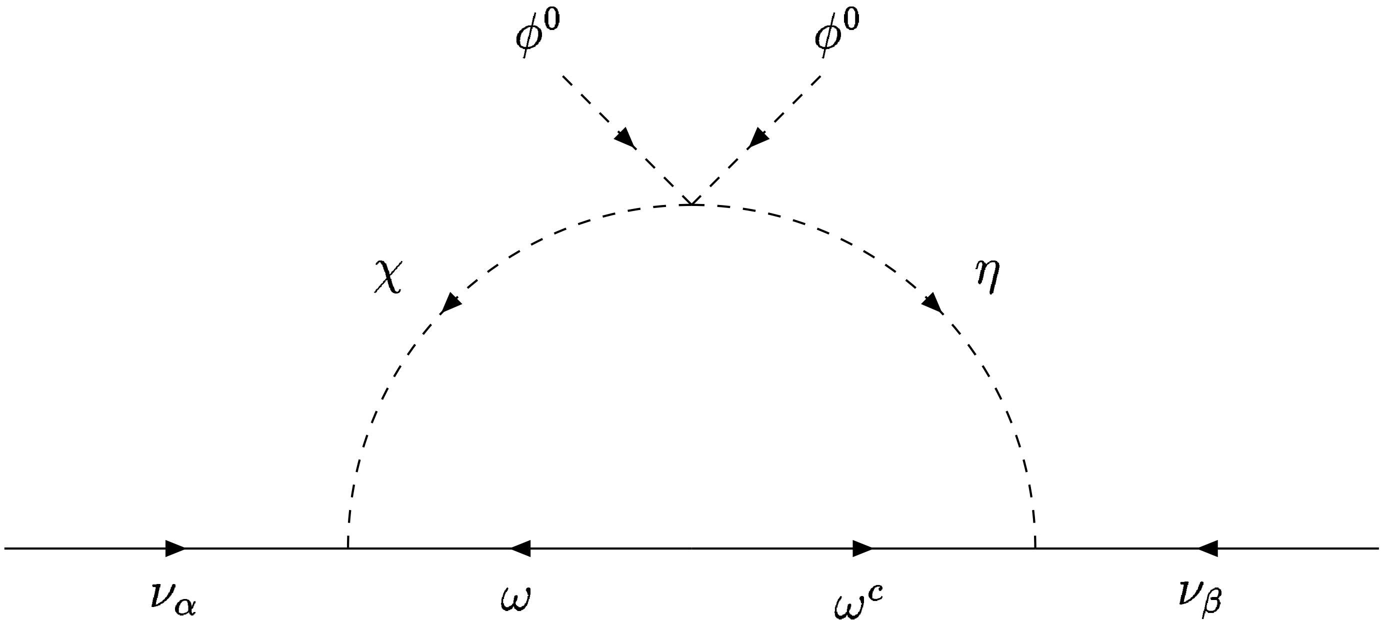
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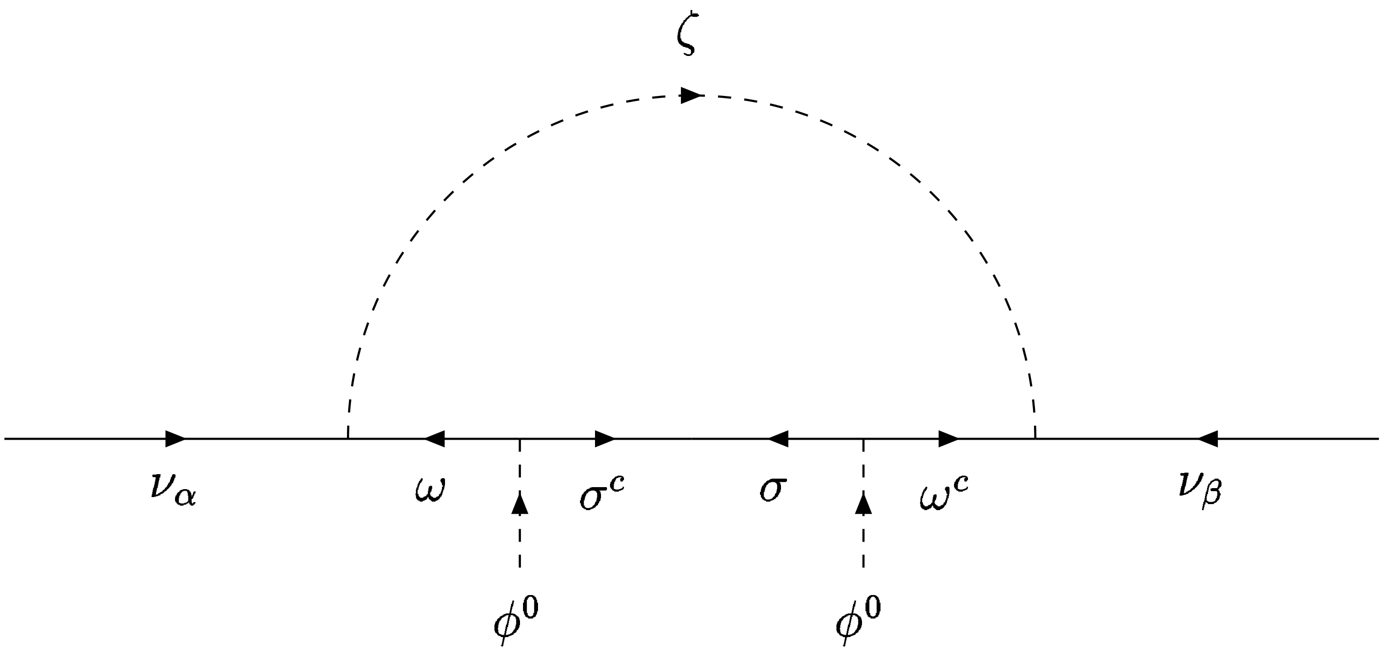


ζ
ν_α
ω
σ^c
σ
ω^c
ν_β
ϕ^0
ϕ^0

Zee(1980): (IV)

$\omega = (\nu, l), \omega^c = l^c$, $\chi = \chi^+, \eta = (\phi^+_{1,2}, \phi^0_{1,2}), \langle \phi^0_{1,2} \rangle \neq 0$.

Ma(2006): (V)

$\omega = \omega^c = N$, $\chi = \eta = (\eta^+, \eta^0), \langle \eta^0 \rangle = 0$.

Note: N interacts with ν, but they are not Dirac mass partners. This is due to an exactly conserved Z_2 symmetry, under which N and (η^+, η^0) are odd, and all SM particles are even.

Result: (A) η^0_R or η^0_I 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)]

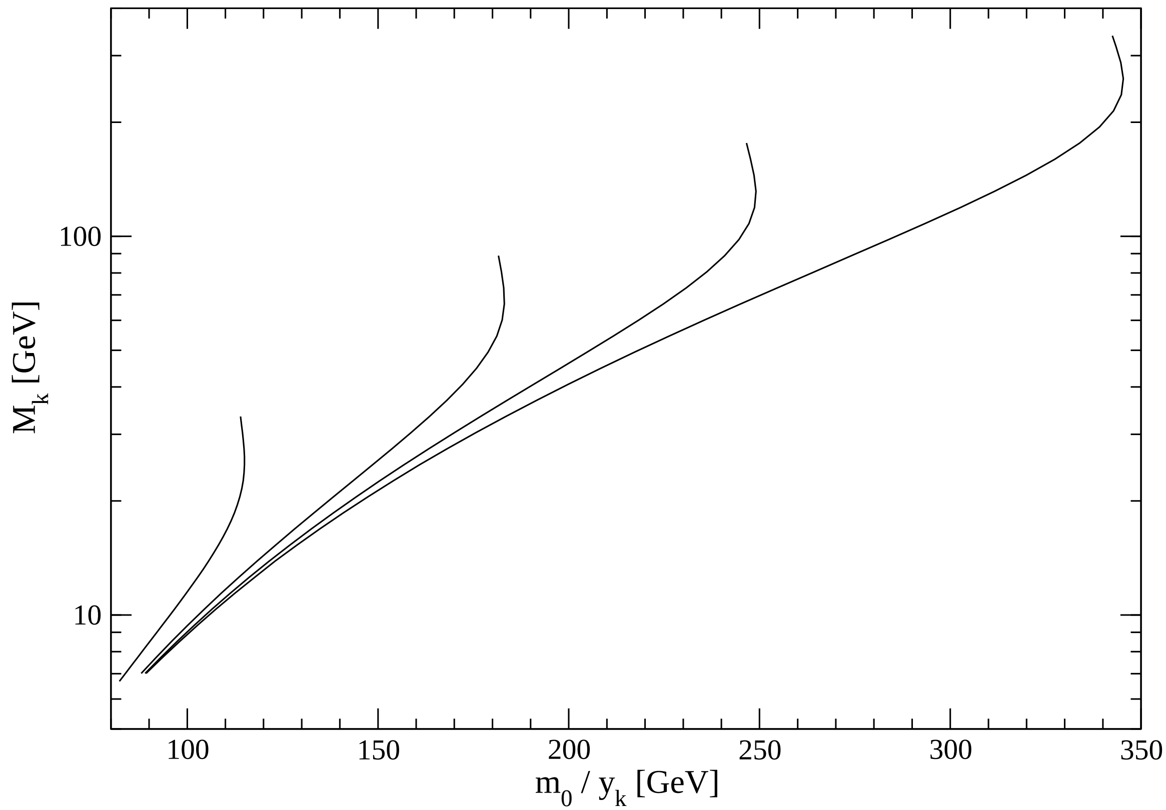


Figure 1: M_k versus m_0/y_k for $y_k = 0.3, 0.5, 0.7, 1.0$ (left to right) for $\Omega_d h^2 = 0.12$, where y_k is an effective Yukawa coupling.

Neutrino Mass and Leptogenesis

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h_{\alpha i} h_{\beta i} M_i}{16\pi^2} [f(M_i^2/m_R^2) - f(M_i^2/m_I^2)],$$

where $f(x) = -\ln x/(1-x)$. Let
$m_R^2 - m_I^2 = 2\lambda_5 v^2 << m_0^2 = (m_R^2 + m_I^2)/2$, then

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h_{\alpha i} h_{\beta i}}{M_i} I(M_i^2/m_0^2),$$

$$I(x) = \frac{\lambda_5 v^2}{8\pi^2} \left(\frac{x}{1-x}\right) \left[1 + \frac{x \ln x}{1-x}\right].$$

For $x_i >> 1$, i.e. N_i very heavy,

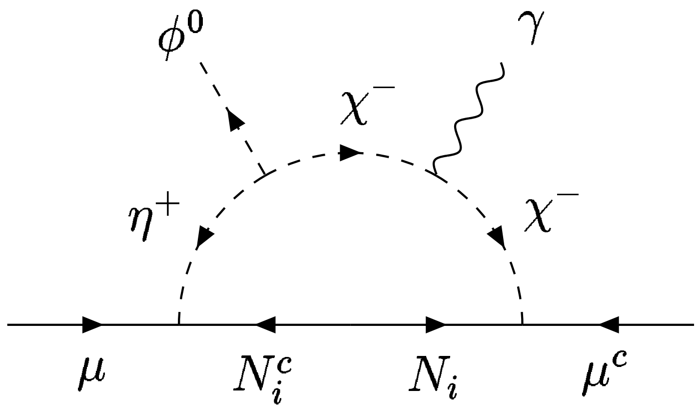
$$(\mathcal{M}_\nu)_{\alpha\beta} = \frac{\lambda_5 v^2}{8\pi^2} \sum_i \frac{h_{\alpha i} h_{\beta i}}{M_i} [\ln x_i - 1]$$

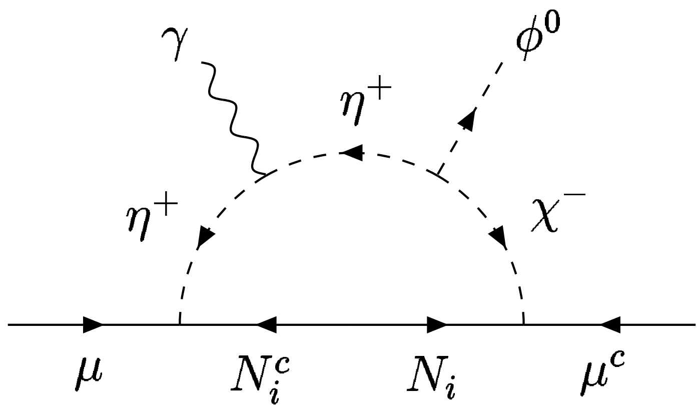
instead of the canonical seesaw $v^2 \sum_i h_{\alpha i} h_{\beta i} / M_i$.
In leptogenesis, the lightest M_i may then be much below the Davidson-Ibarra bound of about 10^9 GeV, thus avoiding a potential conflict of gravitino overproduction and thermal leptogenesis. In this scenario, η^0 is dark matter.

Muon $g-2$ and Neutrino Mass

Hambye/Kannike/Ma/Raidal(2006):

particles	$SU(2)\times U(1)$	$U(1)_L$	$(-1)^L$	Z_2
$L_\alpha = (\nu_\alpha, l_\alpha)$	$(2, -1/2)$	1	$-$	$+$
l^c_α	(1,1)	–1	$-$	$+$
$\Phi = (\phi^+, \phi^0)$	(2,1/2)	0	$+$	$+$
N_i	(1,0)	1	$-$	$-$
N^c_i	(1,0)	–1	$-$	$-$
$\eta = (\eta^+, \eta^0)$	(2,1/2)	0	$+$	$-$
χ^-	(1,–1)	0	$+$	$-$


ϕ^0
γ
χ^-
η^+
χ^-
μ
N_i^c
N_i
μ^c


γ
ϕ^0
η^+
η^+
χ^-
μ
N_i^c
N_i
μ^c

Mixing of χ^+ and η^+:

$$\Delta a_\mu = \frac{-\sin\theta\cos\theta}{16\pi^2}\sum_i h_{\mu i}h'_{\mu i}\frac{m_\mu}{M_i}[F(x_i) - F(y_i)],$$

where $x_i = m_X^2/M_i^2$, $y_i = m_Y^2/M_i^2$, and
$F(x) = [1 - x^2 + 2x\ln x]/(1-x)^3$.
Let $y_i << x_i \simeq 1$, $M_i \sim 1$ TeV,
$(-h_{\mu i}h'_{\mu i}\sin\theta\cos\theta/24\pi^2) \sim 10^{-5}$, then $\Delta a_\mu \sim 10^{-9}$,
whereas

$$(\Delta a_\mu)_{\mathrm{exp't}} = (22.4 \pm 10) \text{ to } (26.1 \pm 9.4) \times 10^{-10}.$$

Neutrino Mass: Allow soft breaking of $U(1)_L$, i.e.

$$\frac{1}{2}m_{ij}N_i^c N_j^c + \frac{1}{2}m'_{ij}N_i N_j + H.c.,$$

$$\text{then} \quad (\mathcal{M}_\nu)_{\alpha\beta} = \sum_{i,j} h_{\alpha i} h_{\alpha j} \tilde{m}_{ij}, \quad \text{where} \quad \tilde{m}_{ij} =$$

$$\frac{\lambda_5 v^2 m_{ij}}{8\pi^2 (M_i^2 - M_j^2)} \left[\frac{M_i^2}{m_0^2 - M_i^2} + \frac{M_i^4 \ln(M_i^2/m_0^2)}{(m_0^2 - M_i^2)^2} - (i \leftrightarrow j) \right].$$

Let $M_{i,j} \sim 1$ TeV, $m_{ij} \sim 0.1$ GeV, $h_{\alpha i} \sim 10^{-2}$, $\lambda_5 \sim 0.1$, $m_0 \sim v \sim 10^2$ GeV, then the entries of $\mathcal{M}_\nu \sim 0.1$ eV.

Suppose the $h_{\alpha 1}$ couplings are very small, i.e. N_1^c decouples from $\mathcal{M}_\nu$, and that, for example,

$$h_{\alpha i} \simeq h \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1/\sqrt{2} \\ 0 & 0 & 1/\sqrt{2} \end{pmatrix},$$

then in the basis $[\nu_e, (\nu_\mu + \nu_\tau)/\sqrt{2}, (-\nu_\mu + \nu_\tau)/\sqrt{2}]$,

$$\mathcal{M}_\nu \simeq h^2 \begin{pmatrix} \tilde{m}_{22} & \tilde{m}_{23} & 0 \\ \tilde{m}_{23} & \tilde{m}_{33} & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

i.e. $\theta_{23} = \pi/4$, $\theta_{13} = 0$, $m_3 = 0$ (inverted ordering).

Novel TeV Leptogenesis

Let (N_1, N_1^c) be the lightest pair with $h_{\alpha 1}, h'_{\alpha 1} \sim 10^{-7}$ to satisfy the out-of-equilibrium condition for leptogenesis. Rotate

$$\begin{pmatrix} m'_{11} & M_1 \\ M_1 & m_{11} \end{pmatrix} \to \begin{pmatrix} -M_1 + A & B \\ B & M_1 + A \end{pmatrix},$$

where $A = (m'_{11} + m_{11})/2$, $B = (m'_{11} - m_{11})/2$. Choose phases so that $M_1 > 0, A > 0$ are real and $B = |B|e^{i\alpha}$.

Diagonalize above matrix with

$$\begin{pmatrix} e^{i\beta}\cos\theta & -\sin\theta \\ \sin\theta & e^{-i\beta}\cos\theta \end{pmatrix},$$

then $\sin\beta = -M_1 \tan\alpha/C$, $\cos\beta = A/C$, $\tan 2\theta = \cos\alpha|B|C/AM_1$, where $C = \sqrt{A^2 + M_1^2 \tan^2\alpha}$. Let $A^2 << M_1^2 \tan^2\alpha$, then $e^{i\beta} = (A/M_1 \tan\alpha) - i$, and the lepton asymmetry is given by

$$\left(\frac{-1}{64\pi}\right) \frac{|B|^2 \sin\alpha\cos\alpha}{A^2 + |B|^2 \sin^2\alpha} \left[\frac{4(\sum_\alpha |h_{\alpha 1}|^2)^2 - (\sum_\alpha |h'_{\alpha 1}|^2)^2}{2\sum_\alpha |h_{\alpha 1}|^2 + \sum_\alpha |h'_{\alpha 1}|^2}\right].$$

The novel feature of this mechanism is that CP violation originates in the mass matrix, not the Yukawa couplings. However, because $h_{\alpha 1}, h'_{\alpha 1} \sim 10^{-7}$, this effect is too small. Use instead (N_2, N_2^c) with a single lighter N_1, then the lepton asymmetry is $M_1 \Delta M_2 / 64\pi \times$

$$\frac{Im[e^{2i\theta}(2M_1 \sum_\alpha h_{\alpha 1} h^*_{\alpha 2} - M_2 \sum_\alpha h'^*_{\alpha 1} h'_{\alpha 2})^2 + \{M_1 \leftrightarrow M_2\}]}{({M_2}^2 - {M_1}^2)^2 (2 \sum_\alpha |h_{\alpha 1}|^2 + \sum_\alpha |h'_{\alpha 1}|^2)}.$$

For M_2 and M_1 of order 1 TeV and ΔM_2 of order 0.1 GeV, this asymmetry may well be of order 10^{-6} because $h'_{\alpha 2}$ are mostly unconstrained and could be of order unity.

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, muon anomalous magnetic moment, as well as leptogenesis. Two simple examples predict observable bosonic dark matter at the electroweak scale, and perhaps also neutral singlet fermions at the TeV scale.