Stable Interacting Majorana Fermion as keV Warm Dark Matter

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Main points of my proposal:

- Neutrino masses are one-loop quantum effects due to the existence of dark matter.
  E. Ma, Phys. Rev. D 73, 077301 (2006).

- The dark matter candidate is a stable interacting Majorana fermion (scotino) of about 10 keV.
  E. Ma, arXiv:1206.1812.

- Being stable, the scotino is not subject to the observational upper bound of 2.2 keV from galactic X-ray data on the usual decaying sterile neutrino, assuming the standard nonresonant production mechanism from its mixing with the active neutrinos [Dodelson-Widrow].

- Such a stable scotino is also possible in a left-right extension of the standard model.

  E. Ma, Phys. Rev. D 85, 091701 (2012).

Contents

The Gift of Higgs

Since the announcement of its 'discovery' on July 4, 2012, the Higgs boson is now 'confirmed' as the particle which gives all particles their masses. How exactly does this work?

All known fundamental fermions transform under the electroweak gauge symmetry $SU(2)_L \times U(1)_Y$ as follows:

$$(u,d)_L \sim (2, 1/6), \quad (\nu, e)_L \sim (2, -1/2),$$

$$u_R \sim (1, 2/3), \quad d_R \sim (1, -1/3), \quad e_R \sim (1, -1),$$

i.e. all left-handed fermions are doublets and all right-handed fermions are singlets. For a fermion to have a mass, the Dirac equation requires a connection between its left-handed and right-handed components. Since this term must be invariant under $SU(2)_L \times U(1)_Y$, it is impossible unless there exists a scalar doublet (ϕ^+, ϕ^0) such that ϕ^0 acquires a nonzero vacuum expectation value and breaks $SU(2)_L \times U(1)_Y$ to the electromagnetic $U(1)_Q$ which is exactly conserved. At the same time, the originally massless vector gauge bosons $W^\pm, Z^0$ also become massive. This is the gift of Higgs.

The Neutrino Story

Does the neutrino get its mass also from the Higgs? The usual thinking is yes and no. The story goes like this. Since $\nu_R \sim (1,0)$ does not transform at all under $SU(2)_L \times U(1)_Y$, it is not part of the minimal standard model. If it is added nevertheless, then again the neutrino has a Dirac mass, although there is no understanding why it is so small. Everything looks fine and everybody should be happy, but wait!

There is now also a Majorana mass term for ν_R which is not the gift of Higgs. The 2×2 mass matrix spanning

(ν_L, ν_R) is of the form

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix},$$

yielding the famous seesaw formula $m_\nu \simeq -m_D^2/m_R$ for $m_D << m_R$. Thus the neutrino has both a Higgs contribution (m_D) and a non-Higgs contribution (m_R). The existence of ν_R has yet to be proven, but if $m_R \sim$ keV, then it is usually called a sterile neutrino and is an excellent warm dark matter candidate. See for example the recent white paper arXiv:1204.5379.

The Scotogenic Model: A New Paradigm?

In 2006 [E. Ma, Phys. Rev. D 73, 077301 (2006)], it was proposed that neutrino masses are one-loop quantum effects due to the existence of dark matter, i.e. scotogenic from the Greek 'scotos' meaning darkness. The standard model of particle interactions is extended to include 3 singlet Majorana neutral fermions $N_{1,2,3}$ (analogs of ν_R) $+$ one extra scalar doublet (η^+, η^0) in addition to the usual (ϕ^+, ϕ^0). An exactly conserved Z_2 (odd-even) symmetry is imposed so that $N_{1,2,3}$ (scotinos) and (η^+, η^0) are odd and all other particles are even.

The Z_2 symmetry forbids νN coupling to ϕ^0, so there is no Dirac mass linking ν to N, i.e.

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & 0 \\ 0 & m_N \end{pmatrix}$$

at the classical (tree) level. However, at the quantum level, a one-loop diagram induces a Majorana mass for ν, so that

$$\mathcal{M}_\nu = \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix}.$$

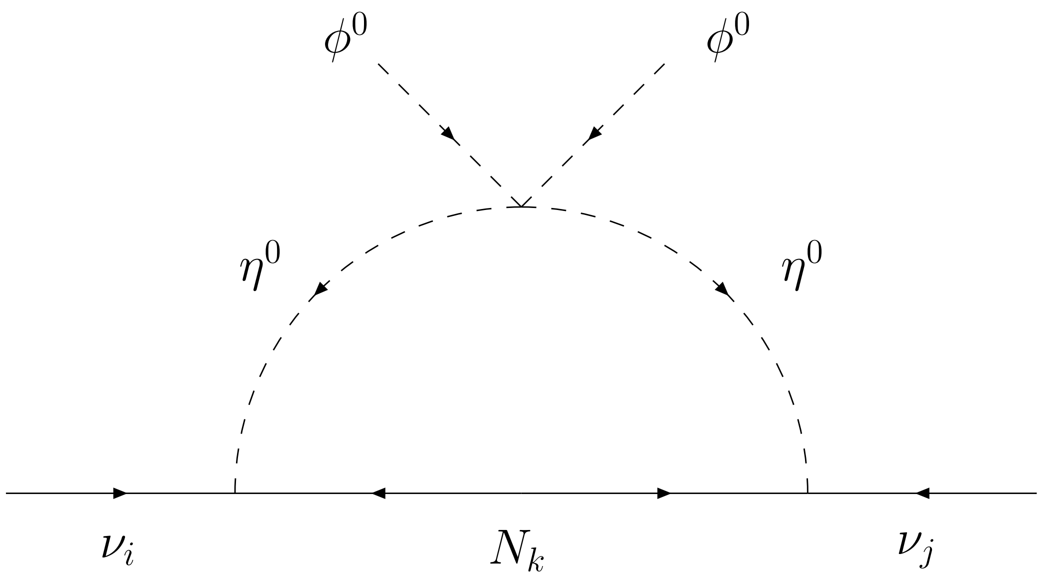

Figure 1: One-loop generation of neutrino mass with Z_2 dark matter.

The $(1/2)\lambda_5(\eta^\dagger\Phi)^2 + H.c.$ term allowed by Z_2 implies that η_R^0 and η_I^0 are split by $\langle\phi^0\rangle = v$ to have different physical masses.

The one-loop diagram can then be exactly calculated, i.e. $(\mathcal{M}_\nu)_{ij} =$

$$\sum_k \frac{h_{ik}h_{jk}M_k}{16\pi^2}\left[\frac{m_R^2}{m_R^2 - M_k^2}\ln\frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2}\ln\frac{m_I^2}{M_k^2}\right].$$

The lightest particle among η_R^0, η_I^0, $N_{1,2,3}$ is absolutely stable and is a good dark matter candidate.

The prejudice in neutrino physics is that neutrino mass comes from new physics beyond the electroweak scale, i.e. $m_R, m_I << M_k$, so

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik}h_{jk}}{16\pi^2 M_k}\left(m_R^2 \ln\frac{M_k^2}{m_R^2} - m_I^2 \ln\frac{M_k^2}{m_I^2}\right).$$

This expression is inversely proportional to M_k, as is in the canonical seesaw mechanism. In this case, η_R^0 or η_I^0 is cold dark matter. Many studies of this and other related scenarios have been made.

However, it was recently (E. Ma, arXiv:1206.1812) noticed that if $M_k << m_R, m_I$, a radically new formula for neutrino mass is obtained, i.e.

$$(\mathcal{M}_\nu)_{ij} = \frac{\ln(m_R^2/m_I^2)}{16\pi^2} \sum_k h_{ik} h_{jk} M_k,$$

which is directly proportional to M_k !!

This possibility has never been contemplated before and allows $N_{1,2,3}$ to be dark matter candidates. Since the masses of $N_{1,2,3}$ are not the gift of Higgs, the neutrino masses are also not the gift of Higgs.

Actually $\ln(m_R^2/m_I^2)$ would be zero without electroweak symmetry breaking, so the gift of Higgs still shows up, but only indirectly.

Bonus: The extra scalar doublet (η^+, η^0) with $m_{\eta^+} \sim 300$ GeV may also change the finite-temperature behavior of the standard-model Higgs sector to allow it to have a strong first-order phase transition for electroweak baryogenesis, i.e. the creation of the present observed matter-antimatter asymmetry of the Universe.

Stable keV Warm Dark Matter

Let $h_{ik}^2 \sim 10^{-3}$, then $m_\nu \sim 0.1$ eV implies $m_N \sim 10$ keV. Since the lightest N (call it N_1) is absolutely stable, there is no $N_1 \to \nu\gamma$ decay which would put an upper bound of 2.2 keV on its mass if it were the usual sterile neutrino which is produced nonresonantly through its mixing with the active neutrinos (Dodelson-Widrow). The stability of N_1 removes the tension between this would-be upper bound and the lower bound of perhaps 5.5 keV from Lyman-α forest observations.

Implications for particle physics:

$$(1) \quad B(\mu \to e\gamma) = \frac{\alpha}{768\pi}\frac{|\sum_k h_{\mu k} h^*_{ek}|^2}{(G_F m^2_{\eta^+})^2} < 2.4 \times 10^{-12}$$

implies $m_{\eta^+} > 310$ GeV $(|\sum_k h_{\mu k} h^*_{ek}|/10^{-3})^{1/2}$.

(2) Anomalous magnetic moment of muon is given by

$$\Delta a_\mu = -\frac{m^2_\mu}{96\pi^2 m^2_{\eta^+}} \sum_k |h_{\mu k}|^2 < 1.23 \times 10^{-13} \frac{\sum_k |h_{\mu k}|^2}{|\sum_k h_{\mu k} h^*_{ek}|},$$

which is much below the experimental uncertainty of 6×10^{-10}.

(3) Since N_k are light, muon decay also proceeds at tree level through η^+ exchange. The inclusive rate is given by

$$\Gamma(\mu \to N_\mu e \bar{N}_e) = \frac{(\sum_k |h_{\mu k}|^2)(\sum_k |h_{ek}|^2) m_\mu^5}{6144\pi^3 m_{\eta^+}^4}$$

$$< 2.5 \times 10^{-8} \frac{(\sum_k |h_{\mu k}|^2)(\sum_k |h_{ek}|^2)}{|\sum_k h_{\mu k} h_{ek}^*|^2} \Gamma(\mu \to \nu_\mu e \bar{\nu}_e),$$

which is much below the experimental uncertainty of 10^{-5} in the determination of G_F.

Implications for cosmology:

(1) Whereas N_1 is absolutely stable, $N_{2,3}$ will decay.

$$\Gamma(N_2 \to N_1 \bar{\nu}_i \nu_j) = \frac{|h_{i2} h^*_{j1}|^2}{256\pi^3 M_2} \left(\frac{1}{m_R^2} + \frac{1}{m_I^2} \right)^2$$

$$\times \left(\frac{M_2^6}{96} - \frac{M_1^2 M_2^4}{12} + \frac{M_1^6}{12} - \frac{M_1^8}{96 M_2^2} + \frac{M_1^4 M_2^4}{8} \ln \frac{M_2^2}{M_1^2} \right) .$$

If this decay lifetime is longer than the age of the Universe of $13.75 \pm 0.11 \times 10^9$ y, then N_2 would still be present and its decay into $N_1 \gamma$ would be subject to galactic X-ray constraints.

As an example, let $M_2 = 50$ keV, $M_1 = 10$ keV, $|h_{i2}h^*_{j1}|^2 = 10^{-6}(M_1/M_2)$, $m_R = 120$ GeV, $m_I = 75$ GeV, then $\Gamma = 3.7 \times 10^{-42}$ GeV, corresponding to a decay lifetime of 5.6×10^9 y.

It will be assumed that $N_{2,3}$ have all decayed into N_1 at the present age of the Universe and only N_1 remains as dark matter today.

(2) The effective $N\bar{N} \to l\bar{l}, \nu\bar{\nu}$ interactions are of order $h^2/m_\eta^2 \sim 10^{-7}$ Gev^{-2}, hence they remain in thermal equilibrium in the early Universe until a temperature of about 200 MeV. Their number density n_N is given by

$$\frac{n_N}{n_\gamma} = \left(\frac{43/4}{g^*_{dec}}\right)\left(\frac{2}{11/2}\right)\frac{3/2}{2},$$

where $g^*_{dec} = 16$, counting $N_{1,2,3}$ in addition to photons, electrons, and the three neutrinos. Their relic abundance at present would then be

$$\Omega_N h^2 \simeq \frac{115}{16}\left(\frac{3M_1}{\mathrm{keV}}\right),$$

where the factor 3 comes from $N_{2,3}$ all decaying into N_1. Since $\Omega_N h^2$ should be 0.1123 ± 0.0035, a dilution factor of about 1.9×10^3 is needed for $M_1 = 10$ keV.

(3) The dilution factor may be accomplished by a particle which decouples after N_1 and decays later as it becomes nonrelativistic, with a large release of entropy. A suitable candidate is a real singlet scalar σ of mass 20 MeV, which decouples also at around 200 MeV as N_1. Let its interaction with the Higgs boson be $\sqrt{2}\lambda_3 v H \sigma^2$, then for $m_H = 125$ GeV, the cross section of $\sigma\sigma \to \mu^+\mu^-$ is consistent with its decoupling at 200 MeV if $\lambda_3 \sim 10^{-3}$. The subsequent $\sigma \to e^+e^-$ decay rate is

$$\Gamma(\sigma \to e^+e^-) = \frac{m_\sigma}{8\pi}\left(\frac{m_e^2}{2v^2}\right)\epsilon^2,$$

where ϵ is the mixing of σ with H. The entropy released is $S \simeq (0.76/16) m_\sigma (\Gamma M_{Pl})^{-1/2}$. For $S \simeq 1.9 \times 10^3$, this implies $\epsilon \simeq 2.0 \times 10^{-8}$.

Implications at the Large Hadron Collider:

$\Gamma(H \to \sigma\sigma) = \lambda_3^2 v^2 / 4\pi m_H \simeq 1.93 \times 10^{-2}$ MeV. Since the total width of H is about 4.3 MeV, this invisible mode is very difficult to establish. On the other hand, $\eta^+ \to l_i^+ N_j$ and $\eta^+ \to \eta_{R,I} W^+$ as well as $\eta_R \to \eta_I Z$ are possible signatures.

Experimental tests of the scotogenic model:

(1) Nonobservation of a galactic keV X-ray line.

(2) Nonobservation of any dark-matter signal at underground experiments.
Latest news from XENON100: 50 Gev dark matter is excluded at 2.0×10^{-45} cm^2.

(3) Nonobservation of dark-matter annihilation products (gamma rays, etc.) from space.

(4) Observation of the exotic scalars $\eta^+, \eta^0_R, \eta^0_I$ in accelerators.

$SU(2)_L$ Neutrinos and $SU(2)_R$ Scotinos

[E. Ma, Phys. Rev. D 85, 091701 (2012).]

$(u, d)_L$ is an $SU(2)_L$ doublet, coupling to $W_L^\pm, \gamma, Z, Z'$.

$(u, h)_R$ is an $SU(2)_R$ doublet, coupling to $W_R^\pm, \gamma, Z, Z'$.

d_R, h_L are singlets, coupling to γ, Z, Z'.

$(\nu, e)_L$ is an $SU(2)_L$ doublet.

$(n, e)_R$ is an $SU(2)_R$ doublet.

ν_R, n_L are singlets.

A symmetry exists to distinguish $n, h, W_R^\pm$ (odd) from the other particles (even).

Neutrino mass is seesaw for (ν_L, ν_R), i.e.

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_{LR} \\ m_{LR} & m_{RR} \end{pmatrix}, \quad m_{LR} << m_{RR}.$$

Scotino mass is seesaw for (n_R, n_L), i.e.

$$\mathcal{M}_n = \begin{pmatrix} 0 & m_{RL} \\ m_{RL} & m_{LL} \end{pmatrix}, \quad m_{RL} << m_{LL}.$$

There is complete analogy between the $SU(2)_L$ and $SU(2)_R$ sectors with the switch $\nu \leftrightarrow n$. However, $m_{W_L} << m_{W_R}$ implies that ν is the neutrino and n is the dark matter. For $m^2_{W_L}/m^2_{W_R} \sim 10^{-5}$, $m_\nu \sim 0.1$ eV implies $m_n \sim 10$ keV. Again n is absolutely stable.

Conventional left-right models with $(\nu, e)_R$ have also been proposed. [Bezrukov: Paris 2011 Workshop; Lindner: Paris 2011 Colloquium.] In this case, ν_R mixes with ν_L, so it is like a sterile neutrino which decays, but it also has additional gauge interactions, so the production mechanism is not limited to neutrino oscillations (Dodelson-Widrow). This may also evade the present galactic X-ray upper bound, but the sterile neutrino must still decay at some level.

In the $SU(2)_R$ scotino model, there is another possible LHC signal from the decay of the exotic h quark:

$$h \to uW_R^- \to ue^-\bar{n}.$$

This looks like a fourth-generation d quark, i.e. $d_4 \to uW_L^- \to ue^-\bar{\nu}$, which has the LHC lower bound of about 500 GeV.

However, $d_4 \to u(\bar{u}d)$ is possible, but $h \to u(\bar{u}h)$ is impossible for the lightest h, so it may be discovered through this important difference.

Conclusion

There is now a very attractive theoretical framework for having a keV Majorana fermion N_1 (scotino) as dark matter. It is not the usual sterile neutrino (ν_S) because it is absolutely stable. In addition, neutrino masses are only nonzero because of quantum effects due to $N_{1,2,3}$ whose masses themselves are not the gift of Higgs.

$$(\mathcal{M}_\nu)_{ij} = \frac{\ln(m_R^2/m_I^2)}{16\pi^2} \sum_k h_{ik} h_{jk} M_k.$$

In a left-right model, ν has $SU(2)_L$ interactions and n has $SU(2)_R$ interactions. Both have seesaw masses. The $SU(2)_L$ and $SU(2)_R$ sectors evolve in the same way (including leptogenesis) in the early Universe. As the $SU(2)_R$ symmetry breaks at a higher energy scale than $SU(2)_L$, n becomes dark matter and ν becomes the neutrino. Hence $n_{1,2,3}$ may all be dark matter.

Both the scotogenic and left-right models are subject to tests at accelerators.