Light Dark Matter and Neutrinos

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Inroduction

Suppose dark matter is a light fermion singlet N.
There are then a number of scenarios.

(1) It mixes slightly with the three active doublet neutrinos ν through the Higgs doublet, and has no other interaction. This is the well-known case of a sterile neutrino, which may be warm dark matter. With a mass of a few keV, it can affect cosmic structure formation just from kinematics.

(2) It does not mix with ν, and there is a symmetry which makes it stable, but it has new interactions.

(2a) The new interactions involve new heavy gauge bosons, which do not couple to neutrinos, as well as heavy scalars which do.

(2b) The new interactions are with neutrinos and heavy scalars.

(2c) The new interactions are with neutrinos and a light scalar in addition to the heavy scalars.

Left-Handed Neutrinos and Right-Handed Scotinos

In an $SU(2)_R$ extension of the Standard Model, $(\nu, l)_R$ is a mandatory doublet. A scalar bidoublet links ν_L with ν_R to form a Dirac mass, then a large Majorana mass for ν_R comes from a heavy scalar $SU(2)_R$ triplet, resulting in a small seesaw neutrino mass. However, there is an alternative scenario, where the Dirac mass is forbidden by a symmetry: E. Ma, PRD (1987); S. Khalil, H.-S. Lee, E. Ma, PRD (2009); S. Khalil, H.-S. Lee, E. Ma, PRD (2010); E. Ma, PRD (2012).

ν_R is replaced by the scotino n_R

particles	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$	S'
$(u,d)_L$	3	2	1	1/6	0
$(u,h)_R$	3	1	2	1/6	–1/2
d_R	3	1	1	–1/3	0
h_L	3	1	1	–1/3	–1
$(\nu,e)_L$	1	2	1	–1/2	0
$(n,e)_R$	1	1	2	–1/2	1/2
(ϕ_L^+,ϕ_L^0)	1	2	1	1/2	0
(ϕ_R^+,ϕ_R^0)	1	1	2	1/2	1/2
η	1	2	2	0	–1/2

The scalar bidoublet ($S' = -1/2$) and its dual ($S' = 1/2$)

$$\eta = \begin{pmatrix} \eta_1^0 & \eta_2^+ \\ \eta_1^- & \eta_2^0 \end{pmatrix}, \qquad \tilde{\eta} = \sigma_2 \eta^* \sigma_2 = \begin{pmatrix} \bar{\eta}_2^0 & -\eta_1^+ \\ -\eta_2^- & \bar{\eta}_1^0 \end{pmatrix}$$

couple to $\bar{\nu}_L n_R$ via η_1^0, $\bar{e}_L e_R$ via η_2^0, and $\bar{u}_L u_R$ via $\bar{\eta}_2^0$, $\bar{d}_L h_R$ via $\bar{\eta}_1^0$.

As ϕ_R^0 acquires a large vacuum expectation value, $SU(2)_R \times U(1)_X$ is broken to $U(1)_Y$ and S' is also broken, but $S = S' + T_{3R}$ remains unbroken. As $SU(2)_L \times U(1)_Y$ is broken to $U(1)_Q$ through ϕ_L^0 and η_2^0, S also remains unbroken as well as global $B - L$.

The imposition of S' in this left-right model thus serves the purpose of having two kinds of particles. All the standard-model particles have $S = 0$. Some of the new particles also have $S = 0$, i.e. Z', η_2^+, η_2^0, ϕ_R^0, whereas others have $S = 1$, i.e. n, W_R^+, $\bar{h}$, ϕ_R^+, η_1^+, $\bar{\eta}_1^0$.

Hence n may be an absolutely stable particle, called the scotino which is a good dark-matter candidate. It is also clearly not the Dirac mass partner of ν_L, nor h_R the Dirac mass partner of d_L.

Whereas neutrinos help the sun shine, i.e. brightness or Yang, scotinos are the dark side or Yin of the Universe.

Both ν_L and n_R are massless as the model stands. The next step is to copy what works so well in the standard model. The fermion singlets ν_R $(L = 1, S = 0)$ and n_L $(L = 1, S = 1)$ are added. This results in the Dirac mass terms $\bar{\nu}_L \nu_R$ and $\bar{n}_L n_R$. Now both L and S are allowed to be softly broken to $(-1)^L$ and $(-1)^S$ by the Majorana mass terms $\nu_R \nu_R$ and $n_L n_L$. Thus both ν_L and n_R obtain seesaw masses. Naively, if the $SU(2)_R$ breaking scale is $10^{2.5}$ that of $SU(2)_L$, then $m_n \sim 10^5 m_\nu \sim 10$ keV if $m_\nu \sim 0.1$ eV. The corresponding Fermi constant for n is then $10^{-5} G_F$, which makes it effectively sterile.

Parallel evolution of ν_L and n_R

The decays of ν_R to $\nu\phi_L^0 - e^-\phi_L^+$ and $\bar{\nu}\bar{\phi}_L^0 - e^+\phi_L^-$ and n_L to $n\phi_R^0 - e^-\phi_R^+$ and $\bar{n}\bar{\phi}_R^0 - e^+\phi_R^-$ both create lepton asymmetries which get converted to a $B-L$ asymmetry through the $SU(2)_L$ and $SU(2)_R$ sphalerons. Matter and dark matter both have $B-L$. They are distinguished only by S. Once past the electroweak phase transition, n becomes effectively a sterile neutrino. For $m_\nu \sim 0.1$ eV, its relic density is about $\Omega_\nu h^2 = 0.001$. To obtain the observed dark-matter value $\Omega_n h^2 = 0.1$ for $m_n \sim 10$ keV, its number density should be $\sim 10^{-3}$ that of neutrinos.

There are two lepton asymmetries in the early Universe, one each from ν_R and n_L decay. Their exact values depend on various parameters such as the CP violation in the 3×3 Yukawa coupling matrices in the $SU(2)_L$ and $SU(2)_R$ sectors respectively.

As the Universe cools below the $SU(2)_R$ and $SU(2)_L$ phase transitions, these are converted into two $B - L$ asymmetries, one for the $S = 0$ quarks and leptons, and the other for the $S = 1$ h quarks and n scotinos.

However, unlike the usual quarks, the h quarks all decay away, leaving only the n scotinos as warm dark matter.

As a very weakly interacting particle of 10 keV, n_R is not observable at the underground experiments searching for dark matter through nuclear recoil.

It is also not easily observable at the Large Hadron Collider (LHC) unless there is a light enough h quark, say of order 1 TeV. These quarks are then easily produced in pairs by gluons. Once produced, $h \to u\bar{n}e^-$ and $\bar{h} \to \bar{u}ne^+$ through $W_R^\pm$ exchange.

They behave thus as fourth-generation d quarks, except for the important fact that the lightest h decays only semileptonically.

This model also predicts two effective Higgs doublets (ϕ_L^+, ϕ_L^0) and (η_2^+, η_2^0).

However, unlike the canonical case where the u quarks couple to one doublet with $m_u \sin^{-1}\beta$ and the d quarks and charged leptons to the other with $m_d \cos^{-1}\beta$ and $m_e \cos^{-1}\beta$, the charged leptons now team up with the u quarks instead with coupling $m_e \sin^{-1}\beta$.

The 125 GeV particle discovered at the LHC in 2012 is presumably very close to being the SM Higgs boson. If a second heavier scalar is found, this model can be tested.

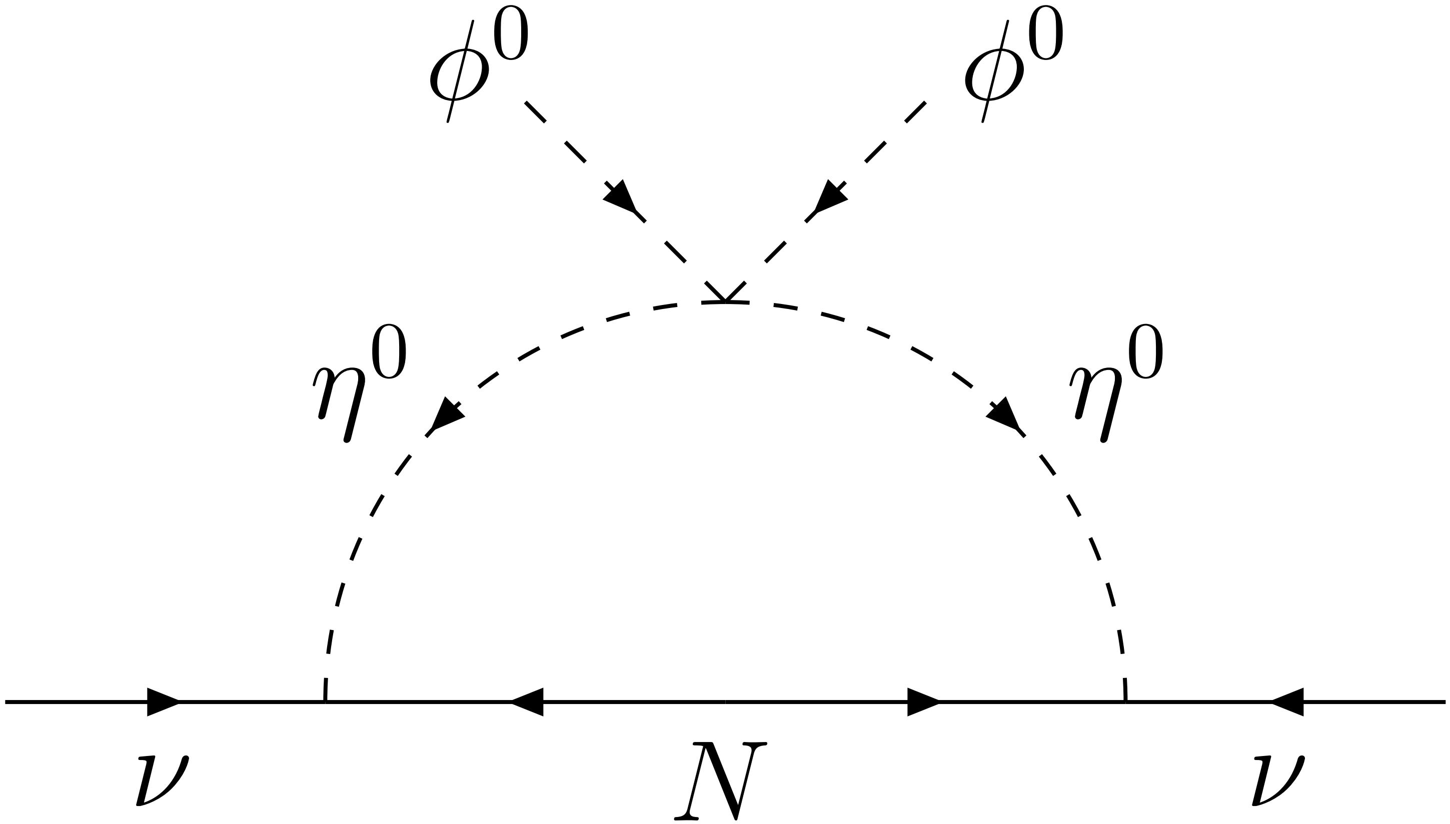
Since Z is a linear combination of W_L^0, W_R^0, B, it also couples to $W_R^+ W_R^-$. This appears to induce an effective one-loop flavor-changing coupling such as $\bar{e}\gamma^\alpha \mu Z_\alpha$ through n exchange or $\bar{u}\gamma^\alpha c Z_\alpha$ through h exchange.

A naive calculation of the integral involved seems to indicate that this effect is not suppressed if m_h is comparable to M_{W_R}, which would be a curious example of non-decoupling. A full calculation taking into account the contributions of the would-be Goldstone modes of the spontaneous symmetry breaking of $SU(2)_R$ shows that it is in fact zero in the limit $SU(2)_L$ is unbroken.

To summarize, the presence of ν_R is unavoidable in a left-right gauge extension of the Standard Model. However, it does NOT have to be the Dirac mass partner of ν_L. In that case, it should be renamed n_R and could function as a scotino, i.e. a dark-matter fermion. It may also obtain a seesaw mass of 1-10 keV and be a good warm dark-matter candidate. In that case, it will escape detection in underground direct-search experiments and in astrophysical indirect searches. At the LHC, it may appear from the decay of the lightest h quark, which has the unique signature of decaying only semileptonically.

Scotogenic Neutrino Mass without Seesaw

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.



ϕ^0
ϕ^0
η^0
η^0
ν
N
ν

The origin of $(\eta^+_, \eta^0)$ goes back to 1978 (Deshpande/Ma) where it was postulated as a possible addition to the Higgs sector of the standard model from symmetry considerations. Its utility as dark matter was not realized until 2006, when it was first used to obtain scotogenic neutrino masses (Ma) as well.

Two months later, it was considered alone (Barbieri/Hall/Rychkov) as a means of modifying the oblique S, T, U parameters in precision electroweak measurements to predict a very heavy SM Higgs boson which has now been proven wrong.

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.

See for example Arhrib et al., JCAP (2014).

However, it was only noted in 2012 (Ma, PLB) 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 !!

Unless $|m_R^2 - m_I^2| << m_{R,I}^2$, this formula for the neutrino mass is NOT inversely proportional to a large scale.

If a flavor symmetry is also imposed, the neutrino mass may be just a scale factor times the N mass matrix.

The concept of lepton number violation may now be naturally implemented.

ν and l have $L = 1$ whereas l^c and N has $L = -1$. They are connected through $(\nu\phi^- + l\bar{\phi}^0)l^c$ and $(\nu\eta^0 - l\eta^+)N$, both of which preserve L.
The only possible term which breaks L to $(-1)^L$ is the Majorana mass term NN. Naturalness in lepton number violation now implies M_N to be smaller than the smallest lepton-number preserving mass, i.e. the electron mass. Hence $M_N = 10$ keV is a very reasonable value, which would make N a good candidate for warm dark matter.

Let $M_N \sim 10$ keV, $m_R = 240$ GeV, $m_I = 150$ GeV, then $m_\nu \sim 0.1$ eV implies $h^2_{ik} \sim 10^{-3}$. 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 5.6 keV from Lyman-α forest observations.

Implications for particle physics:

$$(1) \quad B(\mu \to e\gamma) = \frac{\alpha}{768\pi} \frac{|\sum_k h_{\mu k} h_{ek}^*|^2}{(G_F m_{\eta^+}^2)^2} < 4.2 \times 10^{-13}$$

implies $m_{\eta^+} > 480$ GeV $(|\sum_k h_{\mu k} h_{ek}^*|/10^{-3})^{1/2}$.

(2) Anomalous magnetic moment of muon is given by

$$\Delta a_\mu = -\frac{m_\mu^2}{96\pi^2 m_{\eta^+}^2} \sum_k |h_{\mu k}|^2 < 5.1 \times 10^{-14} \frac{\sum_k |h_{\mu k}|^2}{|\sum_k h_{\mu k} h_{ek}^*|},$$

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

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

$$< 4.35 \times 10^{-9} \frac{(\sum_k |h_{\mu k}|^2)(\sum_k |h_{ek}|^2)}{|\sum_k h_{\mu k} h_{ek}^*|^2} \Gamma(\mu \to \nu_\mu e \bar{\nu}_e),$$

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.

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

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

$$\simeq \frac{|h_{i2} h_{j1}^*|^2 (\Delta M)^5}{1920\pi^3} \left(\frac{1}{m_R^2} + \frac{1}{m_I^2} \right)^2,$$

if $M_2 - M_1 = \Delta M << M_{1,2}$.

As an example, let $\Delta M = 1$ keV, $|h_{i2}h^*_{j1}|^2 = 10^{-6}$, $m_R = 240$ GeV, $m_I = 150$ GeV, then $\Gamma = 6.42 \times 10^{-50}$ GeV, corresponding to a decay lifetime of 3.25×10^{17} y, which is much longer than the age of the Universe, i.e. $13.75 \pm 0.11 \times 10^9$ y. This means that $N_{1,2,3}$ may all be components of dark matter today.

Note that $N_2 \to N_1\gamma$ is now possible with $E_\gamma \simeq \Delta M$, but since ΔM may be small, whereas $M_{1,2,3} \sim 10$ keV, the tension between galactic X-ray data and Lyman-α forest observations is easily relaxed.

(2) The effective $N\bar{N} \to l\bar{l}, \nu\bar{\nu}$ interactions are of order $h^2/m_\eta^2 \sim 10^{-9}$ GeV^{-2}, hence they remain in thermal equilibrium in the early Universe until a temperature of a few GeV. 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

$$\Omega_N h^2 \simeq \frac{115}{16}\left(\frac{\sum_i M_i}{\text{keV}}\right).$$

Since $\Omega_N h^2$ should be 0.1123 ± 0.0035, a dilution factor of about 1.9×10^3 is needed for $\sum_i M_i \sim 30$ 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. It is a well-known mechanism. Some recent papers: Bezrukov/Hettmansperger/Lindner(2010), Nemevsek/Senjanovic/Zhang(2012), King/Merle(2012).

(4) Another solution is to assume that the reheating temperature of the Universe is below a few GeV, so that N_i are not thermally produced. Instead, they come from the decay of a scalar singlet S with the interaction $(f_{ij}/2)SN_iN_j$ where $f_{ij} < 10^{-4}$ for $m_S \simeq 2$ GeV. The interaction $\sqrt{2}\lambda_3 HS^2$ allows S to be thermally produced and to decouple as it becomes nonrelativistic with $\langle \sigma v_{rel} \rangle \sim 10^{-5}$ pb for $\lambda_3 \sim 10^{-3}$. Now S decays to NN, so the relic density of N is reduced by $2M/m_S \simeq 10^{-5}$. Since $\langle \sigma v_{rel} \rangle$ is inversely proportional to relic density, this would yield the correct observed value.

Implications at the Large Hadron Collider:

$\Gamma(H \to SS) = \lambda_3^2 v^2 / 4\pi m_H \sim 0.02$ MeV, compared to $\Gamma_{tot} = 4.3$ MeV. However, $\eta^+ \to l_i^+ N_j$ and $\eta^+ \to \eta_{R,I} W^+$ as well as $\eta_R \to \eta_I Z$ are possible.

Negative impact on the search of dark matter:

(1) Nonobservation of any dark-matter signal at underground experiments. Latest news from LUX (2015): 33 GeV dark matter is excluded at 0.6×10^{-45} cm^2.

(2) Nonobservation of dark-matter annihilation products (gamma rays, etc.) from space. Latest news from PRL (2015): 2-million-year old supervova explains e^+ excess.

To summarize, the dark scalar doublet (η^+, η^0) is useful by itself for many things such as S, T, U, $\Gamma(H \to \gamma\gamma)$, and electroweak baryogenesis.

If it is also used for radiative neutrino mass, then a possible new formula is obtained:

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

This assumes $M_k << m_{R,I}$ and $N_{1,2,3}$ with masses ~ 10 keV may be candidates for warm dark matter and $\eta^\pm, \eta_R, \eta_I$ may be easier to find at the LHC.

Light Dark Matter interacting with Cosmic Neutrinos

By definition, dark matter hardly interacts with photons, but what about cosmic neutrinos? In the scotogenic mechanism, a fundamental interaction $\bar{\nu} N \zeta$ already exists, with N a fermion and ζ a scalar, both odd under dark Z_2. Could that be important?

Boehm *et al.* (2014): To have an appreciable effect on structure formation, thereby solving the missing-satellite and too-big-to-fail problems, N and ζ must both be light, of order MeV.

The power spectrum of the Cosmic Microwave Background (CMB) imposes strong constraints on the possible self-interactions of neutrinos and dark matter as well as interactions between them.

Collision damping from these interactions can erase small scale structure and alter the density profile of satellite galaxies to solve the missing satellite and too-big-to-fail problems.

To obtain as well the correct relic abundance, both N and ζ must be MeV with a mass splitting of keV.

This scenario of light dark matter is difficult to achieve in a complete renormalizable theory, because either N or ζ must have an electroweak doublet component, and as such, is subject to many phenomenological constraints, including radiative neutrino mass.

Arhrib *et al.*, JCAP (2016): Consider the case that N is a singlet and ζ is a mixture of a complex singlet χ and the neutral component η^0 of a doublet. The complete scalar sector consists of the SM Higgs doublet, the inert doublet (η^+, η^0) and the inert singlet χ. We need a solution, with ζ of order MeV, compatible with all data.

$$V = m_1^2\Phi^\dagger\Phi + m_2^2\eta^\dagger\eta + m_3^2\chi^*\chi + \mu[\eta^\dagger\Phi\chi + \Phi^\dagger\eta\chi^*]$$
$$+ (\lambda_1/2)(\Phi^\dagger\Phi)^2 + (\lambda_2/2)(\eta^\dagger\eta)^2 + (\lambda_3/2)(\chi^\dagger\chi)^2$$
$$+ \lambda_4(\eta^\dagger\eta)(\Phi^\dagger\Phi) + \lambda_5(\eta^\dagger\Phi)(\Phi^\dagger\eta)$$
$$+ \lambda_6(\chi^\dagger\chi)(\Phi^\dagger\Phi) + \lambda_7(\chi^\dagger\chi)(\eta^\dagger\eta).$$

Let $\langle\phi^0\rangle = v/\sqrt{2}$, then the 2×2 mass-squared matrix spanning η^0 and χ is given by

$$\mathcal{M}^2 = \begin{pmatrix} m_2^2 + (\lambda_4+\lambda_5)v^2/2 & \mu v/\sqrt{2} \\ \mu v/\sqrt{2} & m_3^2 + \lambda_6 v^2/2 \end{pmatrix}.$$

The SM Higgs coupling matrix to this sector is given by

$$\mathcal{F} = \begin{pmatrix} (\lambda_4 + \lambda_5)v & \mu/\sqrt{2} \\ \mu/\sqrt{2} & \lambda_6 v \end{pmatrix}.$$

The conditions for $\mathcal{F}$ to be proportional to $\mathcal{M}^2$ are

$$m_2^2 = (\lambda_4 + \lambda_5)v^2/2, \quad m_3^2 = \lambda_6 v^2/2.$$

In that case, the decay of the SM Higgs boson h to $\zeta^*\zeta$ is proportional to m_ζ^2. Once the parameters of $\mathcal{M}^2$ are chosen to have a small m_ζ, then this decay is automatically suppressed.

Since $\zeta = \cos\theta\chi + \sin\theta\eta^0$, there is also $Z \to \zeta^*\zeta$ decay with a rate proportional to $\sin^4\theta$. From the invisible width of Z, this implies $\sin\theta < 0.26$ at 95% CL.

Theoretical constraints: unitarity, vacuum stability, and positive squares of physical masses.

Phenomenological constraints: $\Delta S = 0.06 \pm 0.09$, $\Delta T = 0.10 \pm 0.07$; Higgs decays to $\gamma\gamma$, W^-W^+, ZZ, and $\tau^-\tau^+$ from LHC data, assuming all scalars except ζ are heavier than 100 GeV.

Numerical scans show that large regions of parameter space are allowed, with mild $\lambda_{4,5}$ and $\lambda_{6,7}$ correlations.

To summarize, light dark fermion N interacting with neutrinos through a light dark scalar ζ may be relevant for structure formation, as indicated by some astrophysical observations. A complete model is possible, but rather extreme fine tuning is required. It is also very difficult to verify at the LHC, because both N and ζ are invisible and not easy to produce.

If theses interactions are significant, astrophysical neutrino oscillations may be affected as neutrinos travel through dark matter, and may be important for future interpretation of astrophysical neutrino experiments.

Conclusion

The notion of light dark matter is explored through its possible connection to neutrinos. Three examples have been presented.

(1) Whereas ν_L come from $SU(2)_L$, n_R come from $SU(2)_R$ which breaks at a much higher energy scale. They are left-right counterparts of each other, but separated from each other by a symmetry. Just as ν_L is the lightest fermion in the visible sector, n_R is the lightest fermion in the dark sector. This scenario allows n_R to be warm dark matter of order keV, and provides a parallel view of the Universe comprising naturally of visible and dark matter.

(2) The scotogenic paradigm is used to connect neutrino mass to

dark matter with the unconventional assumption that $m_N << m_{R,I}$. In this case, neutrino masses are proportional to dark-matter fermion masses, and it becomes natural for the latter to be order keV (warm dark matter). This implies new interactions for the charged leptons, which have potential impacts on $\mu \to e\gamma$, etc. and may be testable in future experiments.

(3) The fundamental interaction $\nu N \zeta$ is postulated, where both N and ζ are MeV dark matter. Assuming N to be lighter, then ζ decays into $N\nu$. If the mass splitting of N and ζ is only keV, then missing-satellites and too-big-to-fail are not problems. A complete model is possible with one inert scalar doublet and one inert complex scalar singlet, but extreme fine tuning is required.