Leptonic Scalars versus Scalar Leptons

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The SusyVerse

In the Standard Model (SM), there are fermions which have either baryon number $B = 1/3$ (quarks) or lepton number $L = 1$ (leptons), and vector gauge bosons $B = L = 0$, and Higgs bosons $B = L = 0$. In its supersymmetric extension, the scalar partners of the fermionic quarks and leptons are then naturally known as scalar quarks and scalar leptons. Since they share the same B and L, what distinguishes them is spin, i.e. R parity, defined as $(-1)^{3B+L+2j}$.

It is well-known that B and L are automatic symmetries in the SM. If neutrinos are Majorana, then L becomes lepton parity $(-1)^L$. In supersymmetry, B and $(-1)^L$ are not automatic, but if they are assumed to be conserved, then odd R parity defines the dark sector, the lightest particle of which is assumed to be neutral and becomes a candidate for the dark matter of the Universe. This notion is one of the main reasons of the push to discover the SusyVerse in the past four decades. Note that scalar leptons are always connected to leptons through gauginos and higgsinos in supersymmetry.

In general, once new particles are added, their B and L assignments are not automatic, but dictated by how they interact with the SM particles.

This is especially true of a neutral fermion singlet. It does NOT have to be a right-handed neutrino, as most people would assume without thinking twice. See the Brief Review: E. Ma, Mod. Phys. Lett. A32, 1730007 (2017).

In this talk, I will touch upon some other recent new ideas in extending L to accommodate the existence of dark matter (DM).

Dark Parity from Lepton Parity

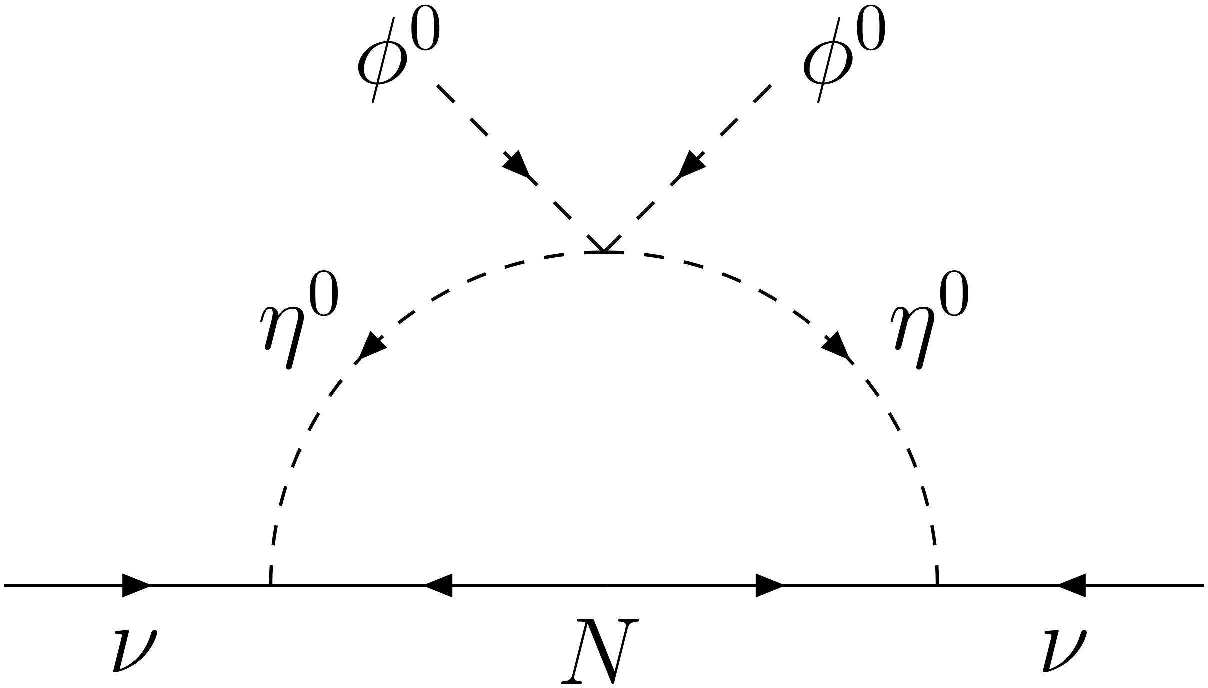
E. Ma, Phys. Rev. Lett. 115, 011801 (2015):
Start with the SM (no susy), add a real singlet scalar S for DM [Silveira/Zee (1985)]. The usual (and obvious) assumption is to postulate a new Z_2 symmetry, under which S is odd and all SM particles are even. However, the same Lagrangian is obtained if lepton parity is used, under which all known leptons are odd as well as S. Now the latter, being a scalar, has odd dark parity, and may be called a leptonic scalar. It is not a scalar lepton in the sense of supersymmetry.

Another minimal addition to the SM is that of a real singlet scalar S and a singlet Majorana fermion χ_L [Pospelov/Ritz/Voloshin(2008)] in the presence of a singlet right-handed neutrino N_R. The conventional assumption for dark matter is again Z_2 under which S and χ_L are odd, and all SM particles are even including N_R. This allows the Yukawa interaction $\bar{\chi}_L N_R S$ and either χ_L or S could be DM.

Once more, the dark Z_2 is not necessary; the same Lagrangian is obtained if S has odd, and χ_L has even lepton parity, so that they both have odd dark parity.

The notion of using lepton parity assignments to new additional scalars and fermions to the SM is applicable also to all generic models of radiative Majorana neutrino mass through DM, i.e. the scotogenic mechanism.

For example, in the one-loop model of
E. Ma, Phys. Rev. D73, 077301 (2006),
instead of the original assumption that the second scalar doublet (η^+, η^0) and the singlet Majorana fermions N be odd under a new dark Z_2, they may simply be assigned odd and even lepton parity. Hence (η^+, η^0) is a leptonic scalar doublet, and not a scalar lepton doublet.


ϕ^0
ϕ^0
η^0
η^0
ν
N
ν

GUT Origin of Dark Parity

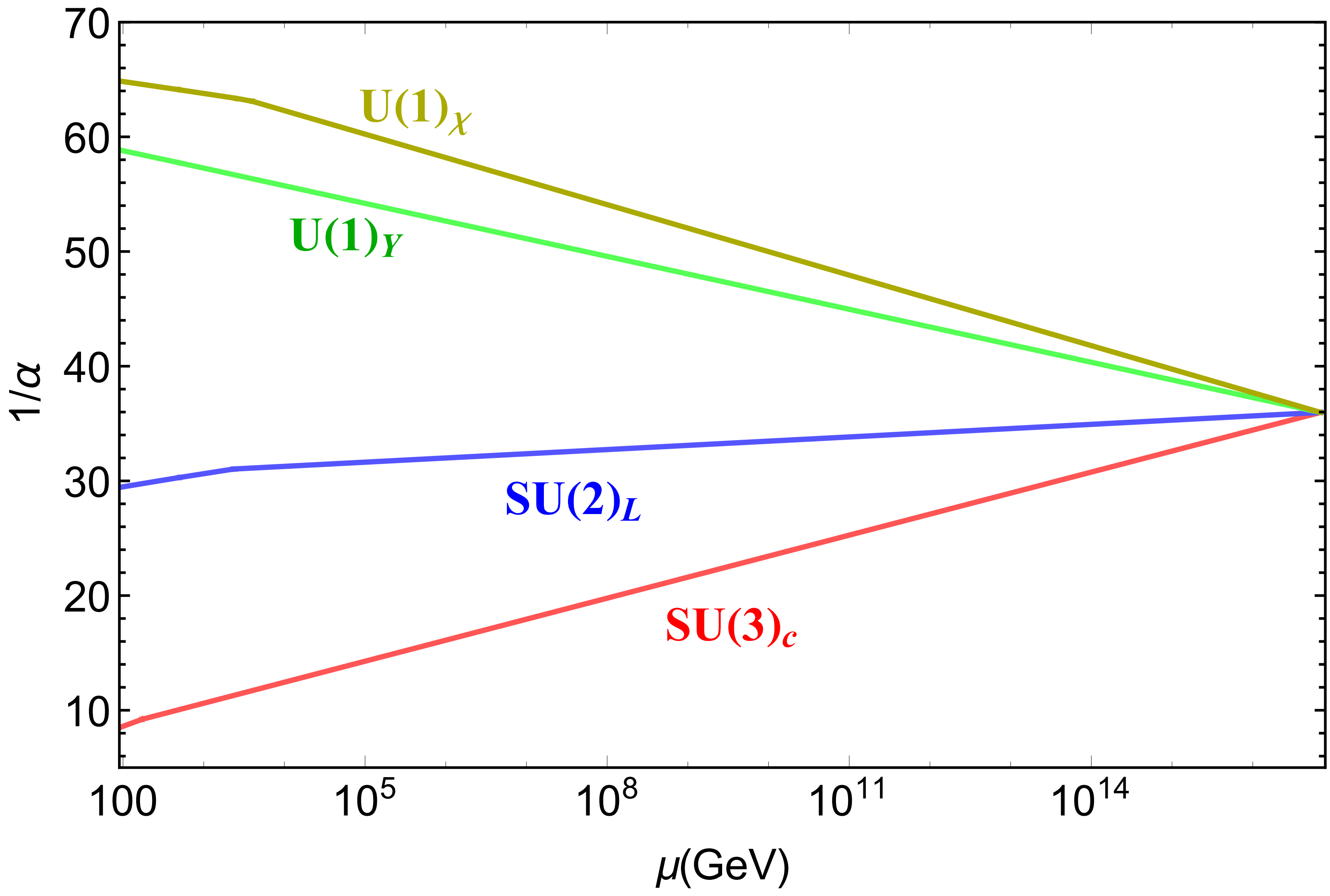
The conventional definition of R parity may be written for SM particles as $(-1)^{3(B-L)+2j}$ [Martin(1992)].
This suggests strongly its origin from
$SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
In the $\underline{16}$ representation of $SO(10)$, quarks and their conjugates have $B-L = \pm 1/3$, whereas leptons and their conjugates have $B-L = \mp 1$. In the $\underline{10}$ representation, the color triplets have $B-L = \mp 2/3$ and the left-right bidoublet has $B-L = 0$.
Hence $(-1)^{3(B-L)}$ is odd and even respectively.

This means that R parity is even/odd and odd/even for fermion/scalar in the $\underline{16}$ and $\underline{10}$ representations respectively. Hence $B-L$ is a possible marker symmetry for dark matter.
However, it is not orthogonal to $U(1)_Y$ of the SM, and since a dark-matter candidate is likely to be a trivial singlet under $SU(3)_C \times SU(2)_L \times U(1)_Y$, a better choice is $U(1)_\chi$ from the decomposition
$SO(10) \to SU(5) \times U(1)_\chi$:
E. Ma, Phys. Rev. D 98, 091701(R) (2018).
$\underline{16} = (5^*, 3) + (10, -1) + (1, -5)$, $\underline{10} = (5^*, -2) + (5, 2)$.

Using $3Q_\chi = 12Y - 15(B-L)$, a good marker symmetry for dark matter is $R_\chi = (-1)^{(Q_\chi + 2j)}$.

The so-called right-handed neutrino is now a singlet, denoted by its conjugate $\nu^c \sim (1,-5)$, instead of belonging to an $SU(2)_R$ doublet. In this context, previous dark-matter assignments are $S \sim (1,-5)$, $\chi \sim (1,0)$, $(\eta^+,\eta^0) \sim (5,-3)$, and $N \sim (1,0)$.

Gauge $U(1)_\chi$ is broken by a scalar $(1,1,0,-10)$ resulting in Z_χ with $m_{Z_\chi} > 4.1$ TeV from LHC data. For example, adding scalar $(1,3,0,-5)$ and fermions $(1,3,0,0)$, $(8,1,0,0)$ allows non-susy gauge unification.


70
60
50
40
30
20
10
1/α
100
10^5
10^8
10^{11}
10^{14}
μ(GeV)
$U(1)_X$
$U(1)_Y$
$SU(2)_L$
$SU(3)_c$

SIDM with Leptonic and Dileptonic Scalars

Lepton number is usually thought of as being an integer L or a parity $(-1)^L$. In the latter case, neutrinos are Majorana, which is the default option. In the former case, they are Dirac, and in the persisting nonobservation of neutrinoless double beta decay, there is a theoretical resurgence of interest in them.

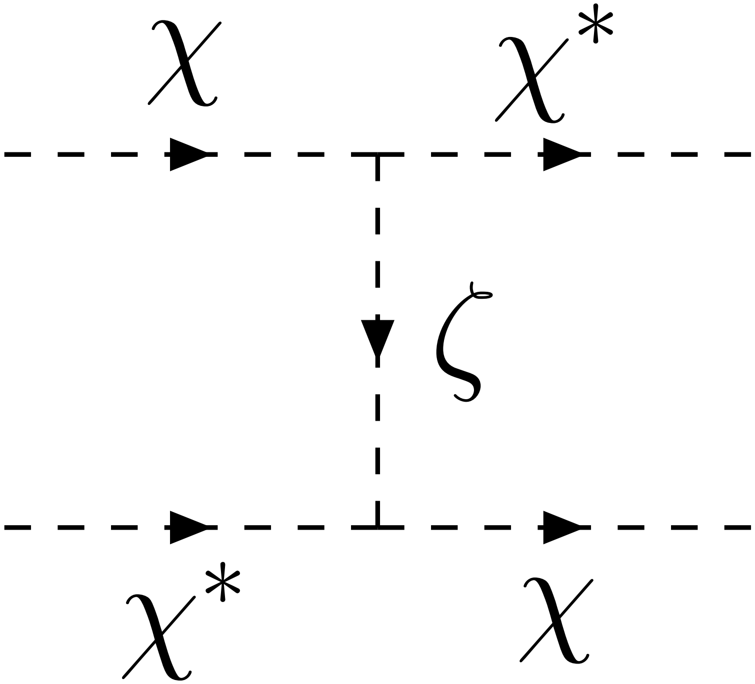
In particular, leptonic and dileptonic scalars may be postulated for dark matter and its mediator in a simple model of self-interacting dark matter (to solve the cusp-core discrepancy in the profile of dwarf galaxies).

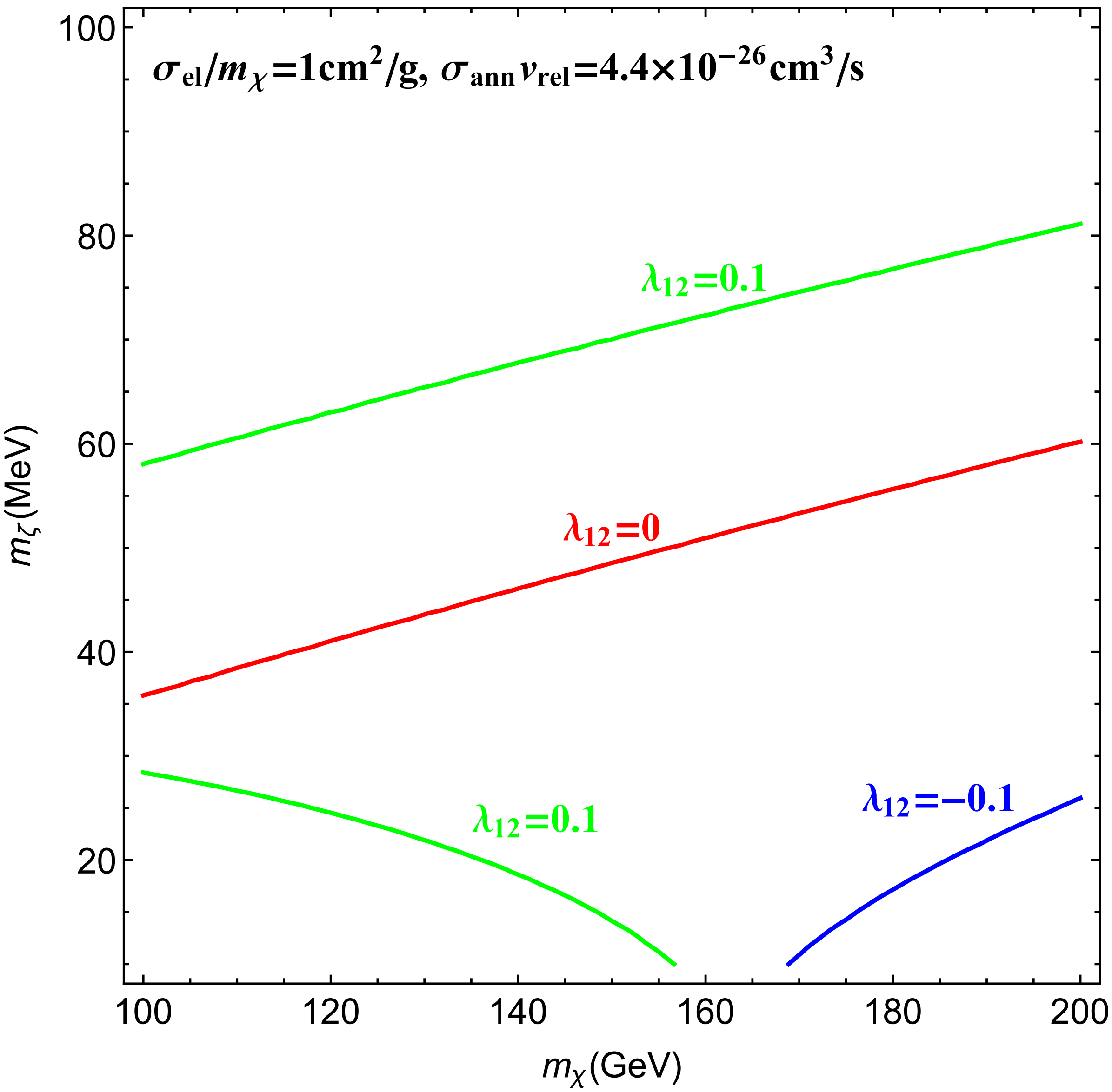
E. Ma, Mod. Phys. A 33, 1850226 (2018):
Under L, let the complex scalars $\chi \sim 1$, $\zeta \sim 2$, implying thus the allowed cubic $\mu_{12}\zeta^*\chi^2$ and quartic $\lambda_{12}(\chi^*\chi)(\zeta^*\zeta)$ interactions. The elastic scattering of χ has the cross section

$$\sigma_{el}(\chi\chi^* \to \chi^*\chi) = \frac{\mu_{12}^4}{4\pi m_\chi^2 m_\zeta^4}.$$

Its annihilation to ζ has the cross section

$$\sigma_{ann}(\chi\chi^* \to \zeta\zeta^*)v_{rel} = \frac{1}{32\pi m_\chi^2}\left(\lambda_{12} - \frac{2\mu_{12}^2}{m_\chi^2}\right)^2.$$


χ
χ^*
ζ
χ^*
χ



$\sigma_{\rm el}/m_\chi$=1cm^2/g, $\sigma_{\rm ann}v_{\rm rel}$=4.4×10^{-26}cm^3/s
λ_{12}=0.1
λ_{12}=0
λ_{12}=0.1
λ_{12}=−0.1
100
80
60
40
20
m_ζ(MeV)
100
120
140
160
180
200
m_χ(GeV)

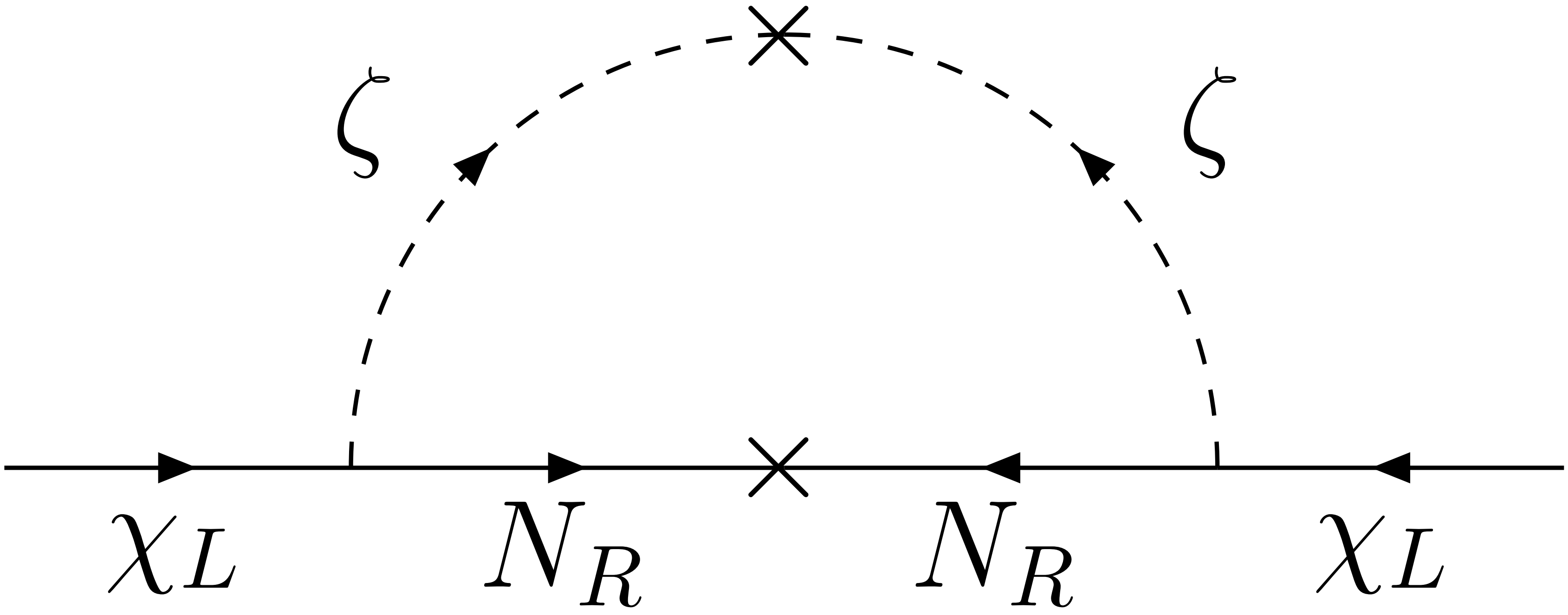
What distinguishes this application of leptonic scalar to SIDM is that the light mediator has $L = 2$. In the conventional scenario, this mediator is either a light gauge boson (which mixes kinetically with the photon) or a light scalar (which mixes with the SM Higgs boson). In either case, it will decay to electrons and would disrupt the CMB (Cosmic Microwave Background) when its production gets enhanced by the Sommerfeld effect in late times. [Galli/Iocco/Bertone/Melchiorri(2009); Bringmann/Kahlhoefer/Schmidt-Hoberg/Walia(2017).]

Here, ζ decays only to two neutrinos!!

Radiative Dileptonic Dark Fermion Mass

A new application of lepton number for dark matter is a variation of the S/χ model. Under L, let $\zeta \sim 1$ and $\chi_L \sim 2$ in the presence of N_R. All dimension-4 terms of the Lagrangian including $f\bar{\chi}_L N_R \zeta$ obey L, whereas the dimension-2 term $\mu^2[\zeta^2 + (\zeta^*)^2]/2$ and the dimension-3 term $(m_N/2)N_R N_R + H.c.$ break it softly by 2 units.

Whereas neutrinos obtain Majorana masses through the conventional seesaw mechanism, i.e. $m_\nu \simeq m_D^2/m_N$, the dark fermion χ obtains a radiative mass in one loop, also anchored by m_N.


ζ
ζ
χ_L
N_R
N_R
χ_L

Let $\zeta = (\zeta_R + i\zeta_I)/\sqrt{2}$ with masses m_R, m_I, split by the μ^2 term, then

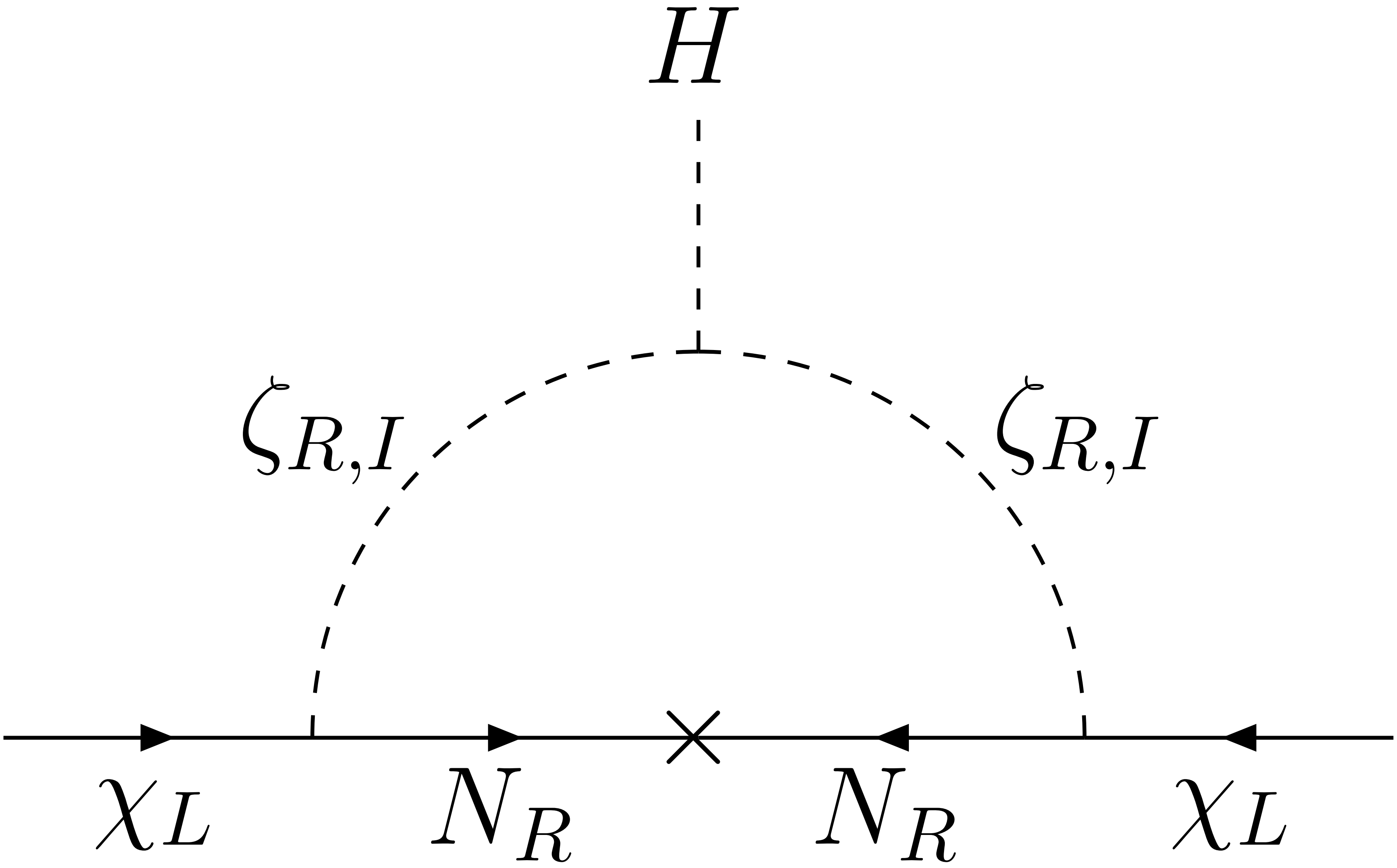
$$m_\chi = \frac{f^2 m_N}{16\pi^2}\left[\frac{m_N^2}{m_R^2 - m_N^2}\ln\frac{m_R^2}{m_N^2} - \frac{m_I^2}{m_I^2 - m_N^2}\ln\frac{m_I^2}{m_N^2}\right]$$

is the analog of the scotogenic neutrino mass.

For $m_R^2 - m_I^2 = \mu^2 << m_0^2 = (m_R^2 + m_I^2)/2 << m_N^2$,

$$m_\chi = \frac{f^2\mu^2}{8\pi^2 m_N}\left[\ln\frac{m_N^2}{m_0^2} - 1\right].$$

Let $m_N = 10^6$ GeV, $m_0 = 1$ TeV, $\mu = 100$ GeV, $f = 0.25$, then $m_\chi = 0.1$ MeV; $m_D = 10$ MeV yields $m_\nu = 0.1$ eV.


H
$\zeta_{R,I}$
$\zeta_{R,I}$
χ_L
N_R
N_R
χ_L

The dark fermion χ interacts only through the very heavy ζ and N particles. If the reheat temperature of the Universe is much below m_ζ, χ may be produced only by the freeze-in mechanism through Higgs decay. The effective one-loop coupling f_H of H to $\chi\chi$ is

$$\frac{\lambda_3 v f^2 m_N}{16\pi^2}\left[\frac{1}{m_R^2 - m_N^2} - \frac{m_N^2 \ln(m_R^2/m_N^2)}{(m_R^2 - m_N^2)^2} - (m_R^2 \to m_I^2)\right],$$

where λ_3 is the $(\Phi^\dagger\Phi)(\zeta^*\zeta)$ coupling and $v/\sqrt{2}$ the vacuum expectation value of ϕ^0. It is proportional to m_χ with the factor $\lambda_3 v/m_0^2(\ln(m_N^2/m_0^2) - 1)$.

The decay rate of the SM Higgs boson to $\chi\chi$ is

$$\Gamma_H = \frac{f_H^2 m_H}{8\pi}\sqrt{1-4x^2}(1-2x^2),$$

where $x = m_\chi/m_H$. The production of χ is through H decay before the latter decouples from the thermal bath.

For $x << 1$, the correct relic abundance from freeze-in through Higgs decay is obtained for $f_H \sim 10^{-12}x^{-1/2}$. In this example, this is satisfied for $\lambda_3 = 0.58$. Thus χ is a possible feebly interacting light dark fermion.

Concluding Remarks

Lepton parity and lepton number are useful concepts for extending the non-susy SM to include dark matter. In the grand-unified theory context, dark parity may be derived from Q_χ based on $SO(10) \to SU(5) \times U(1)_\chi$. Using exact L with Dirac neutrinos, self-interacting dark matter is possible where the light mediator decays only to two neutrinos, thereby not disrupting the CMB. Using softly broken L with Majorana neutrinos, a dark fermion may acquire a small radiative Majorana mass and becomes freeze-in dark matter through Higgs decay.