Scotogenic Dirac Neutrino Masses and Mixing

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Why Dirac Neutrinos ?

In the $SU(3)_C \times SU(2)_L \times U(1)_Y$ standard model (SM), the neutrino ν only appears as part of an $SU(2)_L \times U(1)_Y$ doublet $(\nu, e)_L$. As such, it is massless but neutrino oscillations require that at least two neutrinos are massive. The most accepted way to do this is to add ν_R as a singlet (which is trivial under the SM gauge group), so that $\nu_{L,R}$ are linked by a Dirac mass m_D, but ν_R is also allowed a Majorana mass M. If M is large, we get the famous seesaw mechanism, i.e. $m_\nu \simeq m_D^2/M$, and neutrinos are predicted to be

Majorana! (End of Story)

For years, neutrinoless double beta decay experiments have been the best hope of verifying this theoretical assertion, but to no avail. It is time to reappraise the base assumptions which led to our strong belief that neutrinos are Majorana.

First and foremost is our trust in the SM gauge group, but if that is strictly true, then ν_R has no place in the SM because it is a trivial singlet. Now comes the potent argument based on

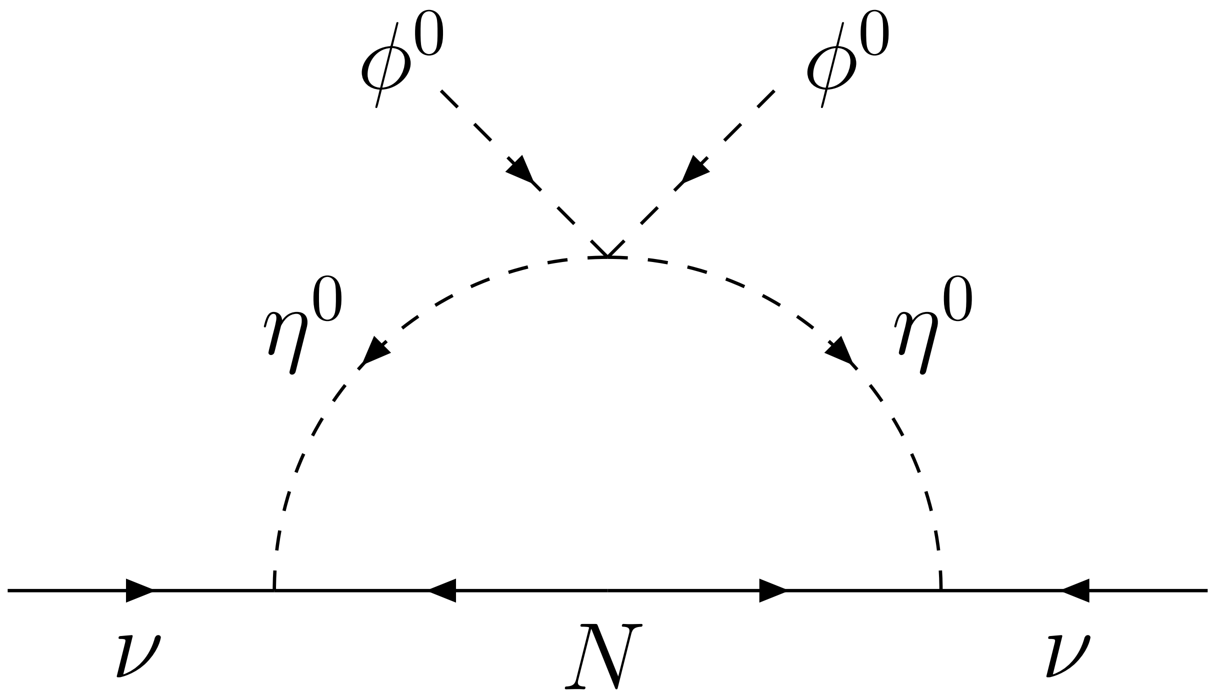
$SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ in which case ν_R must exist as part of an $SU(2)_R \times U(1)_{B-L}$ doublet. Furthermore, the breaking of gauge $B-L$ by a scalar triplet $(\Delta^{++}, \Delta^{+}, \Delta^{0})$ under $SU(2)_R \times U(1)_{B-L}$ implies also a Majorana mass for ν_R from $\langle \Delta^0 \rangle$ which carries two units of $B-L$ charge. We are back to the seesaw mechanism! (End of Story Again)

In 2013, a different story appeared. A simple truth was pointed out (Ma/Picek/Radovcic) that if gauge $U(1)_X$ is broken by a singlet scalar with 3 units of X charge, then it is impossible for a neutral singlet fermion carrying 1 unit of X charge to acquire a Majorana mass. In 2014, this idea was applied to Dirac neutrinos (Ma/Srivastava). The lesson we learned is that the residual symmetry of broken gauge $B - L$ does not have to be Z_2 resulting in Majorana neutrinos. It could be global U(1), or Z_N. This observation led to the renewed interest in Dirac neutrinos and there have been a number of studies in recent years.

In 2013, the first Z_4 model (Heeck/Rodejohann) predicts quadruple beta decay. In 2015, the first Z_3 model (Ma/Pollard/Srivastava/Zakeri) predicts long-lived dark matter which decays to 2 neutrinos.

Why Scotogenic ?

The original idea that neutrino mass is generated in one loop [Ma, PRD 73, 077301 (2006)] through dark matter (scotos is Greek for darkness) assumes a Z_2 parity which is even for ordinary matter and odd for dark matter. This dark parity is subsequently shown [Ma, PRL 115, 011801 (2015)] to be derivable from lepton parity, and more recently [Ma, PRD 98, 091701(R) (2018)] from $SO(10) \to SU(5) \times U(1)_\chi$. Thus a natural link exists between radiative neutrino mass and dark matter. The former exists because neutrinos interact with the latter.


ϕ^0
ϕ^0
η^0
η^0
ν
N
ν

Majorana neutrino masses may be naturally scotogenic because they come from a dimension-five operator. In the absence of mediating particles (singlet neutral fermion, complex triplet scalar, Majorana triplet fermion) at tree level, i.e. the Types I,II,III seesaw, so named in [Ma, PRL 81, 1171 (1998)], particles in the dark sector may be postulated to appear in a loop which generates the neutrino mass.

With the new insight (details later) that SM(dark) particles are fermions/scalars with odd/even(even/odd) Q_χ, no new imposed dark parity is needed.

With Dirac neutrinos, since the dimension-four term $\nu\nu^c\phi^0$ is usually allowed (for $B-L=1$ for ν^c), it must be forbidden by a symmetry which is then softly broken to enable a Dirac mass to appear in one loop. First examples are Gu/Sarkar, PRD 77, 105031 (2008) and Farzan/Ma, PRD 86, 033007 (2012). [Instead of $B-L=1,1,1$ for ν^c, the anomaly-free set $B-L=4,4,-5$ may be chosen [Montero/Pleitez, PLB 675, 64 (2009); Ma/Srivastava, PLB 741, 217 (2015)]. Recent studies include Bonilla/Centelles Chulia/ Cepedello/Peinada/Srivastava, arXiv:1812.01599, and Calle/Restrepo/Yaguna/Zapata, arXiv:1812.05523.]

Interplay of $U(1)_\chi$ and $\Delta(27)$

To accommodate ν_R, keep $SO(10)$ but instead of the left-right decomposition, take $SU(5) \times U(1)_\chi$. Now the fermions belong to $\underline{16} = (5^*, 3) + (10, -1) + (1, -5)$, and the scalars belong to $\underline{10} = (5^*, -2) + (5, 2)$.

Under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$,

$(5^*, 3) = d^c[3^*, 1, 1/3, 3] + (\nu, e)[1, 2, -1/2, 3]$,

$(10, -1) = u^c[3^*, 1, -2/3, -1] + (u, d)[3, 2, 1/6, -1] +$

$e^c[1, 1, 1, -1]$, $\quad (1, -5) = \nu^c[1, 1, 0, -5]$,

$\Phi_1 = (\phi_1^0, \phi_1^-)[1, 2, -1/2, -2]$,

$\Phi_2 = (\phi_2^+, \phi_2^0)[1, 2, 1/2, 2]$.

In previous theoretical studies, $U(1)_\chi$ is mostly ignored, although the Z_χ gauge boson is still routinely searched for, with $m_{Z_\chi} > 4.1$ TeV based on present LHC data. Since ν^c has $Q_\chi = -5$, it couples to ν through the allowed interaction $\nu^c(\nu\phi_2^0 - e\phi_2^+)$. Thus (ν, ν^c) form a Dirac neutrino pair. However, the breaking of $U(1)_\chi$ by the scalar singlet $\zeta_2 \sim (1, -10)$ from the 126 of $SO(10)$ would also make ν^c massive. Hence the seesaw mechanism occurs as in the left-right case, only the context is changed. Since ζ_2 and $\Phi_{1,2}$ all have even Q_χ, $U(1)_\chi$ breaks to $(-1)^{Q_\chi}$ just as L breaks to $(-1)^L$.

All SM fermions + ν_R have odd Q_χ, whereas the scalars $\Phi_{1,2}$ which couple to them have even Q_χ. The residual discrete symmetry $R_\chi = (-1)^{Q_\chi+2j}$ is thus even for all of the SM particles, including the gauge bosons because they have $Q_\chi = 0$ and $j = 1$. It is now an easy step to realize that any fermion/scalar with even/odd $U(1)_\chi$ has odd R_χ and belongs to the dark sector. Previously, motivated by supersymmetry, $(-1)^{3(B-L)+2j}$ has been used as dark parity, which is equivalent to R_χ because $15(B-L) = 12Y - 3Q_\chi$. Note that $W_R^\pm$ is absent here and $U(1)_\chi$ is orthogonal to $U(1)_Y$.

To insist on Dirac neutrinos, $U(1)_\chi$ should not be broken by $\zeta_2 \sim (1, -10)$. If $\zeta_4 \sim (1, -20)$ is used instead, neutrinos are Dirac with Z_4^L as the lepton symmetry. However, the allowed Yukawa Dirac couplings must then be very small. To overcome this possible objection, these tree-level couplings may be forbidden by a symmetry, the simplest being a Z_2 parity where ν_R is odd, as in numerous archival studies. A better motivated symmetry for ν_R is actually a non-Abelian discrete family symmetry such as $\Delta(27)$ [Aranda et al., PRD 89, 033001 (2014)]. Combining this with $U(1)_\chi$ and using a specific particle content, scotogenic Dirac neutrino masses and mixing are obtained in two loops (details later). Whereas $U(1)_\chi$ is only broken spontaneously, $\Delta(27)$ is broken both spontaneously and by explicit soft terms.

[Ma, MPLA 21, 1917 (2006)]: $\Delta(27)$ has two conjugate $3, 3^*$ and nine one-dimensional representations, where

$$3 \times 3 = 3^* + 3^* + 3^*, \quad 3 \times 3^* = \sum_{i=1}^{9} 1_i.$$

Hence $3 \times 3 \times 3$ has 3 invariants: 111+222+333, 123+231+312, 132+321+213.

SIDM Model with Z_4^L and Dark $Z_2 = R_\chi$

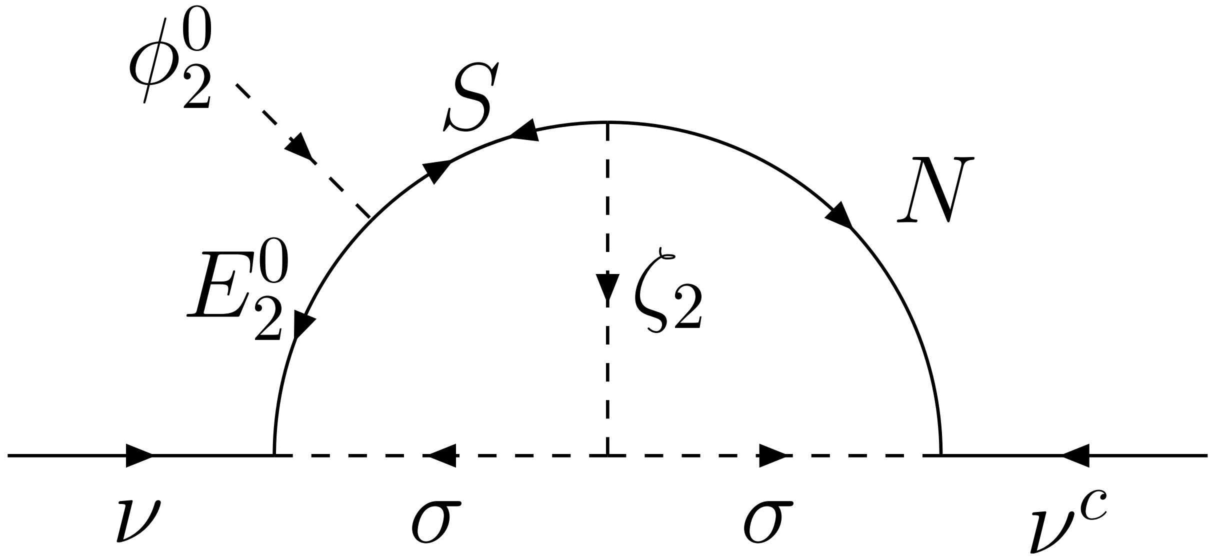
To understand the flatness of the central density profile of dwarf satellite galaxies (the cusp-core problem), the idea of SIDM (Self-Interacting Dark Matter) has been proposed. Typically, $\sigma_{el}/m_\chi \sim 1$ cm^2/g is needed, where χ is the dark matter and σ_{el} is the elastic scattering of χ with itself through the exchange of its mediator ζ. Typical mass ranges are $100 < m_\chi < 200$ GeV and $10 < m_\zeta < 100$ MeV.

Now ζ should decay, either from mixing with the Higgs boson or the $U(1)_Y$ gauge boson. After the freeze-out of

χ from its annihilation to ζ, as the Universe cools, the Sommerfeld enhancement of this cross section through the light ζ becomes much greater because χ is more at rest, and the subsequent decay of ζ to electrons and photons would disrupt the CMB (Cosmic Microwave Background) and be incompatible with observation [Bringmann/Kahlhoefer/Schmidt-Hoberg/Walia, PRL 118, 141802 (2017)]. This problem is evaded if ζ is stable [Ma, PLB 772, 442 (2017); Duerr/Schmidt-Hoberg/Wild, JCAP 1809, 033 (2018)] or if ζ decays only to two neutrinos [Ma/Maniatis, JHEP 1707, 140 (2017); Ma, MPLA 33, 1850226 (2018)].

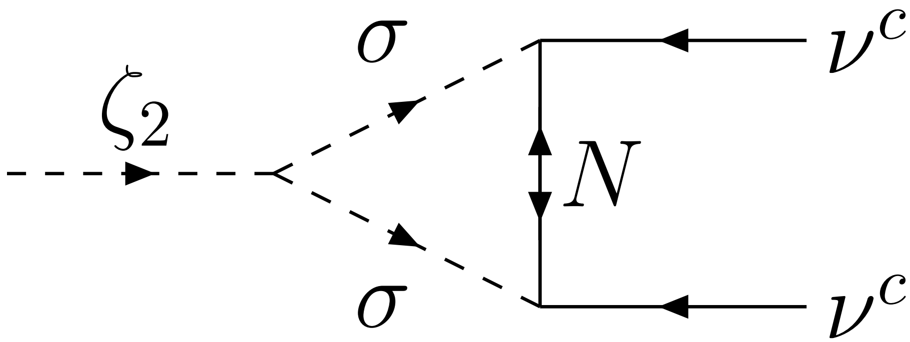
Consider the following particle content:

particle	$SO(10)$	$SU(2)$	$U(1)_Y$	$U(1)_\chi$	$\Delta(27)$	Z_4^L	R_χ
(ν, e)	16	2	$-1/2$	3	3	i	$+$
e^c	16	1	1	-1	$1_1, 1_7, 1_4$	$-i$	$+$
ν^c	16	1	0	-5	3^*	$-i$	$+$
N	126^*	1	0	10	1_1	-1	$-$
(E_2^+, E_2^0)	10	2	$1/2$	2	3	1	$-$
S	45	1	0	0	1_1	1	$-$
(ϕ_1^0, ϕ_1^-)	10	2	$-1/2$	-2	3^*	1	$+$
(ϕ_2^+, ϕ_2^0)	10	2	$1/2$	2	3	1	$+$
σ	16	1	0	-5	3	$-i$	$-$
ζ_2	126	1	0	-10	1_1	-1	$+$
ζ_4	2772	1	0	-20	1_1	1	$+$


ϕ_2^0
S
N
E_2^0
ζ_2
ν
σ
σ
ν^c

The trilinear scalar coupling $\sigma_j \sigma_k \zeta_2^*$ is allowed by $U(1)$, but breaks $\Delta(27)$ softly. The lightest of $\sigma_{1,2,3}$ is assumed to be dark matter and it has self-interactions through the light scalar mediator ζ_2. The $\sigma_1 \sigma_1^*$ annihilation to $\zeta_2 \zeta_2^*$ is a well-known mechanism for generating the correct dark-matter relic abundance of the Universe.

Since ζ_2 transforms as -1 under Z_4^L, it cannot decay to $e^- e^+$ or 2 photons. The would-be dimension-four tree-level coupling to $\nu^c \nu^c$ allowed by $U(1)_\chi$ is forbidden by $\Delta(27)$. However, using the soft $\Delta(27)$ breaking $\sigma_i \sigma_j \zeta_2^*$ term, it does decay to $\nu^c \nu^c$ in one loop.


ζ_2
σ
σ
N
ν^c
ν^c

Cobimaximal Neutrino Mixing and its Deviation

With the particle content of Table 1, Dirac neutrino masses are forbidden at tree level by $\Delta(27)$ and in one loop as well by $U(1)_\chi$. They appear in two loops through the dimension-three trilinear scalar $\sigma_j \sigma_k \zeta_2^*$ terms, which break $\Delta(27)$ softly. Note that S has an allowed Majorana mass term. The $U(1)_\chi$ symmetry is broken by ζ_4 and since it couples to ζ_2^2 and ζ_2 couples to σ^2, the residual symmetry of this model is Z_4^L which enforces the existence of Dirac neutrinos. The Z_4^L column of the table shows that $(\nu, e) \sim i$, $\zeta_2 \sim -1$, $\nu^c, e^c, \sigma \sim -i$, and others ~ 1. In addition, because of the restricted $U(1)_\chi$ couplings, $R_\chi = (-1)^{Q_\chi + 2j}$ is also conserved and acts as dark parity as discussed before.

The 3×3 charged-lepton mass matrix is given by

$$\mathcal{M}_l = \begin{pmatrix} f_e v_1^* & f_\mu v_3^* & f_\tau v_2^* \\ f_e v_2^* & f_\mu v_1^* & f_\tau v_3^* \\ f_e v_3^* & f_\mu v_2^* & f_\tau v_1^* \end{pmatrix} = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}.$$

The $\nu \sigma E_2^0$ couplings have three invariants, but since only v_1 is nonzero, only $E_{2,1}^0$ matters. Hence only the 111, 231, and 321 couplings contribute to the radiative neutrino mass matrix. The coupling matrix linking ν_i to σ_j is then

$$\begin{pmatrix} a & 0 & 0 \\ 0 & 0 & c \\ 0 & s & 0 \end{pmatrix},$$

where $c^2 + s^2 = 1$. The soft breaking $\sigma_i \sigma_j \zeta_2^*$ trilinear couplings are assumed to obey the generalized CP symmetry from $1 - 1$ and $2 - 3$ exchange with complex conjugation [Grimus/Lavoura(2004)], i.e.

$$\begin{pmatrix} b & e & e^* \\ e & d & f \\ e^* & f & d^* \end{pmatrix},$$

where b, f are real. The resulting Dirac neutrino mass matrix is proportional to

$$\mathcal{M} = \begin{pmatrix} ab & ae & ae^* \\ ce^* & cf & cd^* \\ se & sd & sf \end{pmatrix}.$$

If $c = s = 1/\sqrt{2}$, then

$$\mathcal{M}\mathcal{M}^\dagger = \begin{pmatrix} A & D & D^* \\ D^* & B & -E \\ D & -E & B \end{pmatrix},$$

which is diagonalized by a cobimaximal $U_{l\nu}$, i.e. $\theta_{23} = \pi/4$, and $\delta_{CP} = -\pi/2$ for $s_{13} = \sqrt{2}D/\sqrt{3}(B + E - A) > 0$.

Let $\sqrt{2}s - 1 = \epsilon$ and $\sqrt{2}c - 1 = -\epsilon$, then

$$1 - 2s_{23}^2 = \frac{4}{\sqrt{3}} \left(\frac{A+E}{E} \right) \epsilon,$$

$$1 + \sin\delta_{CP} = \frac{21}{4} \left(\frac{s_{13}\Delta_{31}^2}{\Delta m_{21}^2} \right)^2 \epsilon^2.$$

As an example, for $\epsilon = \pm 0.02$ and $A = E$, $s_{23}^2 = 0.48, 0.52$ and $\sin\delta_{CP} = -0.95$.

Details are given in arXiv:1907.04665.

Concluding Remarks

In the framework of $SO(10) \to SU(5) \times U(1)_\chi$, supplemented by the non-Abelian discrete symmetry $\Delta(27)$ which is broken softly, dark matter and Dirac neutrino masses and mixing appear in a new light. There are several possible new insights in the scotogenic context. One such is self-interacting dark matter with a light scalar dilepton mediator which couples only to neutrinos, where lepton number is Z_4^L and the dark parity is just $R_\chi = (-1)^{Q_\chi + 2j}$. Another is a possible residual symmetry, leading to cobimaximal neutrino mixing.

International Workshop on Neutrinos and Dark Matter (NDM-2020)

11-14 January 2020 in Hurghada, Egypt
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Your participation is most welcome!