Leptonic Dark Matter with
Scalar Dilepton Mediator

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**Abstract**

A simple and elegant mechanism is proposed to resolve the problem of having a light scalar mediator for self-interacting dark matter and the resulting disruption to the cosmic microwave background (CMB) at late times by the former’s enhanced Sommerfeld production and decay. The crucial idea is to have Dirac neutrinos with the conservation of U(1) lepton number extended to the dark sector. The simplest scenario consists of scalar or fermion dark matter with unit lepton number accompanied by a light scalar dilepton mediator, which decays to two neutrinos.
Introduction: Whereas the existence of dark matter is universally accepted, its nature is unknown [1]. Even if it is assumed that it consists of one specific fundamental particle, there is no information of what properties it must have, such as mass, spin, and possible interactions with itself or other particles. It must of course have the correct relic abundance and satisfy all present experimental bounds, but these constraints are not very restrictive and are easily satisfied by many models. This uncertain state of affairs has led to numerous diverse proposals for specific candidates of dark matter, most of which are at present not excluded. Is there a hint which would allow us to zero in on one specific candidate? In this paper, it is argued that this may indeed be the case if dark matter is assumed to have self-interactions mediated by a light scalar [2] to explain the central flatness of the density profile of dwarf galaxies [3]. The key is that this light scalar mediator has a large production cross section through Sommerfeld enhancement [4] at late times, and its decay to electrons and photons would disrupt [5] the cosmic microwave background (CMB) and be ruled out [6] by the precise observation data now available [7]. To escape this conundrum, a simple and elegant mechanism is proposed, which points to a specific scenario of dark matter as detailed below.

Predestined Leptonic Scalar Dark Matter: Consider the simple extension of the standard model (SM) of quarks and leptons with only three singlet right-handed neutrinos $\nu_R$, but also with the conservation of $U(1)_L$ lepton number. The theoretical question of where and how this symmetry may come from will be discussed later. In this framework, neutrinos are Dirac fermions with small masses which could be natural consequences of various known mechanisms [8, 9, 10].

A simple and elegant scenario of self-interacting dark matter is now possible with the addition of a neutral scalar ($\chi$) having $L = 1$ and one other ($\zeta$) having $L = 2$. Note first that $\chi$, being a scalar, is now absolutely stable from the conservation of $U(1)_L$ lepton number
alone. It is the analog of deriving dark parity from lepton parity using \((-1)^{L+2j}\) in the case of Majorana neutrinos. Thus \(\chi\) may be considered predestined dark matter because it is the automatic result of an existing symmetry and its chosen particle content.

By itself, \(\chi\) acts as a dark-matter candidate in much the same way as the simplest model of dark matter using a real scalar of odd dark parity. With the scalar dilepton \(\zeta\), it may now have the interaction \(\zeta^*\chi^2\) which enables the enhanced scattering of \(\chi\chi^* \rightarrow \chi^*\chi\) through the exchange of \(\zeta\) as a light scalar mediator. The problem of disrupting the CMB is solved because \(\zeta\) only decays to two neutrinos through the allowed \(\zeta^*\nu_R\nu_R\) coupling. This works because \(\nu_R\) combines with \(\nu_L\) to form a Dirac neutrino of very small mass. In the canonical seesaw mechanism of small Majorana neutrino masses, \(U(1)_L\) breaks to lepton parity, and \(\nu_R\) has its own very large Majorana mass. The resulting \(\nu_L - \nu_R\) mixing is very small, so the decay lifetime of \(\zeta \rightarrow \nu_L\nu_L\) through this mixing is very long if it were the only decay mode. However, since only lepton parity is conserved in that scenario, \(\zeta\) is even and mixes with the SM Higgs boson and could also decay through that mixing to electrons and photons, thereby disrupting the CMB, as in an earlier proposal. If the light scalar mediator decays dominantly to \(\nu_L\nu_L\), then it must belong mostly to an electroweak triplet. A model of this kind is possible but the details are much more complicated.

**Details of the Dark Sector**: The most general scalar potential consisting of \(\chi\), \(\zeta\), and the SM Higgs doublet \(\Phi\) is given by

\[
V = \mu_0^2\Phi^\dagger\Phi + \mu_1^2\chi^*\chi + \mu_2^2\zeta^*\zeta + [\mu_{12}\zeta^*\chi^2 + H.c.] \\
+ \frac{1}{2}\lambda_0(\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_1(\chi^*\chi)^2 + \frac{1}{2}\lambda_2(\zeta^*\zeta)^2 \\
+ \lambda_{01}(\Phi^\dagger\Phi)(\chi^*\chi) + \lambda_{02}(\Phi^\dagger\Phi)(\zeta^*\zeta) + \lambda_{12}(\chi^*\chi)(\zeta^*\zeta).
\]

(1)

With \(\langle\phi^0\rangle = v = 174\text{ GeV}\),

\[
m_H^2 = 2\lambda_0v^2 = (125\text{ GeV})^2, \quad m_\chi^2 = \mu_1^2 + \lambda_0v^2, \quad m_\zeta^2 = \mu_2^2 + \lambda_0v^2.
\]

(2)
The only new Yukawa couplings are

\[ \mathcal{L}_Y = f_{ij} \bar{\zeta} R_i \nu_R j + H.c. \] (3)

With the assumption of \( U(1)_L \) conservation, the \( f_{ij} \) terms fix the leptonic charge of \( \zeta \) to be 2, and the \( \mu_{12} \) term fixes the leptonic charge of \( \chi \) to be 1. Since \( \Phi \) has \( L = 0 \), there is no mixing among \( H, \chi, \) and \( \zeta \). In this simplest model, \( \chi \) is dark matter, whose stability depends only on conserved lepton number, and \( \zeta \) is its light dilepton mediator.

The elastic scattering of \( \chi\chi^* \rightarrow \chi^*\chi \) proceeds via the diagram of Fig. 1. The resulting cross section is given by

\[ \sigma_{el} = \frac{\mu_{12}^4}{4\pi m^2 \chi m_\zeta^2}. \] (4)

Note that for a heavy \( \chi \) and a light \( \zeta \), this may be enhanced sufficiently to affect the central density profile of the dark matter distribution, whereas the \( s \)-channel processes \( \chi\chi^* \rightarrow H \rightarrow \chi\chi^* \) and \( \chi\chi \rightarrow \zeta^* \rightarrow \chi\chi \) as well as the \( t \)-channel processes via \( H \) exchange are negligible compared to it. The same applies to the \( \lambda_1 \) quartic interaction term.

The relic abundance of \( \chi \) is determined by its annihilation cross section \( \times \) relative velocity as the temperature of the Universe falls below its mass. Assuming that \( \lambda_{01} \) is negligible to avoid the constraint from \( H \) exchange in \( \chi \) elastic scattering off nuclei in underground direct-search experiments, the main contributions of \( \chi\chi^* \rightarrow \zeta\zeta^* \) come from the \( \lambda_{12} \) quartic interaction and \( \mu_{12} \), i.e.

\[ \sigma_{ann} v_{rel} = \frac{1}{32\pi m^2 \chi} \left( \lambda_{12} + \frac{2\mu_{12}^2}{m^2 \chi} \right)^2. \] (5)
At temperatures above $m_\chi$, the $\zeta \zeta^* H$ interaction with strength $\sqrt{2} v \lambda_{02}$ allows $\zeta$ (and thus $\chi$) to be in thermal equilibrium with the SM particles. After $\chi$ freezes out, $\zeta$ eventually decays to neutrinos via the $f_{ij}$ terms with a decay rate given by

$$\Gamma(\zeta \to \nu_R \nu_R) = \frac{m_\zeta \sum_{i,j} |f_{ij}|^2}{4\pi}. \quad (6)$$

As a numerical example, let $m_\chi = 150$ GeV, then $\sigma_{\text{ann}} v_{\text{rel}} = 4.4 \times 10^{-26} \text{ cm}^3/\text{s}$ is obtained with $\lambda_{12} + 2 \mu_{12}^2/m_\chi^2 = 0.0923$, which implies that $\mu_{12} < 32.2$ GeV if $\lambda_{12} > 0$. Setting $\sigma_{\text{el}}/m_\chi$ equal to the benchmark value of $1 \text{ cm}^2/\text{g}$ for self-interacting dark matter, the ratio $m_\zeta/\mu_{12} = 0.0015$ is required. Hence $m_\zeta < 48.3$ MeV if $\lambda_{12} > 0$. Using $m_\zeta = 40$ MeV, its decay lifetime is about $2 \times 10^{-16} \text{ s}$ for $\sum_{i,j} |f_{ij}|^2 = 10^{-6}$. This means that before the onset of big bang nucleosynthesis (BBN), $\zeta$ has all decayed away and $\nu_R$ decouples from the rest of the SM particles. In particular, the number of effective massless degrees of freedom used in the standard BBN scenario is unchanged.

The interaction of the leptonic dark matter $\chi$ with quarks and leptons is through the SM Higgs boson $H$. For $m_\chi = 150$ GeV, this elastic cross section $\sigma_0$ is bounded by the latest experimental result [17] to be below $2 \times 10^{-46} \text{ cm}^2$. This translates to an upper bound [18] of $4.4 \times 10^{-4}$ for the $\lambda_{01}$ quartic coupling of Eq. (1). As for the $\lambda_{02}$ quartic coupling, it is constrained by the invisible decay width of $H \to \zeta \zeta^*$, i.e.

$$\Gamma(H \to \zeta \zeta^*) = \frac{\lambda_{02}^2 v^2}{4\pi m_H}. \quad (7)$$

Assuming that this is less than 10% of the SM width of 4.12 MeV, then $\lambda_{02} < 4.6 \times 10^{-3}$.

**Leptonic Fermion Dark Matter** : The scalar leptonic dark matter $\chi$ may be replaced by a Dirac fermion $\psi$. Now the singlets $\psi_R$ and $\nu_R$ both have $L = 1$ and must be distinguished. In other words, a dark $Z_2$ parity must be imposed, so that $\psi$ is odd and all other particles even. The scalar sector consists only of $\Phi$ and $\zeta$. The Yukawa sector has the new terms

$$\mathcal{L}_Y = f_L \zeta^* \psi_L \psi_L + f_R \zeta^* \psi_R \psi_R + \text{H.c.} \quad (8)$$
The analog of Fig. 1 is then Fig. 2. The resulting cross section is given by

\[
\sigma_{el} = \frac{(f_L + f_R)^4 m_\psi^2}{4\pi m_\zeta^4}.
\]

Figure 2: Dark matter $\psi$ elastic scattering by exchanging $\zeta$.

The analog of Eq. (5) is

\[
\sigma_{\text{ann} v_{\text{rel}}} = \frac{f_L^2 f_R^2}{\pi m_\zeta^2}.
\]

Using again $m_\psi = 150$ GeV as an example, and assuming $f_L = f_R = f$, then $f = 0.128$ is obtained, as well as $m_\zeta = 58$ MeV.

Regarding direct detection, $\psi$ has no Yukawa coupling with the SM Higgs boson at tree level, but may do so in one loop as shown in Fig. 3. However, since $\lambda_{02} < 4.6 \times 10^{-3}$ and $f_L f_R = 0.0164$, this contribution is very much negligible.

**Predestined Leptonic Fermion Dark Matter**: To eliminate the need to impose a dark parity for leptonic fermion dark matter, $\psi$ may be assigned $L = 2$ with the addition of a scalar $\eta$ with $L = 4$. Then $\psi$ is predestined dark matter [12] because it is stable as the result of an
existing symmetry and its particle content. Now \( \eta \) (instead of \( \zeta \)) acts as its light mediator, with \( \eta \) decaying into \( \zeta \zeta \), then \( \zeta \rightarrow \nu_R \nu_R \).

**Gauge Origin of Lepton Number Conservation**: It is well-known that with three singlet right-handed neutrinos, \( B - L \) may be implemented as an anomaly-free gauge symmetry. The conventional approach is to break gauge \( B - L \) spontaneously with a scalar having \( L = 2 \). Since this scalar also couples to \( \nu_R \nu_R \), lepton number becomes lepton parity and the three left-handed neutrinos obtain small Majorana masses through the canonical seesaw mechanism. It is however also possible to keep \( B - L \) as a global \( U(1) \) symmetry by using a scalar (\( \rho \)) with \( L = 3 \) \([19, 20]\) instead.

Consider first the simplest self-interacting leptonic dark-matter model with the scalars \( \chi \) (\( L = 1 \)) and \( \zeta \) (\( L = 2 \)). If \( \rho \) (\( L = 3 \)) is used to break \( B - L \) spontaneously, then the allowed terms \( \rho^* \chi^3 \), \( \zeta^* \chi^2 \), and \( \rho^* \zeta \chi \) imply that a residual \( Z_3 \) symmetry remains \([14]\) as lepton number. Whereas this is sufficient to keep neutrinos as Dirac fermions, \( \chi^* \) now transforms as \( \zeta \), hence the former is no longer stable and cannot be dark matter in the present context. In Ref. \([14]\), although \( \zeta \) is not stable, it has a very long lifetime because the three \( \nu_R \) singlets transform as \((-4, -4, 5)\) instead of \((-1, -1, -1)\) under \( B - L \).

Assume instead that \( \rho \) has \( L = 4 \), then the allowed terms are \( \rho^* \zeta^2 \), \( \zeta^* \chi^2 \), and \( \rho^* \zeta \chi^2 \). This results in a residual \( Z_4 \) symmetry \([21, 22]\) as lepton number, with

\[
\nu \sim i, \quad \chi \sim i, \quad \zeta \sim -1. \tag{11}
\]

It allows \( \chi \) to be self-interacting dark matter.

If \( \rho \) has \( L = 5 \), then the terms \( \rho^* \zeta^2 \chi \) and \( \zeta^* \chi^2 \) imply a residual \( Z_5 \) symmetry. If \( \rho \) has \( L = 6 \), then the terms \( \rho^* \zeta^3 \) and \( \zeta^* \chi^2 \) imply a residual \( Z_6 \) symmetry. Both would also have \( \chi \) as dark matter. For \( L = 7 \) or greater, only the term \( \zeta^* \chi^2 \) remains, in which case \( B - L \) is a global symmetry.
Consider next the self-interacting fermion dark matter $\psi$ with imposed dark parity. The scalar sector now consists of $\zeta$ ($L = 2$) and $\rho$. If $\rho$ is assigned $L = 3$, then the spontaneous breaking of gauge $B - L$ results in a conserved global $B - L$ as desired.

Finally, in the case $L = 2$ for $\psi$ as predestined fermion dark matter, the scalar sector consists of $\eta$ ($L = 4$), $\zeta$ ($L = 2$), and $\rho$. If $\rho$ is assigned $L = 3$, then the allowed terms are $\eta^*\zeta^2$ and $\eta^*\zeta^*\rho^2$. This means that $\eta^*$ transforms as $\zeta$ (so that only one is needed), and the residual symmetry is $Z_6$. In that case,

$$\nu \sim \omega, \quad \psi \sim \omega^2, \quad \zeta \sim \omega^2,$$

(12)

where $\omega^6 = 1$. This allows $\psi$ to be self-interacting dark matter.

Some Phenomenological Consequences: In the minimal model of leptonic scalar dark matter, direct detection via Higgs exchange is possible, limited only by $\lambda_{01}$ as a function of $m_\chi$ from present data. It is thus always amenable to observation in the future. In the minimal models of leptonic fermion dark matter, this effect is suppressed in one loop, which means that it is not likely to be observable at all.

If the models are supplemented by a gauge $B - L$ symmetry, the resulting $Z_{B-L}$ gauge boson is constrained through its production and decay at the Large Hadron Collider (LHC) as well as in direct-search experiments. The generic requirement \cite{23} is that the lower bound on $M_{Z_{B-L}}/g_{B-L}$ increases as $g_{B-L}$ decreases. For $g_{B-L} = 0.3$, it is about 8.7 TeV. Note that $Z_{B-L}$ does not need to contribute to the annihilation cross sections of Eqs.(5) and (10). However, if it does, then it may be revealed in direct-search experiments or at the LHC.

Whereas Sommerfeld enhancement may allow $\zeta$ to be produced at present from dark matter annihilation, it is difficult to be observed because it decays only to neutrinos. Also, since neutrinos are Dirac fermions, neutrinoless double beta decay is forbidden. A positive such signal in future experiments would invalidate the proposed theory.
Concluding Remarks: The notion that neutrinos are Dirac fermions leads naturally to the conceptual extension of conserved lepton number to dark matter. This insight allows for the natural implementation of simple, minimal models of self-interacting dark matter with a light scalar dilepton mediator which decays only to neutrinos. As such it solves the problem of the possible disruption to the cosmic microwave background caused by such a light mediator if it decays to electrons and photons. It is simpler and more elegant than the previously proposed scenario \[24, 25, 26\] with a gauge $U(1)_D$ symmetry where $Z_D$ is the light vector mediator which does not decay, or the very recent proposal \[27\] with a gauge $L_\mu - L_\tau$ symmetry.

A byproduct of this investigation is the realization that if gauge $B - L$ is the origin of Dirac neutrino masses, its spontaneous breaking (in the context of the models being discussed) may result in either global $B - L$ or $Z_N$ lepton symmetry. Indeed, examples of $N = 4, 5, 6$ are obtained. This bolsters the notion that lepton symmetry does not need to be either continuous $U(1)$ or odd-even parity, but may in fact be somewhere in between, implying also an intimate connection to dark matter. Instead of $B - L$, the residual $U(1)_\chi$ symmetry in breaking $SO(10)$ to $SU(5)$ may also be used.

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References

[1] For a recent review, see for example B. L. Young, Front. Phys. 12, 121201 (2017).
[2] A. Kamada, M. Kaplinghat, A. B. Pace, and H.-B. Yu, Phys. Rev. Lett. 119, 111102 (2017).
[3] F. Donato et al., Mon. Not. Roy. Astron. Soc. 397, 1169 (2009).
[4] A. Sommerfeld, Ann. Phys. 403, 257 (1931).
[5] S. Galli, F. Iocco, G. Bertone, and A. Melchiorri, Phys. Rev. D80, 023505 (2009).
[6] T. Bringmann, F. Kahlhoefer, K. Schmidt-Hoberg, and P. Walia, Phys. Rev. Lett. 118, 141802 (2017).

[7] P. A. R. Ade et al., PLANCK Collaboration, Astron. Astrophys. 594, A13 (2016).

[8] C. Bonilla, E. Ma, E. Peinado, and J. W. F. Valle, Phys. Lett. B762, 214 (2016).

[9] E. Ma and O. Popov, Phys. Lett. B764, 142 (2017).

[10] E. Ma and U. Sarkar, Phys. Lett. B776, 54 (2018).

[11] E. Ma, Phys. Rev. Lett. 115, 011801 (2015).

[12] E. Ma, arXiv:1803.03891 [hep-ph], LHEP in press.

[13] For a recent review, see P. Athron, et al., GAMBIT Collaboration, Eur. Phys. J. C77, 568 (2017).

[14] E. Ma, N. Pollard, R. Srivastava, and M. Zakeri, Phys. Lett. B750, 135 (2015).

[15] E. Ma, Mod. Phys. Lett. A32, 1750038 (2017).

[16] E. Ma and M. Maniatis, JHEP 1707, 140 (2017).

[17] E. Aprile, et al., XENON Collaboration, Phys. Rev. Lett. 119, 181301 (2017).

[18] C. Kownacki, E. Ma, N. Pollard, O. Popov, and M. Zakeri, Eur. Phys. J. C78, 148 (2018).

[19] E. Ma, I. Picek, and B. Radovcic, Phys. Lett. B726, 744 (2013).

[20] E. Ma and R. Srivastava, Phys. Lett. B741, 217 (2015).

[21] J. Heeck and W. Rodejohann, EPL 103, 32001 (2013).

[22] S. Centelles Chulia, E. Ma, R. Srivastava, and J. W. F. Valle, Phys. Lett. B767, 209 (2017).

[23] M. Klasen, F. Lyonnet, and F. S. Queiroz, Eur. Phys. J. C77, 348 (2017).

[24] E. Ma, Phys. Lett. B772, 442 (2017).

[25] E. Ma, arXiv:1804.00374 [hep-ph].

[26] M. Duerr, K. Schmidt-Hoberg, and S. Wild, arXiv:1804.10385 [hep-ph].

[27] A. Kamada, K. Kaneta, K. Yanagi, and H.-B. Yu, arXiv:1805.00651 [hep-ph].