Dark Gauge U(1) Symmetry for an Alternative Left-Right Model

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Introduction/Motivation

- Restore symmetry between Left-Right sectors
- Generate naturally small neutrino masses
- Accomodate dark matter
Minimal Left-Right Model

- Simple extension of the SM gauge group
- Spontaneous/Explicit breaking of $\text{P} (\text{SU}(2)_L \leftrightarrow \text{SU}(2)_R)$ (also CP)
- Generation of naturally light neutrino masses (Seesaw I/III)

\[
\text{SU}(3)_C \times \text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_{B-L}
\]

- $Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [3, 2, 1, \frac{1}{3}]$, $Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [3, 1, 2, \frac{1}{3}]
- \ell_L = \begin{pmatrix} v_L \\ e_L \end{pmatrix} \equiv [1, 2, 1, -1]$, $\ell_R = \begin{pmatrix} v_R \\ e_R \end{pmatrix} \equiv [1, 1, 2, -1]$. *

- $\eta \sim (1, 2, 2, 0)$, $\Delta_L \sim (1, 3, 1, -1)$, $\Delta_R \sim (1, 1, 3, -1)$
- Seesaw I/II
- $\eta \sim (1, 2, 2, 0)$, $\phi_L \sim (1, 2, 1, 1/2)$, $\phi_R \sim (1, 1, 2, 1/2)$
- Double seesaw through Weinberg dim-5 operator
- Flavour changing neutral currents

* N.G. Deshpande et al., Phys. Rev. D 44, 837 (1991).
Alternative Left-Right Model

\[ SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \]

- \((u, d)_L : (3, 2, 1, \frac{1}{6})\)
- \((h^c, u^c)_L : (\bar{3}, 1, 2, -\frac{1}{6})\)
- \((\nu_E, E)_L : (1, 2, 1, -\frac{1}{2})\)
- \((e^c, n)_L : (1, 1, 2, \frac{1}{2})\)
- \(h_L : (3, 1, 1, -\frac{1}{3})\)
- \(d^c_L : (\bar{3}, 1, 1, \frac{1}{3})\)
- \(\begin{pmatrix} \nu_e & E^c_e \\ e & N^c_e \end{pmatrix}_L : (1, 2, 2, 0)\)
- \(N^c_L : (1, 1, 1, 0)\)

- ALRM is motivated by superstring-inspired E\(_6\) model
- Flavour changing neutral currents are naturally absent at tree level
- \(W^\pm_R\) has lepton number \(\pm 1\) and odd parity so they do not mix with \(W^\pm_L\)
- \(SU(2)_R\) breaking scale can be below as TeV, \(W^\pm_R\) and \(Z'\) are reachable at LHC

\[ ^\dagger \text{E. Ma, Phys. Rev. D 36, 274 (1987); K. S. Babu, X.-G. He, and E. Ma, Phys. Rev. D 36, 878 (1987); J. L. Hewett and T. G. Rizzo,} \]
## Dark Alternative Left-Right Models with Global Symmetries

| Fermion       | $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$ | $S$ |
|---------------|-------------------------------------------------|-----|
| $\psi_L = (\nu, e)_L$ | (1, 2, 1, −1/2) | 1  |
| $\psi_R = (n, e)_R$ | (1, 1, 2, −1/2) | 1/2 |
| $Q_L = (u, d)_L$ | (3, 2, 1, 1/6) | 0  |
| $Q_R = (u, h)_R$ | (3, 1, 2, 1/6) | 1/2 |
| $d_R$ | (3, 1, 1, −1/3) | 0  |
| $h_L$ | (3, 1, 1, −1/3) | 1  |

| Scalar        | $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$ | $S$ |
|---------------|-------------------------------------------------|-----|
| $\Phi$       | (1, 2, 2, 0) | 1/2 |
| $\Phi^* \Phi \sigma_2$ | (1, 2, 2, 0) | −1/2 |
| $\Phi_L$     | (1, 2, 1,1/2) | 0  |
| $\Phi_R$     | (1, 1, 2,1/2) | −1/2 |
| $\Delta_L$   | (1, 3, 1, 1) | −2  |
| $\Delta_R$   | (1, 1, 3, 1) | −1  |

- No tree level FCNC
- Neutrino masses ($m_\nu \sim \langle \Delta_L^0 \rangle \implies L \to (-1)^L, \text{R parity}$)
- Fermionic Dark Matter (Scotinos) ($m_n \sim \langle \Delta_R^0 \rangle$)
- Lepton number given by $L=S-T_{3R}$
- $\langle \phi_1^0 \rangle = 0$ by $S-T_{3R}$
- $h, W_{R}^{\pm}$ has $L=1, \mp 1$
- SM particles are even, $n, h, W_{R}^{\pm}$, and $\Delta_{R}^{\pm}$ are odd under parity

‡ S. Khalil, H.-S. Lee, E. Ma, Phys. Rev. D 79, 041701(R) (2009)
Dark Alternative Left-Right Models II
with Global Symmetries

- No tree level FCNC
- Dirac neutrino masses ($m_\nu \sim \langle \phi^0_L \rangle$)
- Dirac Fermionic Dark Matter (Scotinos) ($m_n \sim \langle \phi^0_R \rangle$)
- Lepton number given by $L = S + T_{3R}$ and is conserved
- $\langle \phi^0_1 \rangle = 0$ by $S + T_{3R}$
- $\nu_R \nu_R$ breaks $L$ and generates Majorana neutrino mass through canonical seesaw
- $n$ remains Dirac fermion protected by residual global $U(1)$ 

$$n, W^+_R \sim 1, h, \phi^{0,-}_1 \sim -1$$

$\S$ S. Khalil, H.-S. Lee, E. Ma, Phys. Rev. D 81, 051702(R) (2010)
The Particle Content of the U(1)$_D$ ALRM

| particles        | SU(3)$_C$ | SU(2)$_L$ | SU(2)$_R$ | U(1)$_X$ | U(1)$_S$ |
|------------------|-----------|-----------|-----------|-----------|-----------|
| $(u, d)_L$       | 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        |
| $(\nu, l)_L$     | 1         | 2         | 1         | −1/2      | 0         |
| $(n, l)_R$       | 1         | 1         | 2         | −1/2      | 1/2       |
| $\nu_R$          | 1         | 1         | 1         | 0         | 0         |
| $n_L$            | 1         | 1         | 1         | 0         | 1         |
| $(\phi^+_L, \phi^0_L)$ | 1     | 2         | 1         | 1/2       | 0         |
| $(\phi^+_R, \phi^0_R)$ | 1     | 1         | 2         | 1/2       | 1/2       |
| $\eta$           | 1         | 2         | 2         | 0         | −1/2      |
| $\zeta$          | 1         | 1         | 1         | 0         | 1         |
| $(\psi^0_1, \psi^-_1)_R$ | 1     | 1         | 2         | −1/2      | 2         |
| $(\psi^+_2, \psi^0_2)_R$ | 1     | 1         | 2         | 1/2       | 1         |
| $\chi^+_R$       | 1         | 1         | 1         | 1         | −3/2      |
| $\chi^-_R$       | 1         | 1         | 1         | −1        | −3/2      |
| $\chi^0_{1R}$    | 1         | 1         | 1         | 0         | −1/2      |
| $\chi^0_{2R}$    | 1         | 1         | 1         | 0         | −5/2      |
| $\sigma$         | 1         | 1         | 1         | 0         | 3         |

C. Kownacki, E. Ma, N. Pollard, OP, M. Zakeri, 1706.06501
Symmetry breaking, Mass Generation, and Flavour Changing Neutral Currents

- $\langle \phi^0_R \rangle = 0$, $\langle \eta_2^0 \rangle = 0$ and conserve $S+T_{3R}$
- All exotic fermions have half integer charges under $S+T_{3R}$
- Particle content and charge assignments result in additional unbroken $Z_2$ symmetry, under which exotic fermions are odd and others are even
- $S+T_{3R}$ is broken to $S'$ by $\langle \sigma \rangle \neq 0$ and gives masses to exotic fermions
- $S'$ charges for exotic fermions are different from $S+T_{3R}$ charges
- Presence of $\zeta$ induces $\zeta^3 \sigma^*$ and $\chi_{1R}^0 \chi_{1R}^0 \zeta$ breaks $S'$ further to $Z_3$
### Particle content of proposed model under \((T_{3R} + S) \times Z_2\)

| particles                  | gauge \(T_{3R} + S\) | global \(S'\) | \(Z_3\) | \(Z_2\) |
|----------------------------|-------------------------|----------------|--------|--------|
| \(u, d, ν, l\)            | 0                       | 0              | 1      | +      |
| \((φ^+_L, φ^0_L, (η^+_2, η^0_2), φ^0_R)\) | 0                       | 0              | 1      | +      |
| \(n, φ^+_R, ζ\)           | 1                       | 1              | \(ω\) | +      |
| \(h, (η^0_1, η^-_1)\)     | −1                      | −1             | \(ω^2\) | +      |
| \(ψ^+_2R, χ^+_R\)         | 3/2, −3/2               | 0              | 1      | −      |
| \(ψ^-_1R, χ^-_R\)         | 3/2, −3/2               | 0              | 1      | −      |
| \(ψ^0_1R, ψ^0_2R\)        | 5/2, 1/2                | 1, −1          | \(ω, ω^2\) | −      |
| \(χ^0_1R, χ^0_2R\)        | −1/2, −5/2              | 1, −1          | \(ω, ω^2\) | −      |
| \(σ\)                     | 3                       | 0              | 1      | +      |
Constraints on the $U(1)_D$ ALRM

- $M(Z') > 4\text{TeV}$
- DM candidates: Fermionic $DM(\chi_0)$ ($\chi_0\bar{\chi}_0 \rightarrow \zeta\zeta^*$), Scalar DM ($\zeta$) ($\zeta\zeta^* \rightarrow HH$)
- $\langle \sigma \times v_{\text{rel}} \rangle_{\chi} = \frac{f_0^4}{4\pi m_{\chi_0}} \frac{(m_{\chi_0}^2 - m_{\zeta}^2)^{3/2}}{(2m_{\chi_0}^2 - m_{\zeta}^2)^2} \left( f_0 \zeta \chi_0 R \chi_0 R \right)$
- $\langle \sigma \times v_{\text{rel}} \rangle_{\zeta} = \frac{\lambda_0^2}{16\pi} \frac{(m_{\zeta}^2 - m_H^2)^{1/2}}{m_{\zeta}^3} \left( \lambda_0 \zeta\zeta^* HH \right)$
- $\nu_R > 35\text{TeV} \implies M_{Z'} > 18\text{TeV}, M_{W_R} > 16\text{TeV}$
Conclusions

- (Alternative, Dark) Left-Right Models have no tree level FCNC
- Generate naturally small neutrino masses (Seesaw I/II/III/Double)
- Rich phenomenology accessible at LHC
- Different variations are possible
- Natural Dark Matter candidates due to residual symmetry
- 2 layers of DM stabilized by $Z_3$ and $Z_2$ in case of Gauged DLRM
### Particle Content of the Model

| Particle | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | L | copies | $Z_2$ |
|----------|-----------|-----------|-----------|---|--------|-------|
| $Q_i = (u, d)_i$ | 3 | 2 | 1/6 | 0 | 3 | + |
| $u^c$ | 3* | 1 | -2/3 | 0 | 3 | + |
| $d^c$ | 3* | 1 | 1/3 | 0 | 3 | + |
| $L_i = (\nu, e)_i$ | 1 | 2 | -1/2 | 1 | 3 | + |
| $e^c$ | 1 | 1 | 1 | -1 | 3 | + |
| $(E^0, E^-)_{L,R}$ | 1 | 2 | -1/2 | 1 | 1 | - |
| $N_{L,R}$ | 1 | 1 | 0 | 1 | 1 | - |
| $\Phi = (\phi^+, \phi^0)$ | 1 | 2 | 1/2 | 0 | 1 | + |
| $s^0_i$ | 1 | 1 | 0 | 0 | 3 | - |
New Lagrangian

\[ \mathcal{L}_{\text{new}} \supset \begin{align*} &N_L \left( E_R^0 \phi^0 - E_R^- \phi^+ \right) \\ &\left( E_R^0 E_L^0 + E_R^+ E_L^- \right) \\ &\left( \bar{\nu} L_i E_R^0 + e_{L_i} E_R^- \right) s_j \end{align*} \]

\[ N_L N_L \]

\[ m_i^2 s_j^2 \]
Scotogenic Neutrino Mass
Mixing of Leptons, $\mathbb{Z}_2$ odd

$$
M_{E,N} = \begin{pmatrix}
0 & m_E & m_D \\
 m_E & 0 & 0 \\
 m_D & 0 & m_N
\end{pmatrix}
$$

$$
m_1 = \frac{m_E^2 m_N}{m_E^2 + m_D^2}
$$

$$
m_{2,3} = \pm \sqrt{m_E^2 + m_D^2} + \frac{m_D^2 m_N}{2 (m_E^2 + m_D^2)}
$$

$$
m_N \ll m_E, m_D
$$
Neutrino Mass

\[ m_\nu = f^2 \frac{m_D m_N}{m_E^2 + m_D^2} F(x) \]

\[ F(x) = \frac{1}{1-x} \left( 1 + \frac{x \ln x}{1-x} \right) \]

\[ x = \frac{m_s^2}{(m_E^2 + m_D^2)} \]

| \( f_{e,\mu,\tau} \) | 0.1 |
| \( x \) | \( \approx 0 \) |
| \( m_N \) | 10 MeV |
| \( m_D \) | 10 GeV |
| \( m_E \) | 1 TeV |
| \( m_\nu \) | 0.1 eV |
Gauge $U(1)_D$
Symmetry for ALRM

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RLM
Introduction
MLRM
ALRM
DLRM
$U(1)_D$ Gauged ALRM

Constraints on the $U(1)_D$ ALRM
Conclusions

Scotogenic Inverse Seesaw Model of Neutrino Mass

Model
Particle Content
Relevant Lagrangian Terms
Neutrino Mass Neutrino Mass Generation Mixing of Leptons

$m_{\nu}$

Z$_3$ symmetry and Neutrino Mixing

$(\nu_i, l_i) \sim 1, 1', 1''$, $s_1 \sim 1$, $(s_2 \pm is_3)/\sqrt{2} \sim 1', 1''$, $l_{iR} \sim 1, 1', 1''$

$$m_s^2 s^2 + m_s^2 (s_2^2 + s_3^2)$$

$$M_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & i/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \end{pmatrix} O^T \begin{pmatrix} I(m_{s1}^2) & 0 & 0 \\ 0 & I(m_{s2}^2) & 0 \\ 0 & 0 & I(m_{s3}^2) \end{pmatrix} O \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \end{pmatrix}$$

$$M_\nu \bigg|_{f_\mu = f_\tau} = \begin{pmatrix} A & C & C^* \\ C & D^* & B \\ C^* & B & D \end{pmatrix}$$

Cobimaximal Mixing: $\theta_{23} = \pi/4$, $\exp(-i\delta) = \pm i$, $\theta_{13} \neq 0$
\[ f_\mu \neq f_\tau \] case

\[
M_\nu = E_\alpha U E_\beta M_d E_\beta U^T E_\alpha \\
M_\nu M_\nu^\dagger = E_\alpha U M_d^2 U^\dagger E_\alpha^\dagger \\
M_\nu^\lambda M_\nu^\lambda & = E_\alpha U [1 + \Delta] M_{\lambda d}^2 \left[ 1 + \Delta^\dagger \right] U^\dagger E_\alpha^\dagger \\
\underbrace{OM_{\text{new}}^2 O^T}
\]

\[
\Delta = U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda - 1 \end{pmatrix} U, \quad M_{\lambda d}^2 = \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & \lambda^2 m_3^2 \end{pmatrix}
\]

\[
\lambda = \frac{f_\mu}{f_\tau}
\]
\[ f_\mu \neq f_\tau \text{ case} \]

\[ \rightarrow \text{ Normal ordering (left) and Inverted ordering (right).} \]
Muon Anomalous Magnetic Moment

\[ \Delta a_\mu = \frac{(g - 2)_\mu}{2} = \frac{f_\mu^2 m_\mu^2}{16\pi^2 m_E^2} \sum_i |U_{\mu i}|^2 G(x_i) \]

\[ G(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6 (1 - x)^4}, \quad x_i = \frac{m_{s_i}^2}{m_E^2} \]

\[ U = O \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \end{pmatrix} \]

\[ x_i \ll 1, \quad m_E \sim 1\text{ TeV} \]

\[ \Delta a = \frac{f_\mu^2 m_\mu^2}{96\pi^2 m_E^2} \approx 10^{-11} f_\mu^2 \]

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\(^{\S}\) S. Kanemitsu and K. Tobe, Phys. Rev. D86, 095025 (2012).
\[
\mu \rightarrow e\gamma
\]

\[
A_{\mu e} = \frac{e f_\mu f_e m_\mu}{32\pi^2 m_E^2} \sum_i U_{ei}^* U_{\mu i} G(x_i)
\]

\[
Br (\mu \rightarrow e\gamma) = \frac{12\pi^2 |A_{\mu e}|^2}{m_\mu^2 G_F^2} < 5.7 \times 10^{-13} \dagger
\]

\[
f_\mu f_e < 0.03
\]

\dagger MEG Collaboration, J. Adams et al., Phys. Rev. Lett. 110, 201801 (2013).
Dark Matter Candidates: $N_L$, $S$

\[-\mathcal{L}_{int} = \frac{\lambda h S}{2} \nu h S^2 + \frac{\lambda h S}{4} h^2 S^2\]

$m_S \lesssim m_h/2$ or $m_S > 150$ GeV
Conclusions

- Inverse Seesaw Neutrino Mass
- $Z_3$ Flavor Symmetry $\implies$ Cobimaximal Mixing
- Deviation from Cobimaximal Mixing
- g-2 and $\mu \rightarrow e\gamma$