Neutrino and Its connection to Dark Matter

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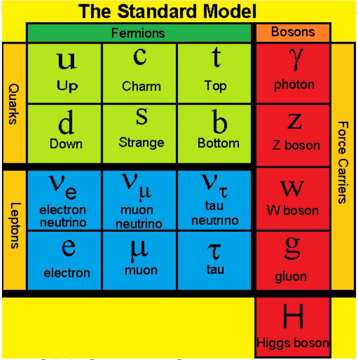
Based on my recent works

1. Heeck, **SP**; **Phys.Rev.Lett. 115 (2015), 121804**
2. **SP**; **Phys.Rev. D93 (2016), 093001**
3. **SP**, Rao; **Phys. Lett. B 759 (2016) 454-458**
4. **SP**, Rodejohann, Yaguna; **JHEP 1609 (2016) 076**

Outline

- ★ **Can Neutrino be a viable Dark Matter candidate ?**
- ★ **Neutrinos in gauged B-L model as Dark Matter**
  - **Triangle Anomaly and neutrinos to surve the purpose**
  - **Dirac neutrino as Dark Matter**
  - **Relic Density, Direct, Indirect and Collider Bound**
- ★ **Neutrinos in Left-Right symmetric model as Dark Matter**
  - **Stability Issue**
  - **Dark Matter Candidates**
- ★ **Neutrino Dark Matter Decay**: Explanation of ultra high energy IceCube events
- ★ **Conclusion**

Standard Model



- Explains the strong, the weak and the electromagnetic interactions
- a beautiful theory explaining all the fundamental particles known to us and their interactions

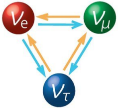
Table: SM Gauge Group: $SU(2)_L \times U(1)_Y \times SU(3)_C$

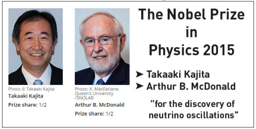
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	u_R d_R	c_R s_R	t_R b_R
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	? e_R	? μ_R	? τ_R

- **Neutrinos are left-handed part of Isospin doublet**
- **No Right-handed Neutrinos**
  Massless Neutrinos
- **No Dark Matter Candidate**

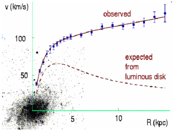
Motivation for Beyond Standard Model Physics

★ **Non-zero Neutrino mass: Theoretical origin ??**

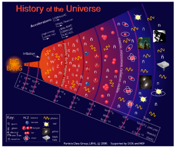


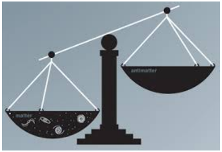


★ **Dark Matter: Constituting 25% energy density of Universe ?**



★ **Baryon Asymmetry: Why present Universe is matter dominated ?**





Connection between Neutrino and Dark Matter ?

Neutrino

- Electrically Neutral Fermion
- No Strong and electromagnetic interaction
- Only Weak interaction

Dark Matter

- Electrically Neutral Particle
- No Strong and electromagnetic interaction
- Only Weak Interaction

Summary: Neutrinos (which are sterile) can be act as a viable Dark matter candidate and shed light on Darkness of the Universe.

Singlet extension of SM and Dark Matter

$$\underline{SU(2)_L \times U(1)_Y \times Z_2}$$

Introduce three Right-handed Neutrinos:

$$\mathbf{N_{1R}} \sim (1,0)_-, \mathbf{N_{2R}} \sim (1,0)_+, \mathbf{N_{3R}} \sim (1,0)_+$$

- Lightest $\mathbf{N_{1R}}$ is Stable under this discrete symmetry
- Other two heavy neutrinos generate light neutrino mass via Seesaw Mechanism
- However, the discrete symmetry seems to be ad hoc.
- Can we ensure the stability of the multiplet automatically ?

Gauging Baryon and Lepton Number

- ★ Baryon (B) and lepton (L) number classical global symmetries in standard model
- ★ Promote global symmetries to local symmetries

$$SU(2)_L \times U(1)_Y \times U(1)_{B,L}$$

$$SU(2)_L \times U(1)_Y \times U(1)_B \times U(1)_L$$

$$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

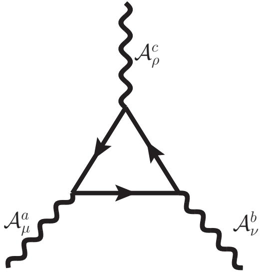
$$SU(2)_L \times U(1)_Y \times U(1)_{L_\alpha - L_\beta}$$

- ★ Dark Matter is the extra lightest neutrino added to SM and its stability is ensured automatically

Triangle Anomaly in Gauge Theory

If we demand renormalizability of a gauge theory we have to ensure that both vector and axial-vector currents must be conserved, but this is not always possible due to presence of triangle anomaly

- ★ Current conservation is generally broken due to quantum fluctuations when the gauge fields combine with the fermion fields
- ★ Anomaly $\propto \pm \mathrm{Tr}[T^a T^b T^c]$
- ★ All anomalies vanishes for SM

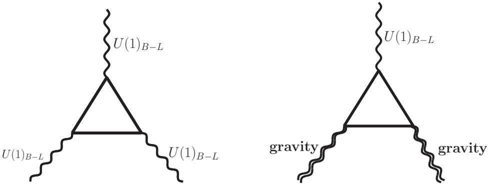


The simplest way to restore the renormalizability of the gauge theory is to make sure that the fermion contributions to the triangle anomaly are indeed canceled as a whole.

$B-L$ gauge Theory and Triangle Anomaly

Fermions	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
$Q_L \equiv (u, d)_L^T$	3	2	1/6	1/3
u_R	3	1	2/3	1/3
d_R	3	1	$-1/3$	1/3
$\ell_L \equiv (\nu,\ e)_L^T$	1	2	$-1/2$	-1
e_R	1	1	-1	-1

$$\mathcal{A}_1\left[U(1)^3_{B-L}\right] = -3$$
$$\mathcal{A}_2\left[(\text{gravity})^2 \times U(1)_{B-L}\right] = -3$$



Additional fermions required for Anomaly cancellation

Gauge Anomalies and connection to Dark Matter

1. Neutrinos originally introduced for Anomaly Cancelation for a self consistent gauge theory can be a viable Dark Matter
2. Fermionic Dark Matter with fractional charges

Exotic Fermions	N_{1R}	N_{2R}	N_{3R}	N_{4R}
$B-L$	-4/3	-2/3	-2/3	-1/3

SP, Yaguna, Rodejohann; JHEP 1609 (2016) 076

3. Fermionic Dark Matter with exotic charges

Exotic Fermions	N_{1R}	N_{2R}	N_{3R}
$B-L$	-4	-4	5

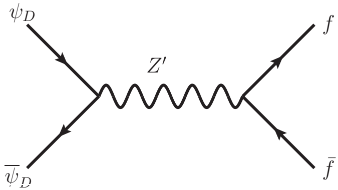
Ernest Ma et al 2015

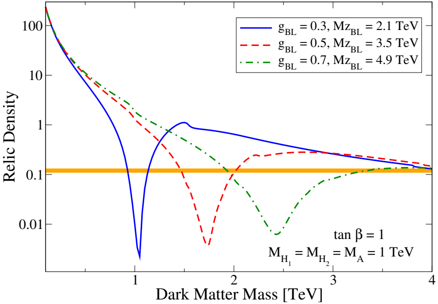
Lightest component is a stable dark matter candidate whose stability ensured automatically (for Case-3,4)

Dark Matter in new $B - L$ gauge Theory

★ Additional fermions form two Dirac fermions and the lightest of them becomes Dark Matter candidate ψ_D

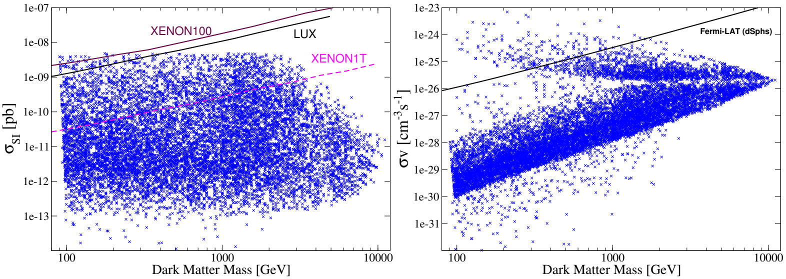
$$-\frac{g_{BL}}{3}\left[\overline{\psi_D}\gamma^\mu\left\{\left(3\cos^2\theta_L+1\right)P_L-2P_R\right\}\psi_D+\cdots\right]Z'_\mu\,.$$





SP, Yaguna, Rodejohann; JHEP 1609 (2016) 076

Direct and Indirect experimental constraints



1. Dark Matter particles may self annihilate to produce a flux of gamma rays, cosmic rays, neutrinos, antimatter which can appear as an excess over the expected background.
2. Since the presence of dark matter in our galaxy is referred through its gravitational effects, **Direct detection** experiments hope to observe dark matter scattering off nuclei targets which are placed in underground laboratories.

Left-Right symmetry and Gauge Anomalies

SP; PRD (2016), arXiv:1512.04739

1. **Gauge Group:** $SU(2)_L \times SU(2)_R \times U(1)_B \times U(1)_L$
2. **Usual quarks and leptons:**

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [2, 1, 1/3, 0]\,, \; q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [1, 2, 1/3, 0]\,,$$
$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \equiv [2, 1, 0, 1]\,, \quad \ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \equiv [1, 2, 0, 1]\,.$$

3. **Non-trivial Triangle Anomalies**

$$\mathcal{A}\left[SU(2)_L^2 \times U(1)_B\right] = 3/2\,, \qquad \mathcal{A}\left[SU(2)_R^2 \times U(1)_B\right] = -3/2\,,$$
$$\mathcal{A}\left[SU(2)_L^2 \times U(1)_L\right] = 3/2\,, \qquad \mathcal{A}\left[SU(2)_R^2 \times U(1)_L\right] = -3/2\,,$$

Gauge Anomaly cancelation and Dark Matter

SP; PRD (2016), arXiv:1512.04739

1. **Simplest way to cancel a gauge anomaly is to include the fermion triplets $\Sigma_L \oplus \Sigma_R$**

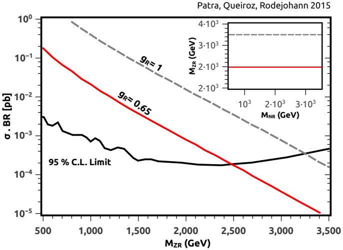
$$\Sigma_L = \begin{pmatrix} \Sigma^0_{L,R} & \sqrt{2}\Sigma^+_{L,R} \\ \sqrt{2}\Sigma^-_{L,R} & -\Sigma^0_{L,R} \end{pmatrix}, \quad \Sigma_R = \begin{pmatrix} \Sigma^0_{R} & \sqrt{2}\Sigma^+_{R} \\ \sqrt{2}\Sigma^-_{R} & -\Sigma^0_{R} \end{pmatrix},$$

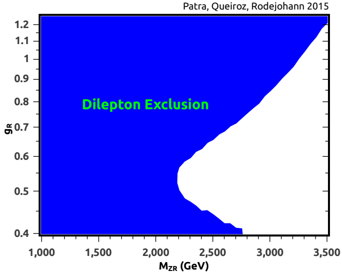
2. **The motivation behind introducing fermion triplets is twofold:**
   - It cancels a nontrivial gauge anomaly making the Left-Right symmetric models anomaly-free theories.
   - The neutral component of these fermion triplets can be stable cold dark matter where the stability is ensured automatically.

LHC bound on $M_{Z'}$ and Dark Matter

SP, **Quirez, Rodejohann; PLB 2015**, arXiv:1506.03456

★ Dileptons searches provides bound on M_{Z_R} using 20.3fb^{-1} ATLAS data





★ The effect of the mass and couplings of the DM particle on the dilepton/dijet bounds is indirect.

★ For a fixed Z' mass, the branching ratio Br.$(Z' \to \ell^+\ell^-)$ increases as $M_{\rm DM}$ approaches $M_{Z'}/2$.

Minimal Left-Right Dark Matter

Heeck, SP; Phys. Rev. Lett. (2015), arXiv:1507.01584

1. Easily accommodate stable TeV-scale dark matter particles.
2. The stability of a newly introduced multiplet arises
   - either accidentally as in the Minimal Dark Matter framework
   - or comes courtesy of the remaining unbroken $\mathbb{Z}_2$ subgroup of $B-L$
3. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (2,1,-1)\,, \qquad \ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \sim (1,2,-1)\,,$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (2,1,1/3), \qquad q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \sim (1,2,1/3)\,,$$

4. Spontaneous symmetry breaking implemented with Higgs triplets $\Delta_R \simeq (1,3,2)$, $\Delta_L \simeq (3,1,2)$ and Bidoublet $\Phi \simeq (2,2,0)$

Matter Parity and stability of Dark Matter

Fields	Lorentz Group	$U(1)_{3(B-L)}$
Quarks q_L and q_R	Fermionic	1
Leptons ℓ_L and ℓ_R	Fermionic	-3
Φ	Scalar	0
$\Delta_{L,R}$	Scalar	6

★ If a $U(1)$ gauge symmetry is spontaneously broken down by a scalar field with charge n under that symmetry, a discrete Z_n symmetry automatically arises in the Lagrangian.

Krauss and Wilzeck 1989

★ Since Δ_R breaks LRSM to SM, we have $Z_6 \simeq Z_2 \times Z_3$.

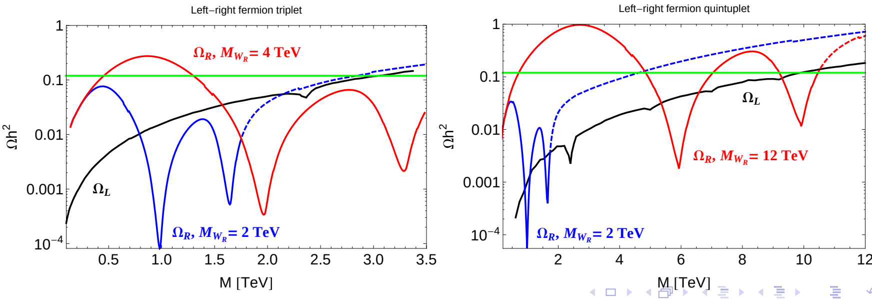
$$\mathbf{Z_2 \simeq (-1)^{3(B-L)}} = \begin{cases} -1 & \text{for fermions} \\ 1 & \text{for bosons} \end{cases}$$

Neutral Fermions as Dark Matter: Examples

- Remarkable Consequences:
  - lightest fermion with an even $3(B-L)$ charge would be stable
  - lightest bososn with odd $3(B-L)$ charge would be stable
- Chiral Fermionic multiplets:
  - $(2j_1+1, j_2+1, 0) \oplus (2j_2+1, 2j_1+1, 0)$
  - Bi-multiplet structure $\psi \sim (\mathbf{2\ j{+}1}, \mathbf{2\ j{+}1}, 0)$

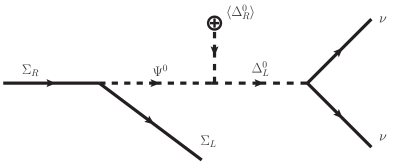
$$j_{1,2}, j \in \mathbb{N}.$$

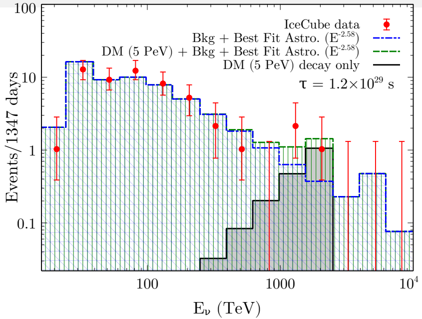
- Example: Triplet and Quintuplet Dark Matter



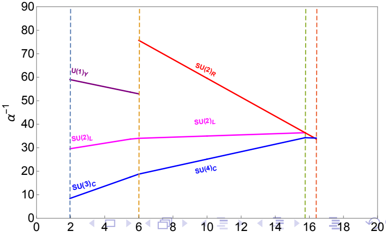
Neutrino DM Decay for IceCube data

Borah, Dasgupta, Dey, SP, Tomar; arXiv:1704.04138





- PeV scale Neutrino Dark Matter decay with life time 10^{29} sec.
- Embedded the PeV scale framework within unified GUT model.



Summary

- ★ **Neutrino (sterile): being electrically neutral can be a viable dark matter candidate**
- ★ Gauge theory of leptons and baryons where induced triangle gauge anomaly cancelation require additional neutrinos can be viable dark matter candidate
- ★ **Neutrino Dark Matter Decay**: Explanation of ultra high energy IceCube events
- ★ **Neutrinos May be useful candle to light up the Darkness of the universe**