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Left-Right Cosmology with spontaneous D-parity breaking

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Predictive Model for DM, DE Neutrino Masses and Leptogenesis at the TeV Scale

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Standard Model and Beyond...

Standard Model constitutes the fundamental matters of nature, which can be accounted for 4% (roughly) of the total energy budget of the Universe.

However, it doesn't have any explanation for the origin of matter constituents.

It is silent about the remaining 96% (roughly) of the total energy budget of the Universe:

Dark Matter (DM) $\simeq 23\%$

Dark Energy (DE) $\simeq 73\%$

Neutrino $\leq 0.76\%$

Thus SM requires extension to include DM, DE and Neutrino masses for which we have strong evidences.

Neutrino masses in extension of SM

Out of two $SU(2)_L$ doublets: $\ell(Y=-1)$ and $\phi(Y=+1)$, an $SU(2)_L \times U(1)_Y$ singlet can be constructed as follows:

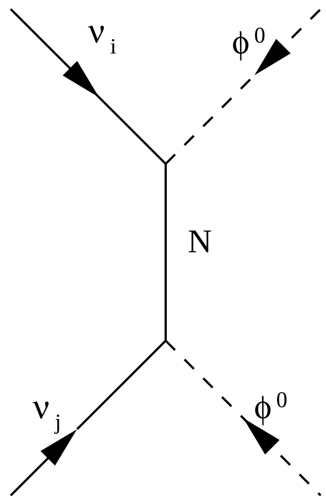
$$2 \otimes \bar{2} = 3 \oplus 1$$

Case-I: Canonical Seesaw

Let us add a singlet (or triplet) right handed neutrino (N_R) with $Y=0$ to the SM. The Corresponding Lagrangian will be

$$-\mathcal{L}_{N_R} \supseteq \frac{1}{2}(M_R)_{ij}\overline{(N_{iR})^c}N_{jR} + h_{ij}\overline{\ell_{iL}}\phi N_{jR} + h.c.$$

Where $\ell \longrightarrow$ lepton doublet and $\phi \longrightarrow$ Higgs doublet.



The type-I seesaw then gives

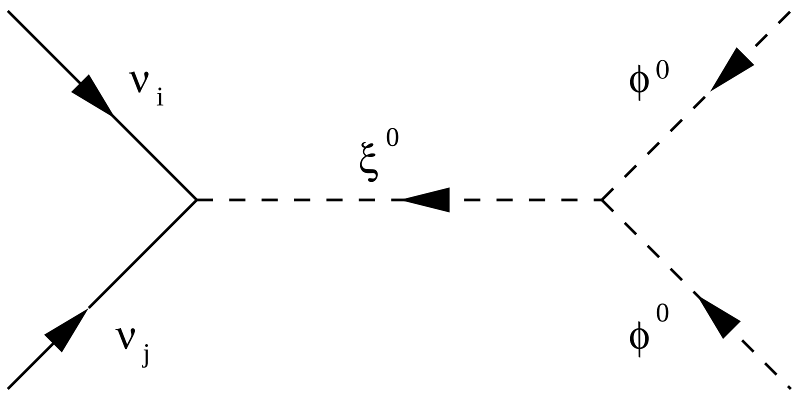
$$m_\nu^I = -h\left(\frac{\langle\phi\rangle^2}{M_R}\right)h^T$$

For $M_R \simeq \mathcal{O}(10^9) - \mathcal{O}(10^{15})$ **GeV one can get sub-eV neutrino masses with** $h \simeq \mathcal{O}(10^{-3}) - \mathcal{O}(1)$**.**

Case-2: Triplet Seesaw

Let us add a triplet scalar ξ with $Y = 2$ to the SM. The corresponding Lagrangian will be

$$-\mathcal{L}_\xi \supseteq M_\xi^2(\xi^\dagger \xi) + f_{ij}\xi \ell_i \ell_j + \mu \xi^\dagger \phi\phi + h.c.$$



The type-II seesaw then gives

$$m_\nu^{II} = f\langle\xi\rangle = -f\mu\left(\frac{\langle\phi\rangle^2}{M_\xi^2}\right)$$

For $\mu \sim M_\xi \simeq \mathcal{O}(10^9)$ **GeV -** $\mathcal{O}(10^{15})$ **GeV one can get sub-eV neutrino masses with**

$$f \simeq \mathcal{O}(10^{-3}) - \mathcal{O}(1)$$

.

Lepton number violation

$$N_j \rightarrow \left\{ \begin{array}{cc} \overline{\ell_i} & \phi \\ \ell_i & \phi^\dagger \end{array} \right\} \rightarrow \Delta L = 2 \;\; through \;\; h_{ij}$$

$$\xi \rightarrow \left\{ \begin{array}{c} \ell_i \ell_j \\ \phi\phi \end{array} \right\} \rightarrow \Delta L = 2 \;\; through \;\; f_{ij}, \mu$$

If the decay of N and ξ additionally satisfy (i) C and CP violation, and (ii) Out-of-thermal equilibrium, then a net lepton asymmetry can be generated (assuming that CPT is conserved).

Note: The same coupling gives neutrino masses as well as lepton asymmetry.

Minimum scale of L-number violation

We saw that neutrino masses are suppressed by the scale of lepton number violation, i.e., the mass scale of right handed neutrino or the mass scale of triplet scalar.

Given the L-violation channel, what should be the minimum mass scale of L-violation so that one can get both neutrino masses as well as lepton asymmetry ?

This can be estimated by computing the CP-asymmetry in the respective channels. For example, let us consider:

$$N_j \rightarrow \left\{ \begin{array}{cc} \overline{\ell_i} & \phi \\ \ell_i & \phi^\dagger \end{array} \right\} \rightarrow \Delta L = 2 \;\; through \;\; h_{ij}$$

Fukugita and Yanagida, PLB, 1986

The amount of CP asymmetry in N_1 decay (assuming a normal hierarchy in the right handed neutrino sector) is given by,

$$\epsilon_1^{\mathbf{Lep}} \simeq \frac{\mathbf{3}}{\mathbf{16}\pi} \sum_{\mathbf{j=2,3}} \frac{\mathrm{Im}\left[(h^\dagger h)^2_{1j}\right]}{(h^\dagger h)_{11}} \left(\frac{M_1}{M_j}\right)$$

The maximum value of this CP asymmetry can be given as

$$\epsilon_1^{\mathbf{Lep}} \lesssim \epsilon_1^{\mathbf{max}} \simeq \frac{3M_1}{16\pi\langle\phi\rangle^2}\sqrt{\Delta m^2_{atm}}$$

Davidson and Ibarra, PLB, 2003

Buchmuller, Bari and Plumacher, NPB, 2003

See some conspiracy: Raidal, Strumia and Turzynski, PLB, 2005

The observed baryon asymmetry then gives a minimum scale of L-number violation to be

$$M_1 \gtrsim \mathcal{O}(10^9) GeV \left(\frac{n_B/n_\gamma}{6.15 \times 10^{-10}} \right) \left(\frac{10^{-3}}{\frac{n_{N1}}{s}\delta} \right) \left(\frac{\langle \phi \rangle}{174 GeV} \right)^2 \left(\frac{0.05 eV}{\sqrt{\Delta m^2_{atm}}} \right)$$

Similarly in the type-II seesaw one can maximize the CP-asymmetry and can get a minimum scale of L-number violation to be

$$\mathbf{M}_\xi \gtrsim \mathcal{O}(\mathbf{10^{10}})\mathbf{GeV} \cdots\cdots$$

Ma and Sarkar, PRL, 1998

Hambye and Senjanovic, PLB, 2004

Sahu and Sarkar, PRD, 2006

Summary...

Neutrino masses and leptogenesis can be realized in both singlet as well as triplet scenario.

If neutrino masses and leptogenesis originate from the same source of L-number violation ($\Delta L = 2$), then there is no hope to see their signature in collider, because their mass scales are far above the present collider energy scale.

What is next ?

Lessons from existing physics

There is no one-to-one correspondence between the parameters deciding the fate of neutrino masses and the paramters deciding the fate of leptogensis even though they originate from the same source of L-violation ($\Delta L = 2$).

$Model$	$Leptogenesis$	$Neutrino\ Masses$
$SM + 3N$	15	9
$SM + 2N$	9	8

Why, then, lepton asymmetry and neutrino masses should originate from same source of L-violation ($\Delta L = 2$) ?

We also want to have some collider signature...

Recipe

step-I: Add both singlets($Y = 0$) as well as triplets ($Y = 2$) to the SM.

step-II: Introduce a symmetry to make sure that L-number violation giving neutrino masses should not conflict with the L-number violation giving lepton asymmetry.

How to do that ?

Particle content in the proposed Model

$Purpose$	$Particles$	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_X$
$\nu - Mass$	Δ	$(1,3,2)$	0
	ξ	$(1,3,2)$	-2

$Purpose$	$Particles$	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_X$
$\mathsf{L} - asy$	S_a	$(1,1,0)$	0
	η^-	$(1,1,-2)$	1

$Purpose$	$Particles$	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_X$
$\mathsf{S}M fields$	ϕ	$(1,2,1)$	0
	ℓ_L	$(1,2,-1)$	1
	e_R	$(1,1,-2)$	1

$Purpose$	$Particles$	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_X$
$\mathrm{D}ark Matter$	χ	$(1, 2, 1)$	2

We also introduce an acceleron field $\mathcal{A}$ (for Dark Energy), whose origin is beyond the scope of this model.

The allowed Lagrangian symmetric under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$ is given by

$$
\begin{aligned}
-\mathcal{L} \supseteq\ & M_\xi^2(\xi^\dagger \xi) + f_{ij}\xi \ell_{iL}\ell_{jL} + M_\Delta^2(\Delta^\dagger \Delta) \\
& + \mu(\mathcal{A})\Delta^\dagger \phi\phi + h_{ia}\bar{e}_{iR} S_a \eta^- + M_{sab} S_a S_b \\
& + y_{ij}\phi \bar{\ell}_{iL} e_{jR} + h.c. \\
& + V(\phi, \chi, \eta) + \Lambda^4 \ln\left(\frac{\bar{\mu}}{\mu(\mathcal{A})}\right)
\end{aligned}
$$

Consequences...

No neutrino masses at the tree level, because ξ can not acquire a vev.

$\triangle$ can acquire a small vev for $M_\triangle \simeq \mathcal{O}(10^{10})$ GeV:

$$\langle \Delta \rangle = -\mu(\mathcal{A}) \frac{\langle \phi \rangle^2}{M_\triangle^2}$$

But it can not give neutrino masses, because it does not couple to neutrino.

L-number is exact in the scalar sector, which will give the Majoron problem.

What to do ?

Let us break the $U(1)_X$ symmetry, at TeV scale, to Z_2 by introducing soft terms:

$$-\mathcal{L}_{soft} = m_s^2 \Delta^\dagger \xi + m_\eta \eta^- \phi \chi + H.c.$$

where Z_2 symmetry works as follows:

$$\begin{array}{rcl} \eta^- & \longrightarrow & -\eta^- \\ \chi & \longrightarrow & -\chi \\ S & \longrightarrow & -S \end{array}$$

While all other particles, under Z_2, go to themselves.

(1) L-number is explicitly broken in the scalar sector $\longrightarrow$ No Majoron problem.

(2) Mixing between Δ and ξ $\longrightarrow$ Neutrino can get mass

(3) Surviving Z_2 symmetry $\longrightarrow$ The lightest neutral component of χ can be a candidate of dark matter

Neutrino Masses

The effective L-number violating coupling is then given by

$$-\mathcal{L}_{eff} = f_{ij}\xi\ell_i\ell_j + \mu(\mathcal{A})\frac{m_s^2}{M_\Delta^2}\xi^\dagger\phi\phi$$
$$+f_{ij}\frac{m_s^2}{M_\xi^2}\Delta\ell_i\ell_j + \mu(\mathcal{A})\Delta^\dagger\phi\phi + h.c.$$

The field ξ then acquires an induced VEV,

$$\langle\xi\rangle = \left(-\mu(\mathcal{A})\frac{\langle\phi\rangle^2}{M_\Delta^2}\right)\left(\frac{m_s^2}{M_\xi^2}\right)$$

The neutrino mass is then given by

$$m_\nu = f_{ij}\langle\xi\rangle = -f_{ij}\left(\mu(\mathcal{A})\frac{\langle\phi\rangle^2}{M_\Delta^2}\right)\left(\frac{m_s^2}{M_\xi^2}\right)$$

Consequences...

ξ and $\triangle$ can have different masses, but contribute equally to neutrino masses.

If $m_s \sim M_\xi \sim$ a few 100 GeV and $M_\triangle \sim 10^{10}$ GeV then m_ν can be in the sub-eV scale.

Therefore, the decay of ξ can be studied in the following channels:

$$\xi^{\pm\pm} \longrightarrow \left\{ \begin{array}{c} \ell^\pm \ell^\pm \\ h^\pm W^\pm \\ W^\pm W^\pm \end{array} \right.$$

Barenboim et.al. PLB. 1997; Huitu et.al. NPB. 1997

Ma, Raidal and Sarkar, NPB. 2001

Chun, Lee and Park, PLB. 2003

Singlet Leptogenesis

The decay of the singlet fermions S_a, $a = 1, 2, 3$ can generate a net lepton asymmetry at the TeV scale through

$$S_a \rightarrow \left\{ \begin{array}{cc} e^{-}_{iR} & \eta^{+} \\ e^{+}_{iR} & \eta^{-} \end{array} \right\} \rightarrow \Delta L = 2 \;\; through \;\; h_{ia}$$

If we assume a normal hierarchy in the singlet sector, then the out-of-equilibrium decay of lightest singlet, say S_1, occurs at

$$h^{(1)} \equiv \sqrt{(h^\dagger h)_{11}} \lesssim 8.4 \times 10^{-7} \sqrt{\frac{M_{S_1}}{10TeV}}$$

Note that the small couplings, required for out-of-equilibrium decay, will not affect the neutrino masses.

The interference of one loop and self-energy diagrams with the tree level diagram, in the decay of S_1, can produce a CP-asymmetry

$$\epsilon_1 \simeq \frac{3}{16\pi}\frac{\mathrm{Im}[(\mathbf{h}^{\dagger}\mathbf{h})^2_{12}]}{(\mathbf{h}^{\dagger}\mathbf{h})_{11}}\frac{M_{S_1}}{M_{S_2}}$$

The lepton asymmetry then can be estimated as

$$\mathbf{Y_L} \equiv \frac{n_L - n_{\bar{L}}}{s} = \epsilon_1 \left(\frac{n_{S1}}{s}\right)\kappa$$

where

$(n_{S_1}/s) \longrightarrow$ **number density of S_1 in a comoving volume**

$s = \frac{2\pi^2}{45} g_* T^3 \longrightarrow$ **entropy density**

$\kappa \longrightarrow$ **dilution factor**

A part of the L-asymmetry can be converted to B-asymmetry via the sphaleron processes which are in thermal equilibrium above the EW phase transition.

The required B-asymmetry, given by WMAP, is

$$\left(\frac{n_B}{n_\gamma}\right)_0 = 7\left(\frac{a}{1-a}\right) \mathbf{Y_L} = 6.15 \times 10^{-10}$$

This gives a constraint:

$$\mathbf{h}^{(2)} \equiv \sqrt{\left|\frac{\mathrm{I}m\left(h^\dagger h\right)^2_{12}}{(h^\dagger h)_{11}}\right|} \gtrsim \frac{8 \times 10^{-4}}{\sqrt{\kappa}} \sqrt{\frac{M_{S_2}}{M_{S_1}}}$$

$h^{(1)}$ **and** $h^{(2)}$ **combinely then satisfy**

$$\frac{h^{(1)}}{h^{(2)}} \lesssim 1.0 \times 10^{-3} \sqrt{\kappa} \sqrt{\frac{M_{S_1}}{10TeV} \frac{M_{S_1}}{M_{S_2}}}$$

Consequences...

A successful leptogenesis, at TeV scale, requires at least three orders of magnitude hierarchy in the Yukawa couplings.

The small Yukawa couplings in the singlet sector does not affect the neutrino masses.

"Singlet Leptogenesis" thus works for a wide range of paramters, without affecting the prediction for neutrino masses and collider signature.

See also Hambye, Frigerio and Ma, JCAP.2006

Dark matter

Let us write down the potential:

$$\begin{aligned} V(\phi,\chi) &= -\mu^2|\phi|^2 + m^2|\chi|^2 + \lambda_1|\phi|^4 + \lambda_2|\chi|^4 \\ &\quad +\lambda_3|\phi|^2|\chi|^2 + \lambda_4|\phi^\dagger\chi|^2 \end{aligned}$$

The above potential is invariant under Z_2, under which

$$\chi \rightarrow -\chi$$

The surviving Z_2 symmetry stabilizes the neutral component of χ and thus making it a candidate of Dark Matter.

Ma, PRD. 2006

For μ^2, m_χ^2, λ_1, $\lambda_2 > 0$, the minimum of the potential can be given as

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{and} \quad \langle\chi\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

The quantum fluctuations around the minimum then can be given as

$$\phi = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix} \quad \text{and} \quad \chi = \begin{pmatrix} \chi^+ \\ \frac{S+iA}{\sqrt{2}} \end{pmatrix}$$

The masses of S and A are then given as

$$\mathbf{m_S^2 = m_A^2 = m^2 + (\lambda_3 + \lambda_4)v^2}$$

Since S and A have gauge interactions, one additional constraint on the mass scale of S is:

$$m_S < M_W$$

This restricts the following catastrophic self annihilations:

$$SS \to W^+W^-, ZZ, hh$$

A pair of S, however, can be annihilated to $W^+W^-, ZZ, hh, \bar{f}f, \cdots$ through the exchange of h

The coannihilation $SA \to \bar{f}f$ through the exchange of Z is also allowed.

Small mass splitting is required in order to avoid large coannihilation. A small mass splitting may be generated through the loop correction.

Barbieri, Hall and Rychkov, PRD. 2006

Honrez, Nezri, Oliver and Tytgat, JCAP. 2007

Dark energy and Neutrino masses

Mass Varying Neutrinos (MaVaNs) can behave as a negative pressure fluid which could be the origin of cosmic acceleration.

Let's postulate m_ν to be a dynamical field, i.e., m_ν depends on a scalar field $\mathcal{A}$ and $\partial m_\nu / \partial \mathcal{A} \neq 0$.

$$
\begin{aligned}
-\mathcal{L}_{DE} &= f_{ij}\mu(\mathcal{A})\frac{v^2 m_s^2}{M_\xi^2 M_\Delta^2}\nu_i\nu_j + h.c. + \Lambda^4 \ln\left(|\mu_0/\mu(\mathcal{A})|\right) \\
&= m_\nu n_\nu + V_0(m_\nu) \equiv V(m_\nu)
\end{aligned}
$$

Gu, Wang and Zhang, PRD. 2003

Fardon, Nelson and Weiner, JCAP. 2004

Ma and Sarkar, PLB, 2006; Wetterich, arXiv:0706.4427

As the universe expands, the background neutrino density decreases and hence the neutrino mass increases (Why ? See below). This drives V_0 towards a non-zero, but small, positive value:

$$\mathbf{V_0 \simeq 10^{-12} eV^4 \to \Lambda \simeq 10^{-3} eV}$$

Eqn. of State for DE

At the minimum of the potential

$$\mathbf{V'(m_\nu) = n_\nu + V_0'(m_\nu) = 0}$$

Let us define:

$$\mathbf{w} + 1 = -\frac{\partial \ln V(m_\nu)}{3 \partial \ln R}$$

where R is the scale factor of expansion.

On substituting the value of $V(m_\nu)$ we can get

$$\mathbf{w+1} = \frac{\Omega_\nu}{\Omega_\nu + \Omega_A} = -\frac{m_\nu V_0'(m_\nu)}{V(m_\nu)}$$

Since $\Omega_\nu \ll \Omega_A$, V_0 is required to be flat. Thus one gets

$$\mathbf{w \simeq -1}$$

which is required for Dark Energy.

For small (dw/dn_ν), one will get

$$\begin{aligned} m_\nu &\propto n_\nu^w \\ &\propto \frac{1}{n_\nu} \end{aligned}$$

This implies that neutrino mass increases for decreasing number density, thus keeping ρ_ν constant.

Summary and Conclusions

We proposed “singlet leptogenesis” which works at TeV scales.

The model has a characteristic that the origin of neutrino masses is independent of leptogenesis.

The model could, therefore, be extended to explain the dark matter of the Universe.

If neutrino mass varies with the cosmological time scale then it also explains the origin of dark energy.

The model predicts a few hundred GeV triplet scalar whose same sign dilepton decay can be studied at LHC/ILC.