Flowering to bloom and bloom to gloom of PeV scale supersymmetric left-right symmetric models

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- Parity violation could be of dynamical origin
- See saw mechanism generically suggests an M_R scale considerably smaller than the scale of coupling constant unification
- It is appealing to look for left-right symmetry

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- ν_R state to form a doublet with e_R under the new $SU(2)_R$

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- Demand identical gauge charges $g_L = g_R$.
- the minimal extension of the SM Higgs is to a bidoublet $\Phi \to u_L^\dagger \Phi u_R$

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- Could the new symmetries appear at energy **Just Beyond the Standard Model** (JBSM)?

Minimal SUSY L-R Model – MSLRM

The minimal set of Higgs superfields required is,

$$\begin{aligned} \Phi_i &= (1,2,2,0), & i &= 1,2, \\ \Delta &= (1,3,1,2), & \bar{\Delta} &= (1,3,1,-2), \\ \Delta_c &= (1,1,3,-2), & \bar{\Delta}_c &= (1,1,3,2), \end{aligned} \tag{1}$$

where the bidoublet is doubled so that the model has non-vanishing Cabibo-Kobayashi-Maskawa matrix. The number of triplets is doubled to have anomaly cancellation.
Under discrete parity symmetry the fields are prescribed to transform as,

$$\begin{aligned} Q &\leftrightarrow Q_c^*, & L &\leftrightarrow L_c^*, & \Phi_i &\leftrightarrow \Phi_i^\dagger, \\ \Delta &\leftrightarrow \Delta_c^*, & \bar{\Delta} &\leftrightarrow \bar{\Delta}_c^*, & \Omega &\leftrightarrow \Omega_c^*. \end{aligned} \tag{2}$$

MSLRM - more Higgs fields

Supersymmetry is too restrictive to allow spontaneous parity breaking

- In non-supersymmtric version, the scalar potential has quartic terms respecting $L \leftrightarrow R$

$$V \sim \rho(Tr\Delta_R^\dagger\Delta_R)^2 + \rho(Tr\Delta_L^\dagger\Delta_L)^2 + \beta Tr\Delta_R^\dagger\Delta_R Tr\Delta_L^\dagger\Delta_L$$

- We get extremum at $(\Delta_L, \Delta_R) = (v, 0)$ and an equivalent one at $(\Delta_L, \Delta_R) = (0, v)$, separated by an extremum along the line $\Delta_L = \Delta_R$.

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- From available quadratic terms, the D terms make charge breaking vacua more favorable than charge preserving ones.

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- All of these are dangerous terms and supersymmetry forbids them.
- From available quadratic terms, the D terms make charge breaking vacua more favorable than charge preserving ones.

It seems difficult to break parity spontaneously.

Spontaneous parity breaking, preserving electromagnetic charge invariance, and retaining R parity, ...
... can all be achieved by introducing two new triplet Higgs fields with the following charges.

$$\Omega = (1,3,1,0), \qquad \Omega_c = (1,1,3,0) \tag{3}$$

The F-flatness and D-flatness conditions lead to the following set of vev's for the Higgs fields as one of the possibilities,

$$\langle\Omega_c\rangle = \begin{pmatrix} \omega_c & 0 \\ 0 & -\omega_c \end{pmatrix}, \qquad \langle\Delta_c\rangle = \begin{pmatrix} 0 & 0 \\ d_c & 0 \end{pmatrix}, \tag{4}$$

This ensures spontaneous parity violation [Aulakh, Bajc, Melfo, Rasin, Senjanovic (1998 ...)]

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- This means Leptogenesis is postponed to a lower energy scale closer to M_{EW}.
- Low scale violation of $B-L$ natural, not a high scale like $10^9 - 10^{14}$ GeV

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Domain walls must disappear and leave behind enough entropy to create thermal equilibrium at 10 MeV
Senjanovic and Rai (1992); Preskill Trivedi Wilczek Wise (1991); Kawasaki, Takahashi PLB (2005)

$$\delta V \equiv |V_L^{\text{eff}} - V_R^{\text{eff}}| \propto T_D^4 \gtrsim (1 Mev)^4$$

Models of wall evolution

For the theory of a generic neutral scalar field ϕ, the effective higher dimensional operators can be written as

$$V_{eff} = \frac{C_5}{M_{Pl}}\phi^5 + \frac{C_6}{M_{Pl}^2}\phi^6 + \dots \tag{5}$$

But this is only instructional because in realistic theories, the structure and effectiveness of such terms is conditioned by

- Gauge invariance and supersymmetry
- Presence of several scalar species
- The dynamics of domain walls

Domain wall dynamics in radiation dominated phase

[Kibble; Vilenkin]

The dynamics of the walls is determined by two quantities :

- Tension force $f_T \sim \sigma/R$, where σ is energy per unit area and R is the average scale of radius of curvature
- Friction force $f_F \sim \beta T^4$ for walls moving with speed β in a medium of temperature T.

The two get balanced at time $t_R \sim R/\beta$ being the time scale by which the wall portions that started with radius of curvature scale R straighten out.

Scaling law for the growth of the scale $R(t)$ on which the wall complex is smoothed out.

$$R(t) \approx (G\sigma)^{1/2} t^{3/2} \tag{6}$$

Now the energy density of the domain walls goes as $\rho_W \sim (\sigma R^2/R^3) \sim (\sigma/Gt^3)^{1/2}$. In radiation dominated era this ρ_W becomes comparable to the energy density of the Universe ($\rho \sim 1/(Gt^2)$) around time $t_0 \sim 1/(G\sigma)$.

Next, we consider destabilization of walls due to pressure difference $\delta\rho$ arising from small asymmetry in the conditions on the two sides. This effect competes with the two quantities mentioned above. Since $f_F \sim 1/(Gt^2)$ and $f_T \sim (\sigma/(Gt^3))^{1/2}$, it is clear that at some point of time, $\delta\rho$ would exceed either the force due to tension or the force due to friction. For either of these requirements to be satisfied before $t_0 \sim 1/(G\sigma)$ we get

$$\delta\rho \geq G\sigma^2 \approx \frac{M_R^6}{M_{Pl}^2} \sim M_R^4 \frac{M_R^2}{M_{Pl}^2} \tag{7}$$

We may read this formula by defining a factor

$$\mathcal{F} \equiv \frac{\delta\rho}{M_R^4} \tag{8}$$

where M_R^4 is the energy density in the wall complex immediately at the phase transition, which relaxes by factor $\mathcal{F}$ at the epoch of their decay. The factor $\mathcal{F}$ is strongly dependent on the assumed model of evolution of the wall complex, and is found to be M_R^2/M_{Pl}^2 in this model.

Domain wall dynamics in a matter dominated phase

[Kawasaki and Takahashi(2004), Anjishnu Sarkar and UAY(2006)]
Assume the initial wall complex relaxes to roughly one wall per horizon at a Hubble value H_i with the initial energy density in the wall complex $\rho_W^{(in)} \sim \sigma H_i$
Let the temperature at which the domain walls are formed be $T \sim \sigma^{1/3}$. So

$$H_i^2 = \frac{8\pi}{3} G \sigma^{\frac{4}{3}} \sim \frac{\sigma^{\frac{4}{3}}}{M_{Pl}^2} \tag{9}$$

From Eq.(**??**) we get,

$$T_D^4 \sim \frac{\sigma^{11/6}}{M_{Pl}^{3/2}} \sim \frac{M_R^{11/2}}{M_{Pl}^{3/2}} \sim M_R^4 \left(\frac{M_R}{M_{Pl}}\right)^{3/2} \tag{10}$$

Now requiring $\delta\rho > T_D^4$ we get,

$$\delta\rho > M_R^4 \left(\frac{M_R}{M_{Pl}}\right)^{3/2} \tag{11}$$

Thus in this case we find $\mathcal{F} \equiv (M_R/M_{Pl})^{3/2}$, a milder suppression factor than in the radiation dominated case above..

Parity breaking from Planck suppressed effects

Unlike the renormalizable soft terms and their potential origin in the hidden sector, here we look for the parity breaking operators to arise at Planck scale.
Several caveats :

- However, the structure of supergravity ensures that at the renormalisable level gravity couples separately to the left sector and right sector with no mixing terms.
- It is very difficult to see how gravitational instanton effects will necessarily impact this discrete symmetry
- Thus effectivley we have to assume an unknown reason for absence of parity or its spontaneous breaking in the hidden sector, communicated by gravity.
- Regardless of their origin, the structure of the symmetry breaking terms in the scalar potential will be the same as what can be derived from the Kahler potential formalism

Planck scale terms in ABMRS model

$$V^R_{eff} \sim \frac{a(c_R + d_R)}{M_{Pl}} M_R^4 M_W + \frac{a(a_R + d_R)}{M_{Pl}} M_R^3 M_W^2$$

and likewise $R \leftrightarrow L$. Hence,

$$\delta\rho \sim \kappa^A \frac{M_R^4 M_W}{M_{Pl}} + \kappa'^A \frac{M_R^3 M_W^2}{M_{Pl}}$$

$$\kappa^A_{RD} > 10^{-10} \left(\frac{M_R}{10^6 \mathrm{GeV}} \right)^2$$

For M_R scale tuned to 10^9GeV needed to avoid gravitino problem after reheating at the end of inflation, $\kappa_{RD} \sim 10^{-4}$, a reasonable constraint. but requires κ^A_{RD} to be $O(1)$ if the scale of M_R is an intermediate scale 10^{11}GeV.

$$\kappa^A_{MD} > 10^{-2}\left(\frac{M_R}{10^6\mathrm{GeV}}\right)^{3/2},$$

which seems to be a modest requirement, but taking $M_R \sim 10^9$GeV being the temperature scale required to have thermal leptogenesis without the undesirable gravitino production, leads to $\kappa_{MD} > 10^{5/2}$.

$$\kappa^A_{WI} > 10^{-4}\left(\frac{10^6\mathrm{GeV}}{M_R}\right)^{15}\left(\frac{T_D}{10\mathrm{GeV}}\right)^{12},$$

This makes the model rather strongly predictive. For example if $T_D \sim 10^4$GeV, then M_R is forced to be closer to the gravitino scale 10^9Gev.

$\not{P}$ from soft SUSY breaking terms

In the minimal SUSY L-R model introduced above, consider soft terms

$$\begin{aligned}\mathcal{L}^1_{soft} &= m_1^2\mathrm{Tr}(\Delta\Delta^\dagger) + m_2^2\mathrm{Tr}(\bar{\Delta}\bar{\Delta}^\dagger) \\ &\quad + m_3^2\mathrm{Tr}(\Delta_c\Delta_c^\dagger) + m_4^2\mathrm{Tr}(\bar{\Delta}_c\bar{\Delta}_c^\dagger) \qquad (12)\end{aligned}$$

$$\begin{aligned}\mathcal{L}^2_{soft} &= \alpha_1\mathrm{Tr}(\Delta\Omega\Delta^\dagger) + \alpha_2\mathrm{Tr}(\bar{\Delta}\Omega\bar{\Delta}^\dagger) \\ &\quad + \alpha_3\mathrm{Tr}(\Delta_c\Omega_c\Delta_c^\dagger) + \alpha_4\mathrm{Tr}(\bar{\Delta}_c\Omega_c\bar{\Delta}_c^\dagger) \qquad (13)\end{aligned}$$

$$\mathcal{L}^3_{soft} = \beta_1\mathrm{Tr}(\Omega\Omega^\dagger) + \beta_2\mathrm{Tr}(\Omega_c\Omega_c^\dagger) \qquad (14)$$

$$\mathcal{L}_{soft} = \mathcal{L}^1_{soft} + \mathcal{L}^2_{soft} + \mathcal{L}^3_{soft} \qquad (15)$$

T_D/GeV	$\sim$	10	10^2	10^3
$(m^2 - m^{2\prime})/\text{GeV}^2$	$\sim$	10^{-4}	1	10^4
$(\beta_1 - \beta_2)/\text{GeV}^2$	$\sim$	10^{-8}	10^{-4}	1

Table : Differences in values of soft supersymmetry breaking parameters for a range of domain wall decay temperature values T_D. The differences signify the extent of parity breaking.

We now look for a way to generate this difference in V^{eff} from SUSY breaking mechanism.

Gauge mediated SUSY breaking

Implement this idea by introducing two singlet fields X and X', respectively even and odd under parity.

$$X \leftrightarrow X, \qquad X' \leftrightarrow -X'. \tag{16}$$

The messenger sector superpotential then contains terms

$$\begin{aligned} W &= \lambda X \left(\Phi_L \bar{\Phi}_L + \Phi_R \bar{\Phi}_R\right) \\ &+ \lambda' X' \left(\Phi_L \bar{\Phi}_L - \Phi_R \bar{\Phi}_R\right) \end{aligned} \tag{17}$$

- Φ_L, $\bar{\Phi}_L$ and Φ_R, $\bar{\Phi}_R$ are complete representations of a simple gauge group embedding the L-R symmetry group.

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- Φ_L, $\bar{\Phi}_L$ and Φ_R, $\bar{\Phi}_R$ are complete representations of a simple gauge group embedding the L-R symmetry group.
- Require under parity

$$\Phi_L \leftrightarrow \Phi_R; \qquad \bar{\Phi}_L \leftrightarrow \bar{\Phi}_R$$

As a result of the dynamical SUSY breaking we expect the fields X and X' to develop nontrivial vev's and F terms and hence give rise to mass scales

$$\Lambda_X = \frac{\langle F_X \rangle}{\langle X \rangle}, \qquad \Lambda_{X'} = \frac{\langle F_{X'} \rangle}{\langle X' \rangle}. \tag{18}$$

Assume

$$\langle X \rangle \neq \langle X' \rangle \simeq M_{SUSY}$$

Now the messenger fermions receive respective mass contributions

$$\begin{aligned} m_{f_L} &= |\lambda \langle X \rangle + \lambda' \langle X' \rangle| \\ m_{f_R} &= |\lambda \langle X \rangle - \lambda' \langle X' \rangle| \end{aligned} \tag{19}$$

while the messenger scalars develop the masses

$$\begin{aligned} m^2_{\phi_L} &= |\lambda \langle X \rangle + \lambda' \langle X' \rangle|^2 \pm |\lambda \langle F_X \rangle + \lambda' \langle F_{X'} \rangle| \\ m^2_{\phi_R} &= |\lambda \langle X \rangle - \lambda' \langle X' \rangle|^2 \pm |\lambda \langle F_X \rangle - \lambda' \langle F_{X'} \rangle| \end{aligned} \tag{20}$$

We thus have both SUSY and parity breaking communicated through these particles.

The difference between the mass squared of the left and right sectors are obtained as

$$\begin{aligned}
\delta m_\Delta^2 &= 2\left[\left(\frac{\lambda\langle F_X\rangle + \lambda'\langle F_{X'}\rangle}{\lambda\langle X\rangle + \lambda'\langle X'\rangle}\right)^2 - \left(\frac{\lambda\langle F_X\rangle - \lambda'\langle F_{X'}\rangle}{\lambda\langle X\rangle - \lambda'\langle X'\rangle}\right)^2\right] \\
&\quad \times \left\{\left(\frac{\alpha_2}{4\pi}\right)^2 + \frac{6}{5}\left(\frac{\alpha_1}{4\pi}\right)^2\right\} \\
&= 2(\Lambda_X)^2\left[\left(\frac{1+\tan\gamma}{1+\tan\sigma}\right)^2 - \left(\frac{1-\tan\gamma}{1-\tan\sigma}\right)^2\right]\left\{\left(\frac{\alpha_2}{4\pi}\right)^2 + \frac{6}{5}\right. \\
&= 2(\Lambda_X)^2 f(\gamma,\sigma)\left\{\left(\frac{\alpha_2}{4\pi}\right)^2 + \frac{6}{5}\left(\frac{\alpha_1}{4\pi}\right)^2\right\}
\end{aligned}$$

where,

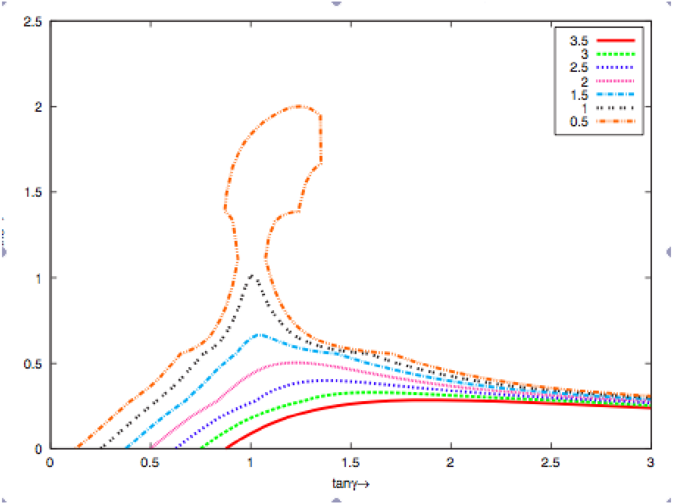
$$f(\gamma,\sigma) = \left(\frac{1+\tan\gamma}{1+\tan\sigma}\right)^2 - \left(\frac{1-\tan\gamma}{1-\tan\sigma}\right)^2 \tag{22}$$

We have brought Λ_X out as the representative mass scale and parameterised the ratio of mass scales by introducing

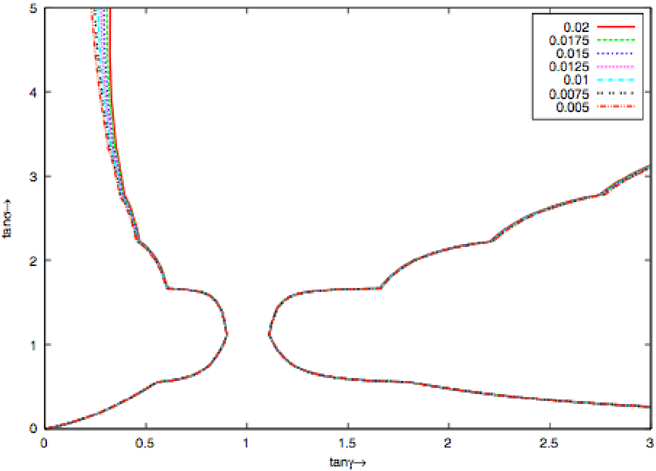
$$\tan\gamma = \frac{\lambda'\langle F_{X'}\rangle}{\lambda\langle F_X\rangle}, \quad \tan\sigma = \frac{\lambda'\langle X'\rangle}{\lambda\langle X\rangle} \tag{23}$$

T_D/GeV $\sim$	10	10^2	10^3
Adequate $(m^2 - m'^2)$	10^{-7}	10^{-3}	10
Adequate $(\beta_1 - \beta_2)$	10^{-11}	10^{-7}	10^{-3}

Table : Entries in this table are the values of the parameter $f(\gamma, \sigma)$, required to ensure wall disappearance at temperature T_D displayed in the header row. The table should be read in conjuction with table 1, with the rows corresponding to each other.



Contours of f corresponding to $m^2 - m'^2 = (2.15 \pm 1.5) \times 10^3$ $(GeV)^2$ in steps of $0.5 \times 10^3 (GeV)^2$. Substantial region of parameter space available.



Contours of f corresponding to $m^2 - m'^2 = (1.25 \pm 0.75) \times 10$ $(GeV)^2$ in steps of $0.15 \times 10(GeV)^2$. Note the extreme fine tuning needed.

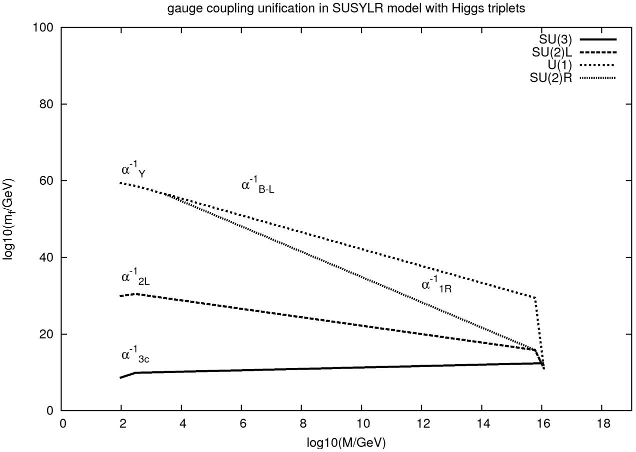
Guide to model building

- SUSY Left-Right can have parity breaking scale close to TeV scale

$$SU(2)_R \otimes U(1)_{B-L} \to U(1)_R \otimes U(1)_{B-L}$$

  (Aulakh, Bajc, Melfo, Senjanovic)
- Consistent cosmoloy of such models is possible. Small explicit parity breaking can be induced
  - by SUSY breaking communicating messengers (Anjishnu Sarkar, Sasmita Mishra and UAY (2009)
  - by Planck scale terms (Sasmita Mishra and UAY (2009)
- unification in $SO(10)$ can be achieved (Debasish Borah and UAY (2010))

Low $B - L$ and consistent unification



Metastable vacua

The dilemma of phenomenology with broken supersymmetry

- An R symmetry in the theory is required for SUSY breaking
- R symmetry is spontaneously broken leading to R-axions which are unacceptable
- If we give up R symmetry, the ground state remains supersymmetric

Solution : Break R symmetry mildly, governed by a small parameter ϵ.

- Supersymmetric vacuum persists, but this can be pushed far away in field space.
- Presence of the small breaking ensures SUSY breaking local minimum since the latter eixsts in the limit of $\epsilon \rightarrow 0$.
- Ensure that the metastable breaking is compatible with the age of the Universe

The Intrilligator-Seiberg-Shih realisation

- $N = 1$ SQCD with a low energy theory referred to as the "macroscopic" or "free magnetic theory" which is IR free.
- The high energy theory is known as the "microscopic" or "free electric theory" and it is $SU(N_c)$ SQCD which is UV free
- Seiberg duality says, $SU(N_c)$ SQCD (UV free) with $N_f(> N_c)$ flavors of quarks is dual to a $SU(N_f - N_c)$ gauge theory (IR free) with N_f^2 singlet mesons M and N_f flavors of quarks $q, \tilde{q}$

The tree-level superpotential of the macroscopic theory with squarks ϕ and mesons Φ is

$$W = h\mathrm{Tr}\left[\varphi\Phi\tilde{\varphi}\right] - h\mu^2\mathrm{Tr}\Phi. \tag{24}$$

Minimizing the above superpotential gives rise to the supersymmetric minima at

$$\langle hM \rangle = \Lambda_m \epsilon^{2N/(N_f-N)} \mathbf{1}_{N_f} = \mu \frac{1}{\epsilon^{(N_f-3N)/(N_f-N)}} \mathbf{1}_{N_f} \tag{25}$$

where $\epsilon \equiv \frac{\mu}{\Lambda_m}$.
While SUSY breaking is ensured by a rank condition ensuring R parity breaking, the energy of this vacuum is given by

$$V_{\rm meta} = |h\mu^2|^2 (N_f - N) > 0, \tag{26}$$

Left-Right symmetric theory with ISS mechanism

The particle content of the electric theory is

$$Q^a_L \sim (3,1,2,1,1), \quad \tilde{Q}^a_L \sim (3^*,1,2,1,-1)$$

$$Q^a_R \sim (1,3,1,2,-1), \quad \tilde{Q}^a_R \sim (1,3^*,1,2,1)$$

where $a = 1, N_f$ with the gauge group G_{33221}. This SQCD has $N_c = 3$, and we need $N_f \geq 4$.
For $N_f = 4$ the dual magnetic theory has Left Right gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and the following particle content

$$\phi_L^a(2,1,-1), \quad \tilde{\phi}_L^a(2,1,1)$$

$$\phi_R^a(1,2,1), \quad \tilde{\phi}_R^a(1,2,-1)$$

$$\Phi_L \equiv \mathbf{1} + \mathrm{Adj}_{\mathbf{L}} = \begin{pmatrix} \frac{1}{\sqrt{2}}(S_L + \delta_L^0) & \delta_L^+ \\ \delta_L^- & \frac{1}{\sqrt{2}}(S_L - \delta_L^0) \end{pmatrix}$$

$$\Phi_R \equiv \mathbf{1} + \mathrm{Adj}_{\mathbf{R}} = \begin{pmatrix} \frac{1}{\sqrt{2}}(S_R + \delta_R^0) & \delta_R^+ \\ \delta_R^- & \frac{1}{\sqrt{2}}(S_R - \delta_R^0) \end{pmatrix} \quad (27)$$

The Left-Right symmetric renormalizable superpotential of this magnetic theory is

$$W^0_{LR} = h\mathrm{Tr}\phi_L\Phi_L\tilde{\phi}_L - h\mu^2\mathrm{Tr}\Phi_L + h\mathrm{Tr}\phi_R\Phi_R\tilde{\phi}_R - h\mu^2\mathrm{Tr}\Phi_R \quad (28)$$

The tree level Kähler potential is

$$K_0 = \mathrm{Tr}\phi^\dagger_L\phi_L + \mathrm{Tr}\tilde{\phi}^\dagger_L\tilde{\phi}_L + \mathrm{Tr}\phi^\dagger_R\phi_R + \mathrm{Tr}\tilde{\phi}^\dagger_R\tilde{\phi}_R + \mathrm{Tr}\Phi^\dagger_L\Phi_L + \mathrm{Tr}\Phi^\dagger_R\Phi_R \quad (29)$$

The non-zero F-terms giving rise to SUSY breaking are

$$F_{\Phi_L} = h\phi_L\tilde{\phi}_L - h\mu^2\delta_{ab} \qquad \mathrm{and} F_{\Phi_R} = h\phi_R\tilde{\phi}_R - h\mu^2\delta_{ab} \quad (30)$$

where $a, b = 1, 4$ here and SUSY is broken by rank condition [Dine and Nelson; Intriligator, Shih, Seiberg].

After integrating out the right handed chiral fields, the superpotential becomes

$$W_L^0 = h\mathrm{Tr}\phi_L\Phi_L\tilde{\phi}_L - h\mu^2\mathrm{Tr}\Phi_L + h^4\Lambda^{-1}\mathrm{det}\Phi_R - h\mu^2\mathrm{Tr}\Phi_R \quad (31)$$

which gives rise to SUSY preserving vacua at

$$\langle h\Phi_R\rangle = \Lambda_m\epsilon^{2/3} = \mu\frac{1}{\epsilon^{1/3}} \quad (32)$$

where $\epsilon = \frac{\mu}{\Lambda_m}$. Thus the right handed sector exists in a metastable SUSY breaking vacuum whereas the left handed sector is in a SUSY preserving vacuum breaking D-parity spontaneously.

Supersymmetry breaking in metastable vacua

we assume that the differences in the left and right sectors brought about by Λ_m suppressed operators are of the order $\frac{1}{M_{Pl}}$. We write the next to leading order terms allowed by the gauge symmetry in the superpotential as well as Kähler potential.

$$W^1_{LR} = \quad f_L \quad \frac{\mathrm{Tr}(\phi_L \Phi_L \tilde{\phi}_L)\mathrm{Tr}\Phi_L}{\Lambda_m} + f_R \frac{\mathrm{Tr}(\phi_R \Phi_R \tilde{\phi}_R)\mathrm{Tr}\Phi_R}{\Lambda_m} + \quad f'_L \frac{(\mathrm{Tr}\Phi_L)^4}{\Lambda_m} + f'_R \frac{(\mathrm{Tr}\Phi_R)^4}{\Lambda_m}$$

In the effective potential after the two sectors decouple, the terms of order $\frac{1}{\Lambda_m}$ are given by

$$V^1_R = \frac{h}{\Lambda_m} S_R[f_R(\phi^0_R \tilde{\phi}^0_R)^2 + f'_R \phi^0_R \tilde{\phi}^0_R S^2_R + (\delta^0_R - S_R)^2((\phi^0_R)^2 + (\tilde{\phi}^0_R)^2)]$$

Planck scale terms in metastable SUSY breaking model

The minimization conditions give $\phi\tilde{\phi} = \mu^2$ and $S^0 = -\delta^0$. Denoting $\langle\phi^0_R\rangle = \langle\tilde{\phi}^0_R\rangle = \mu$ and $\langle\delta^0_R\rangle = -\langle S^0_R\rangle = M_R$, we have

$$V^1_R = \frac{hf_R}{\Lambda_m}(|\mu|^4 M_R + |\mu|^2 M_R^3) \tag{33}$$

where we have also assumed $f'_R \approx f_R$. For $|\mu| < M_R$ Thus the effective energy density difference between the two types of vacua is

$$\delta\rho \sim h(f_R - f_L)\frac{|\mu|^2 M_R^3}{\Lambda_m} \tag{34}$$

Cosmological constraint

Thus for walls diasappearing in matter dominated era, we get

$$M_R < |\mu|^{5/9} M_{Pl}^{4/9} \tag{35}$$

with $\mu \sim$Tev,

$$M_R < 1.3 \times 10^{10} \text{ GeV} \tag{36}$$

Similarly for the walls disappearing in radition dominated era,

$$M_R < |\mu|^{10/21} M_{Pl}^{11/21}; \tag{37}$$

$$M_R < 10^{11} \text{ GeV} \tag{38}$$

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- Cosmology with spontaneous parity violation provides substantial quantititive inputs on construction of JBSM.