Right handed symmetry at a low scale

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Overview

- Issues with thermal leptogensis
- Parity symmetric world at PeV scale –> SUSY L-R
- Successful non-thermal Leptogenesis in SUSY L-R
- Linking SUSY breaking and L-R Parity breaking in GMSB
- Excited leptons in left-right symmetric case

Genesis of baryogenesis

- CP violation discovery 1964
- CMBR discovery also 1965 ...
- The possibility of *explaining* baryon asymmetry

$$\frac{n_B}{s} \cong 10^{-9}$$

- Weinberg Brandeis lectures 1965; specific model Sakharov 1967

GUT scale baryogenesis

(Sakharov 1967; Yoshimura; Weinberg 1978)

1. There should exist baryon number B violating interaction

$$\begin{aligned} X \;\rightarrow\; & qq \qquad \Delta B_1 = \frac{2}{3} \\ & \bar{q}\bar{l} \qquad \Delta B_2 = -\frac{1}{3} \end{aligned}$$

2. Charge conjugation C must be violated

$$\mathcal{M}(X \rightarrow qq) \neq \mathcal{M}(\bar{X} \rightarrow \bar{q}\bar{q})$$

3. CP violation

$$r_1 = \frac{\Gamma(X \rightarrow qq)}{\Gamma_1 + \Gamma_2} \neq \frac{\bar{\Gamma}(\bar{X} \rightarrow \bar{q}\bar{q})}{\bar{\Gamma}_1 + \bar{\Gamma}_2} = \bar{r}_1$$

4. Out of equilibrium conditions
   Reverse reactions don't get the time to reverse the products

Net baryon asymmetry

$$
\begin{aligned}
B &= \Delta B_1 r_1 + \Delta B_2(1 - r_1) \\
&\quad + (-\Delta B_1)\bar{r}_1 + (-\Delta B_2)(1 - \bar{r}_1) \\
&= (\Delta B_1 - \Delta B_2)(r_1 - \bar{r}_1)
\end{aligned}
$$

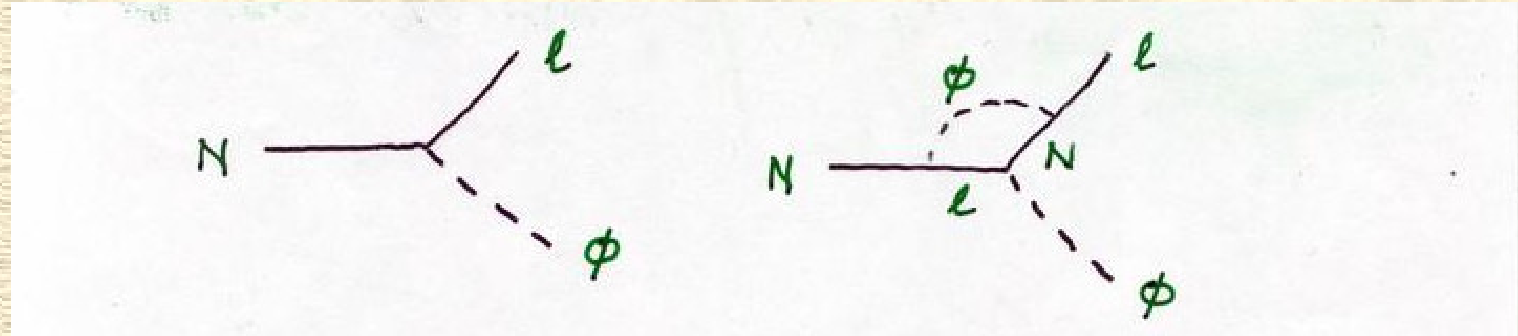
- GUTs generically involve new gauge forces which mediate B violation
- Higgs scalar interactions can be natural source of CP violation
- The Particle Physics rates and expansion rate of the Universe compete

$$
\Gamma_X \cong \alpha_X m_X^2 / T; \qquad H \cong g_*^{1/2} T^2 / M_{\mathrm{Pl}}
$$

Leptogenesis - thermal case

(Fukugita and Yanagida 1986)

- Out of equilibrium decay of heavy Majorana neutrinos

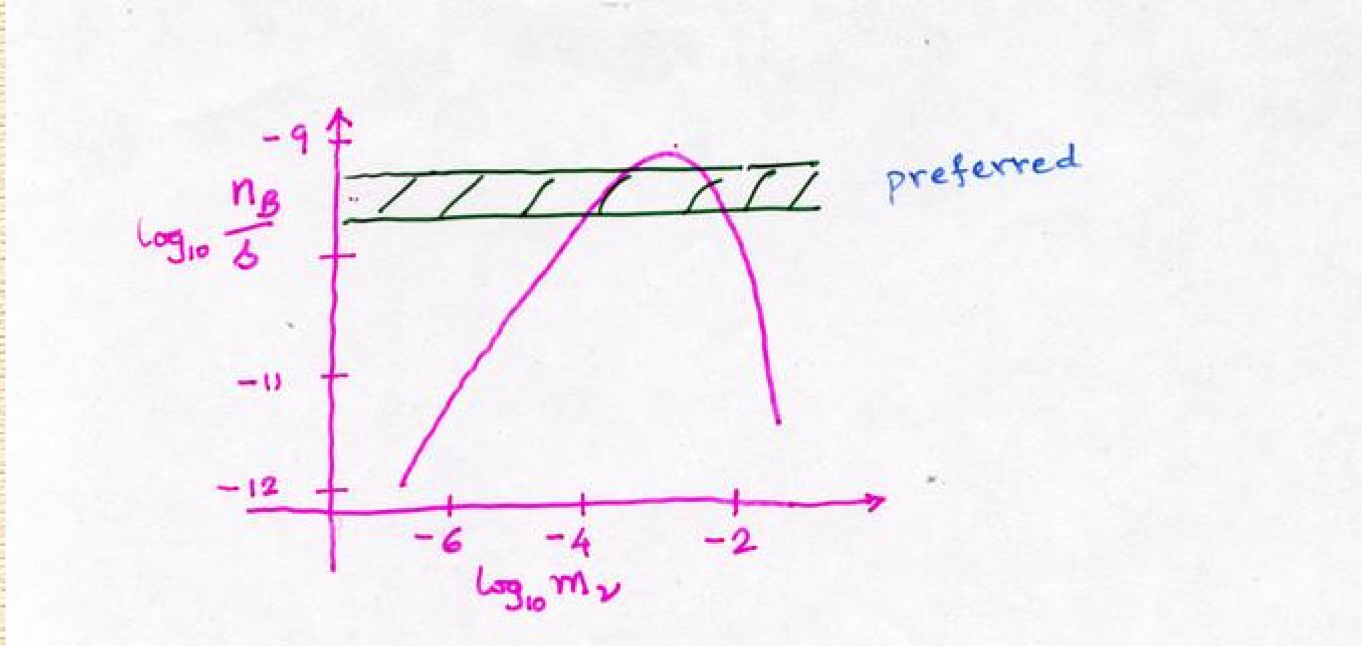


- Easy to arrange CP violation due to complex vacuum expectation values of scalar fields producing the mass

$$\frac{r-\bar{r}}{r} \sim \frac{1}{v^2 m_{_D}^2} \mathrm{Im}(m_{_D}^\dagger m_{_D})^2$$

- Need to have comparable, faster, expansion rate of the Universe

Thermal leprogenesis in SO(10) (Buchmuller, Di Bari, Plumacher)



m_ν too small : Yukawa couplings too small to bring heavy N into equilibrium
m_ν too large : Erasure processes too efficient

$$M_N \gtrsim O(10^9)\mathrm{GeV}\left(\frac{2.5\times 10^{-3}}{Y_N}\right)\left(\frac{0.05\mathrm{eV}}{m_\nu}\right)$$

$M_N \gtrsim 10^9$ GeV – does not sit well with hierarchy in non-SUSY case

– Tension with with SUSY unification gravitino overproduction

Mass and CP phase constraint

- Analysis of see-saw formula with three generations taken into account show, for thermal leptogenesis, (Davidson and Ibarra)

$$|\varepsilon_{CP}| \leqslant 10^{-7}\left(\frac{M_1}{10^9\mathrm{GeV}}\right)\left(\frac{m_3}{0.05\mathrm{eV}}\right)$$

- This can be too small for producing the asymmetry

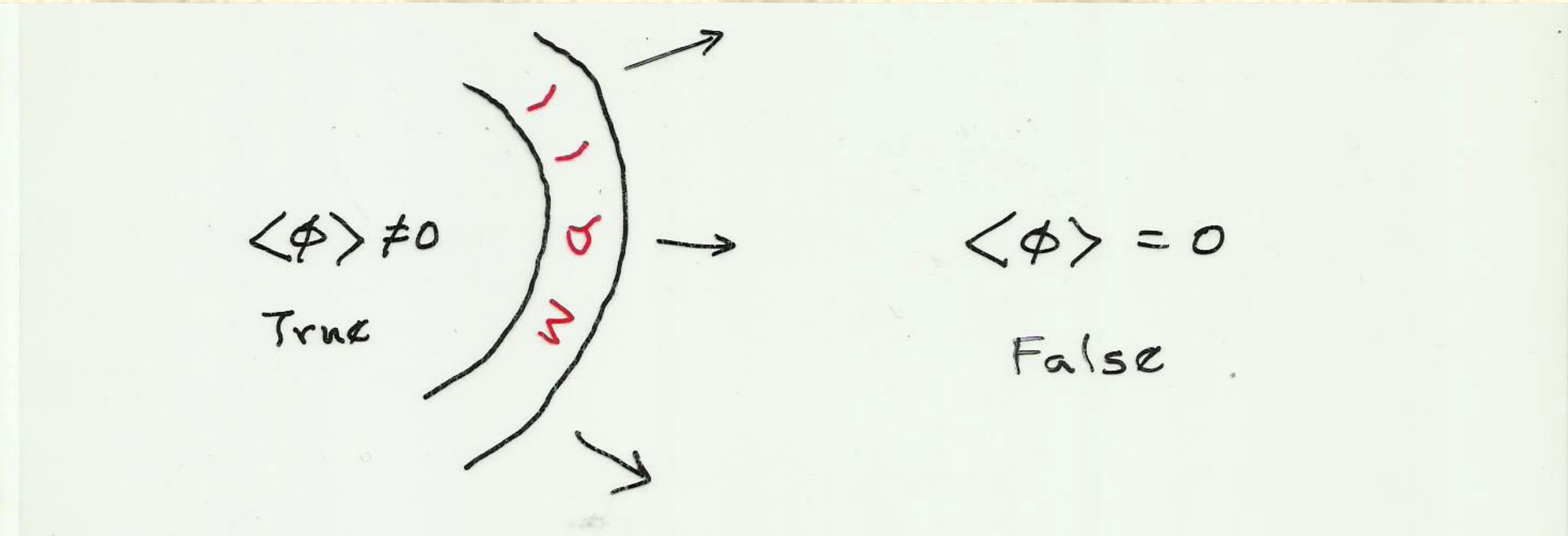
Resonant Leptogenesis with complex Yukawa couplings remains a viable option.

Non-thermal $L + B$-genesis via domain walls

- B and L are known to be accidental symmetries of SM at tree level
- $B + L$ turns out to be anomalous

$$Tr(T^a\{\tau^b, \tau^c\}) \neq 0$$

- Anomalous processes are suppressed at $T = 0$; unsuppressed for $T \gg M_W$
- Two conclusions :
  - Any $B + L$ generated at high scale will be erased
  - ... there is a way to violate $B + L$ just as we cool below M_W
- First order phase transition in SM requires Higgs mass to be $\lesssim 90$GeV
- But other ways of making domain walls exist

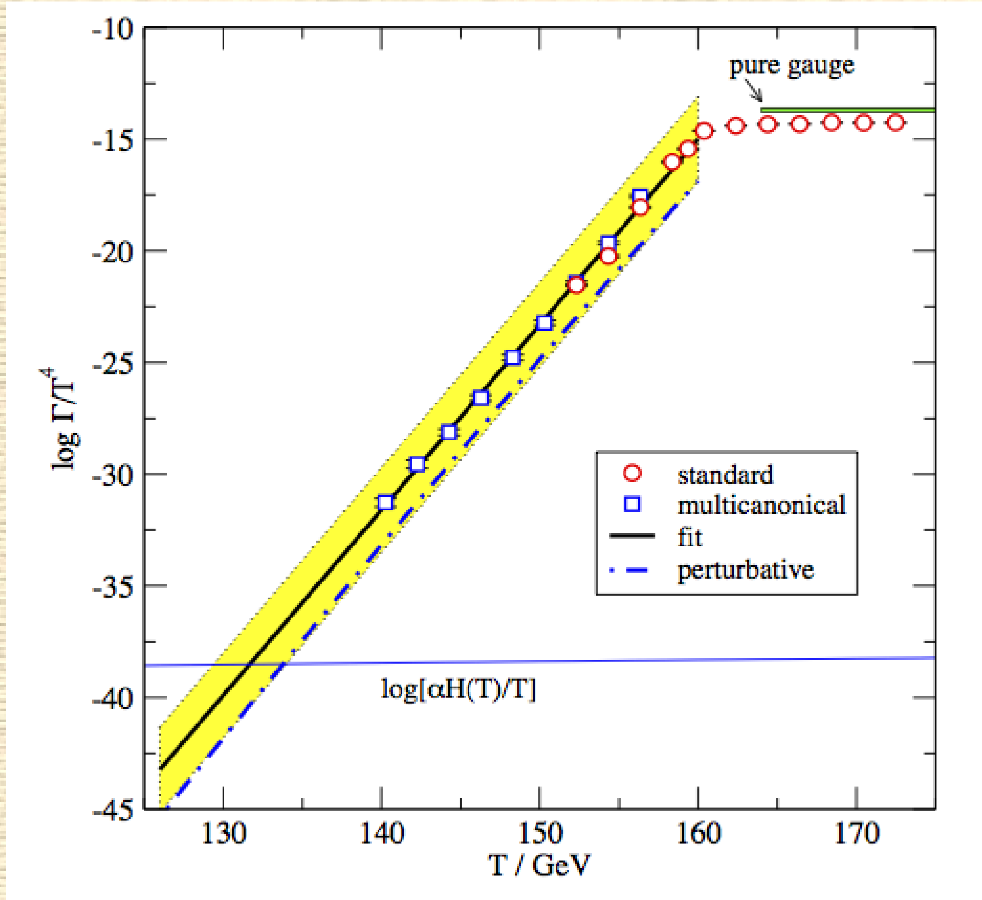


– Thick wall, slow bubbles : scalar condensate with transient CP phase; sphalerons fit in the wall

– Thin wall, fast bubbles : CP phase as before, fermions scatter from the walls

– Observational possibility – Gravitational waves from bubble wall decays (Grojean, Servant, Caprini, Durrer)

Sphaleron rate with Higgs boson



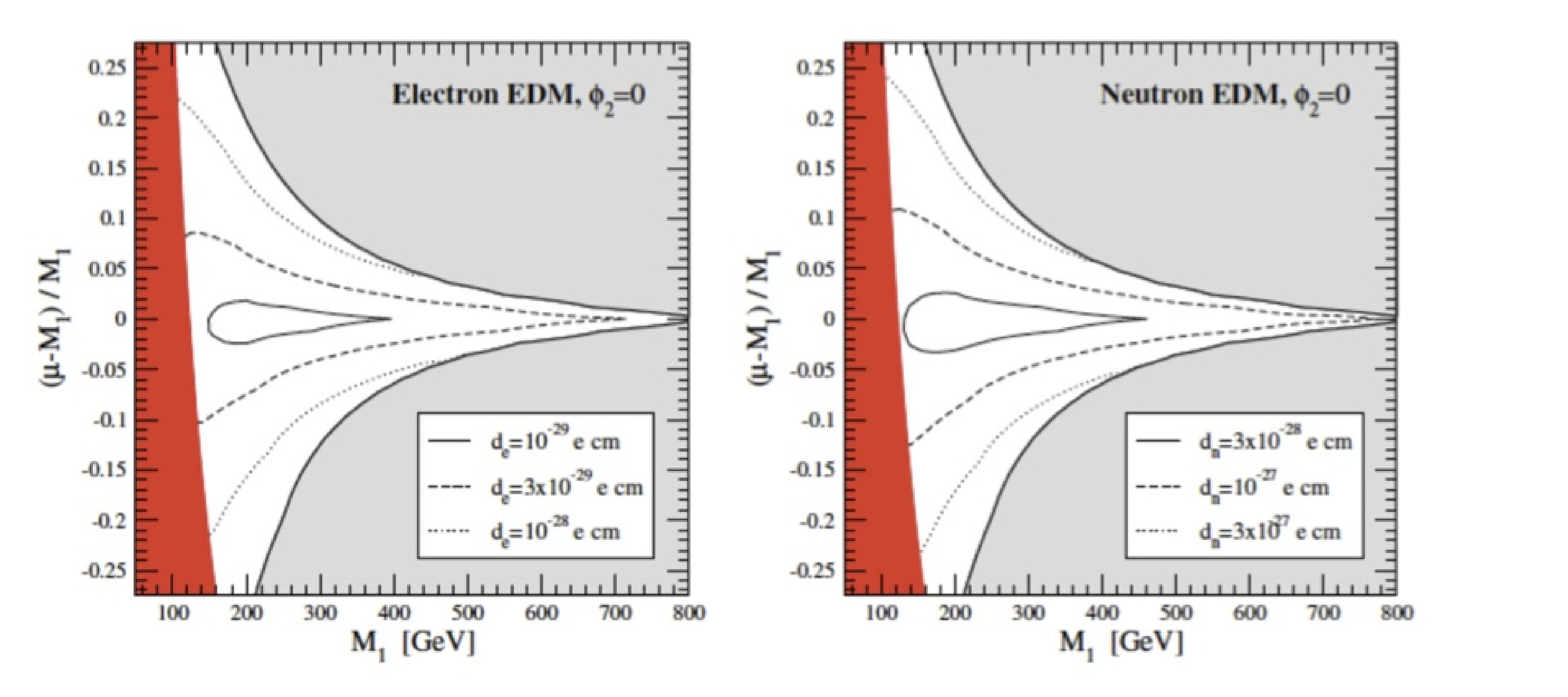
Rummukainen et al (2014)

In either case we need to go beyond the SM :

→ CKM phase acquired at the wall; but magnitude too small

- $\longrightarrow$ At least two scalars as order parameters of the phase transition. Minimal model : 2 Higgs Doublets
- $\longrightarrow$ MSSM as realistic and adequate but in tension with 7 TeV data

Electron EDM and SUSY CP violation



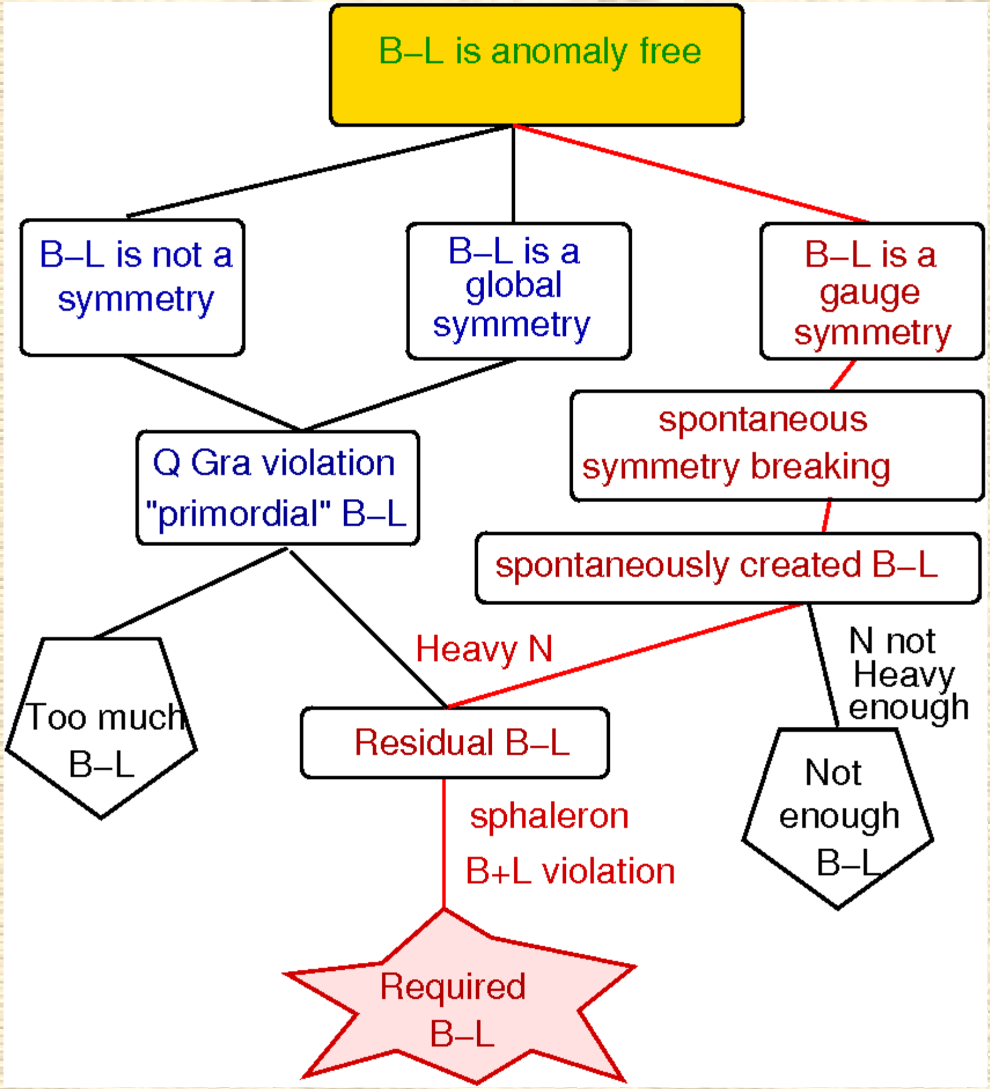
Morrissey and Ramsey-Musolf (2012)

Morrissey and Ramsey-Musolf (2012)

$$d_f \cong \sin\delta_{\rm CP}\left(\frac{m_f}{\rm MeV}\right)\left(\frac{1\rm TeV}{M}\right)^2 \times 10^{-26} e\,{\rm cm}$$

With $M \sim 500$GeV for sufficient abundance at 100GeV, $\delta_{\rm CP} \sim 0.01$ and not adequate source of baryon asymmetry from the walls.
SUSY partner becoming heavy (split SUSY) can suppress the one-loop EDM, yet preserve B-genesis –> untestable from EDM.

What choices did der Alte have?



Neutrino mass and unification

How do we accommodate the neutrino mass?

- $M_{_L}\overline{\nu^C_{_L}}\nu_{_L}$ violates the $\mathrm{SU}(2)_{_L}$ invariance.
- Higher order operator :

$$\mathcal{L} \sim \frac{c_1}{\Lambda_\nu}\mathrm{Tr}\left(\phi\tilde{\phi}^\dagger l_{_L}\bar{l^C_{_L}}\right) \sim \frac{c_1}{\Lambda_\nu}\overline{\nu^C_{_L}}\langle\phi\rangle^2\nu_{_L}$$

- This means there is a scale $\Lambda_\nu \sim O(10^{15})$GeV with some new physics which gives rise to the $m_\nu \sim O(0.1)$eV
- No new species required but the new scale forced to be GUT
- We have not yet seen any sign of GUT scale
  - generically expect proton decay

“Just” Beyond the SM ?

GUT naturalness of gauge coupling unification —> see-saw M_N was expected to fit in.
But note that

$$
\begin{aligned}
m_N &\approx \frac{m_D^2}{m_\nu} \\
&\approx 10^{14}\mathrm{GeV}\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)\left(\frac{m_D}{100\,\mathrm{GeV}}\right)^2 \\
&\approx 10^{4}\mathrm{GeV}\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)\left(\frac{m_D}{1\,\mathrm{MeV}}\right)^2
\end{aligned}
$$

So in the absence of any suggestive high scale, may as well explore the PeV scale.

Left-right as JBSM

Just Beyond the Standard Model ... $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

$$Q = \tau_L^3 + \tau_R^3 + \frac{1}{2}X$$

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
$\begin{bmatrix} \nu_L \\ e_L^- \end{bmatrix}$	$+\frac{1}{2}$ $-\frac{1}{2}$	0 0		0 -1
$\begin{bmatrix} \nu_R \\ e_R^- \end{bmatrix}$	0 0	$+\frac{1}{2}$ $-\frac{1}{2}$		0 -1

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
$\begin{bmatrix} u_L \\ d_L \end{bmatrix}$	$+\frac{1}{2}$ $-\frac{1}{2}$	0 0		$+\frac{2}{3}$ $-\frac{1}{3}$
$\begin{bmatrix} u_R \\ d_R \end{bmatrix}$	0 0	$+\frac{1}{2}$ $-\frac{1}{2}$		$+\frac{2}{3}$ $-\frac{1}{3}$

Gauged $B - L$

$$\begin{array}{lcccc} & \tau_L^3 & \tau_R^3 & \frac{1}{2}X & Q \\ \lceil\ \nu_L\ \rceil & +\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ \lfloor\ e_L^-\ \rfloor & -\frac{1}{2} & 0 & -\frac{1}{2} & -1 \\ \lceil\ \nu_R\ \rceil & 0 & +\frac{1}{2} & -\frac{1}{2} & 0 \\ \lfloor\ e_R^-\ \rfloor & 0 & -\frac{1}{2} & -\frac{1}{2} & -1 \end{array}$$

$$\begin{array}{lcccc} & \tau_L^3 & \tau_R^3 & \frac{1}{2}X & Q \\ \lceil\ u_L\ \rceil & +\frac{1}{2} & 0 & +\frac{1}{6} & +\frac{2}{3} \\ \lfloor\ d_L\ \rfloor & -\frac{1}{2} & 0 & +\frac{1}{6} & -\frac{1}{3} \\ \lceil\ u_R\ \rceil & 0 & +\frac{1}{2} & +\frac{1}{6} & +\frac{2}{3} \\ \lfloor\ d_R\ \rfloor & 0 & -\frac{1}{2} & +\frac{1}{6} & -\frac{1}{3} \end{array}$$

- In praise of $B - L$ ... the only conserved charge of SM which is not gauged! –> Hereby it gains the status of being gauged

Minimal SUSY L-R Model – MSLRM

The minimal set of Higgs superfields required is,

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

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,

$$
\begin{aligned}
Q &\leftrightarrow Q_c^*, & L &\leftrightarrow L_c^*, & \Phi_i &\leftrightarrow \Phi_i^\dagger, \\
\Delta &\leftrightarrow \Delta_c^*, & \bar{\Delta} &\leftrightarrow \bar{\Delta}_c^*, & \Omega &\leftrightarrow \Omega_c^*.
\end{aligned}
\tag{1}
$$

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

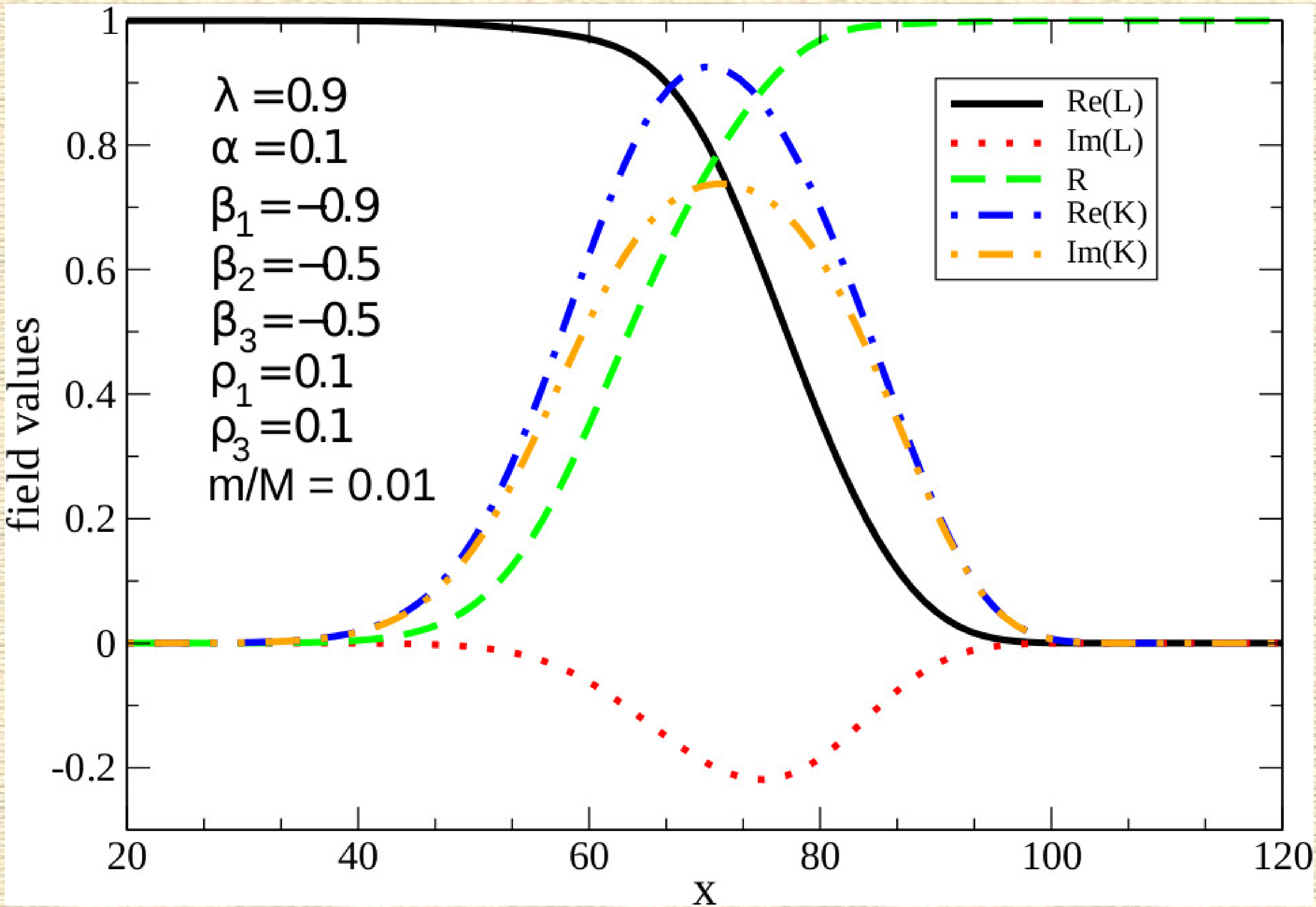
$$\langle\Omega_c\rangle = \begin{pmatrix} \omega_c & 0 \\ 0 & -\omega_c \end{pmatrix}, \quad \langle\Delta_c\rangle = \begin{pmatrix} 0 & 0 \\ d_c & 0 \end{pmatrix}, \quad \langle\Phi_i\rangle = \begin{pmatrix} \kappa_i & 0 \\ 0 & \kappa_i' \end{pmatrix} \tag{2}$$

This ensures spontaneous parity violation [Aulakh, Bajc, Melfo, Rasin, Senjanovic (1998 ...)] Mass scale see-saw

- An R symmetry ensures Ω mass terms in superpotential are vanishing, no new spurious mass scale
- Leads naturally to a see-saw relation
$$\boxed{M_{B-L}^2 = M_{EW} M_R}$$
- Leptogenesis postponed to an energy scale closer to M_{EW} not a high scale like $10^9 - 10^{14}$ GeV

Non-thermal leptogenesis

Example of simulated domain walls in a Left-Right symmetric model

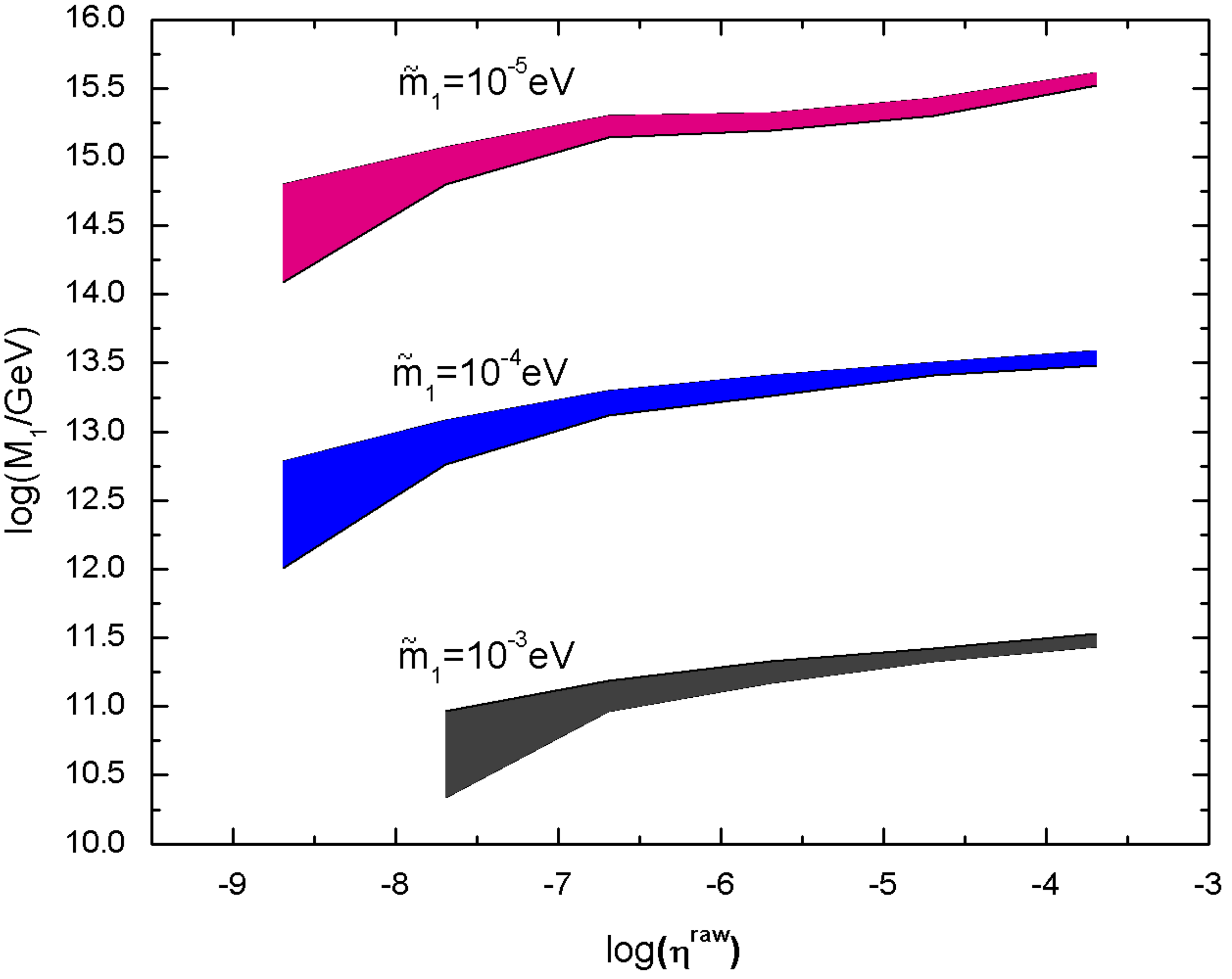


If we ask the reverse question : if the N mass is not as high as required for thermal Leptogenesis, do we still have the scope for producing baryon asymmetry?
The answer is yes. (Cline, Rabikumar and UAY, PRD 2002; Anjishnu Sarkar, UAY PRD 2003)

- The left-right symmetric model has domain walls, with sufficient CP violation provided by the scalar condensates to produce lepton number at a low scale.
- The effect is the same as having bubble walls
- Open question : relating the dynamical $O(1)$ CP phase to static phases in EDM etc.

Can this lepton asymmetry survive?

This question was answered in the affirative, solving Boltmann equations (Narendra Sahu and UAY PRD 2005)



$\tilde{m}_1=10^{-5}$eV
$\tilde{m}_1=10^{-4}$eV
$\tilde{m}_1=10^{-3}$eV
log(M$_1$/GeV)
log(η^{raw})
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
-9
-8
-7
-6
-5
-4
-3

Washout with low scale W_R

Dhuria, Hati, Rangarajan and Sarkar (2015)

Wash out factor K estimated to be in the range 10^9 to 10^{11} for $M_{W_R}\sim 2$TeV.

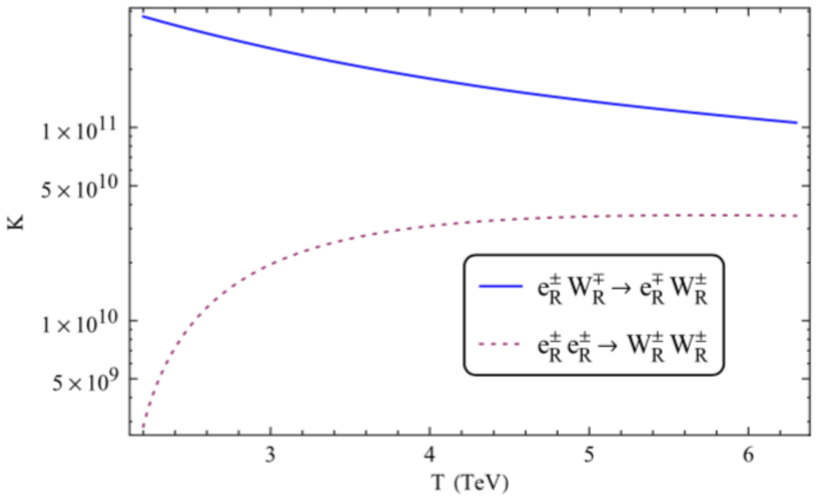


FIG. 2 (color online). Plot showing K as a function of temperature (T) with $M_{W_R} = 2.1$ TeV for the scattering processes $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ and $e_R^\pm e_R^\pm \to W_R^\pm W_R^\pm$ (including both Δ_R^{++} and N_R mediated diagrams) for $v_R > T > M_{W_R}$.

Domain wall based mechanism for $\eta_{\rm raw}$ and compatible lower bound on M_{W_R} needs to be checked in this context.

Relating SUSY breaking and Parity breaking

- In GUT context Left-Right model obtained in SO(10) models with Pati-Salam as intermediate group.
- D-parity $\mathrm{SU}(2)_L \leftrightarrow \mathrm{SU}(2)_R$ remains unbroken and implies $g_L = g_R$
- Breaking of this is achieved by proposing a new singlet field odd under D parity

In SUSY context, continuing to be agnostic about high scale, we can have an alternative
(Anjishnu Sarkar, Sasmita Mishra and UAY)

- SUSY breaking resides in a hidden sector.
- Left-Right needs to be broken with least possible damage to core principle
- Could the effects have the same origin?

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

$$\begin{aligned}
\mathcal{L}^{1}_{soft} &= m_1^2 Tr(\Delta\,\Delta^\dagger) + m_2^2 Tr(\bar{\Delta}\,\bar{\Delta}^\dagger) \\
&\quad + m_3^2 Tr(\Delta_c\,\Delta_c^\dagger) + m_4^2 Tr(\bar{\Delta}_c\,\bar{\Delta}_c^\dagger) \qquad (3)\\
\mathcal{L}^{2}_{soft} &= \alpha_1 Tr(\Delta\,\Omega\,\Delta^\dagger) + \alpha_2 Tr(\bar{\Delta}\,\Omega\,\bar{\Delta}^\dagger) \\
&\quad + \alpha_3 Tr(\Delta_c\,\Omega_c\,\Delta_c^\dagger) + \alpha_4 Tr(\bar{\Delta}_c\,\Omega_c\,\bar{\Delta}_c^\dagger) \qquad (4)\\
\mathcal{L}^{3}_{soft} &= \beta_1 Tr(\Omega\,\Omega^\dagger) + \beta_2 Tr(\Omega_c\,\Omega_c^\dagger) \qquad (5)
\end{aligned}$$

$$\mathcal{L}_{soft} = \mathcal{L}^{1}_{soft} + \mathcal{L}^{2}_{soft} + \mathcal{L}^{3}_{soft} \qquad (6)$$

- Demand that the soft parameters differ in the two possible phases $\mathrm{SU}(2)_L \otimes U(1)_Y$ and $\mathrm{SU}(2)_R \otimes U(1)_{\tilde{Y}}$
- Demand that the pressure difference created is enough to get rid of the domain walls well before Big Bang Nucleosynethesis

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

Table 1. 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.

$$X \leftrightarrow X, \qquad X' \leftrightarrow -X'. \tag{7}$$

The messenger sector superpotential then contains terms

$$\begin{aligned} W &= \lambda X \left(\Phi_L \bar{\Phi}_L + \Phi_R \bar{\Phi}_R\right) \\ &\quad + \lambda' X' \left(\Phi_L \bar{\Phi}_L - \Phi_R \bar{\Phi}_R\right) \end{aligned} \tag{8}$$

- 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

$$\Lambda_X = \frac{\langle F_X \rangle}{\langle X \rangle}, \qquad \Lambda_{X'} = \frac{\langle F_{X'} \rangle}{\langle X \rangle}. \tag{9}$$

Assume

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

Now the messenger fermions receive respective mass contributions

$$\begin{aligned} m_{f_L} &= |\lambda \langle X \rangle + \lambda' \langle X' \rangle| \\ m_{f_R} &= |\lambda \langle X \rangle - \lambda' \langle X' \rangle| \end{aligned} \tag{10}$$

while the messenger scalars develop the masses

$$\begin{aligned} m^2_{\phi_L} &= |\lambda \langle X \rangle + \lambda' \langle X' \rangle|^2 \pm |\lambda \langle F_X \rangle + \lambda' \langle F_{X'} \rangle| \\ m^2_{\phi_R} &= |\lambda \langle X \rangle - \lambda' \langle X' \rangle|^2 \pm |\lambda \langle F_X \rangle - \lambda' \langle F_{X'} \rangle| \end{aligned} \tag{11}$$

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

The effect of this breaking can be calculated on the Higgs scalars by usual methods.

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

$$\begin{aligned}
\delta m_{\Delta}^2 &= 2\Big[\Big(\frac{\lambda\langle F_X\rangle+\lambda'\langle F_{X'}\rangle}{\lambda\langle X\rangle+\lambda'\langle X'\rangle}\Big)^2-\Big(\frac{\lambda\langle F_X\rangle-\lambda'\langle F_{X'}\rangle}{\lambda\langle X\rangle-\lambda'\langle X'\rangle}\Big)^2\Big] \\
&\quad\times\Big\{\Big(\frac{\alpha_2}{4\pi}\Big)^2+\frac{6}{5}\Big(\frac{\alpha_1}{4\pi}\Big)^2\Big\} \\
&= 2(\Lambda_X)^2\Big[\Big(\frac{1+tan\gamma}{1+tan\sigma}\Big)^2-\Big(\frac{1-tan\gamma}{1-tan\sigma}\Big)^2\Big]\Big\{\Big(\frac{\alpha_2}{4\pi}\Big)^2+\frac{6}{5}\Big(\frac{\alpha_1}{4\pi}\Big)^2\Big\} \\
&= 2(\Lambda_X)^2 f(\gamma,\sigma)\Big\{\Big(\frac{\alpha_2}{4\pi}\Big)^2+\frac{6}{5}\Big(\frac{\alpha_1}{4\pi}\Big)^2\Big\} \qquad (12)
\end{aligned}$$

where,

$$f(\gamma,\sigma)=\Big(\frac{1+tan\gamma}{1+tan\sigma}\Big)^2-\Big(\frac{1-tan\gamma}{1-tan\sigma}\Big)^2 \qquad (13)$$

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

$$t\,a\,n\gamma = \frac{\lambda' \langle F_{X'} \rangle}{\lambda \langle F_X \rangle}, \quad t\,a\,n\sigma = \frac{\lambda' \langle X' \rangle}{\lambda \langle X \rangle} \tag{14}$$

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}

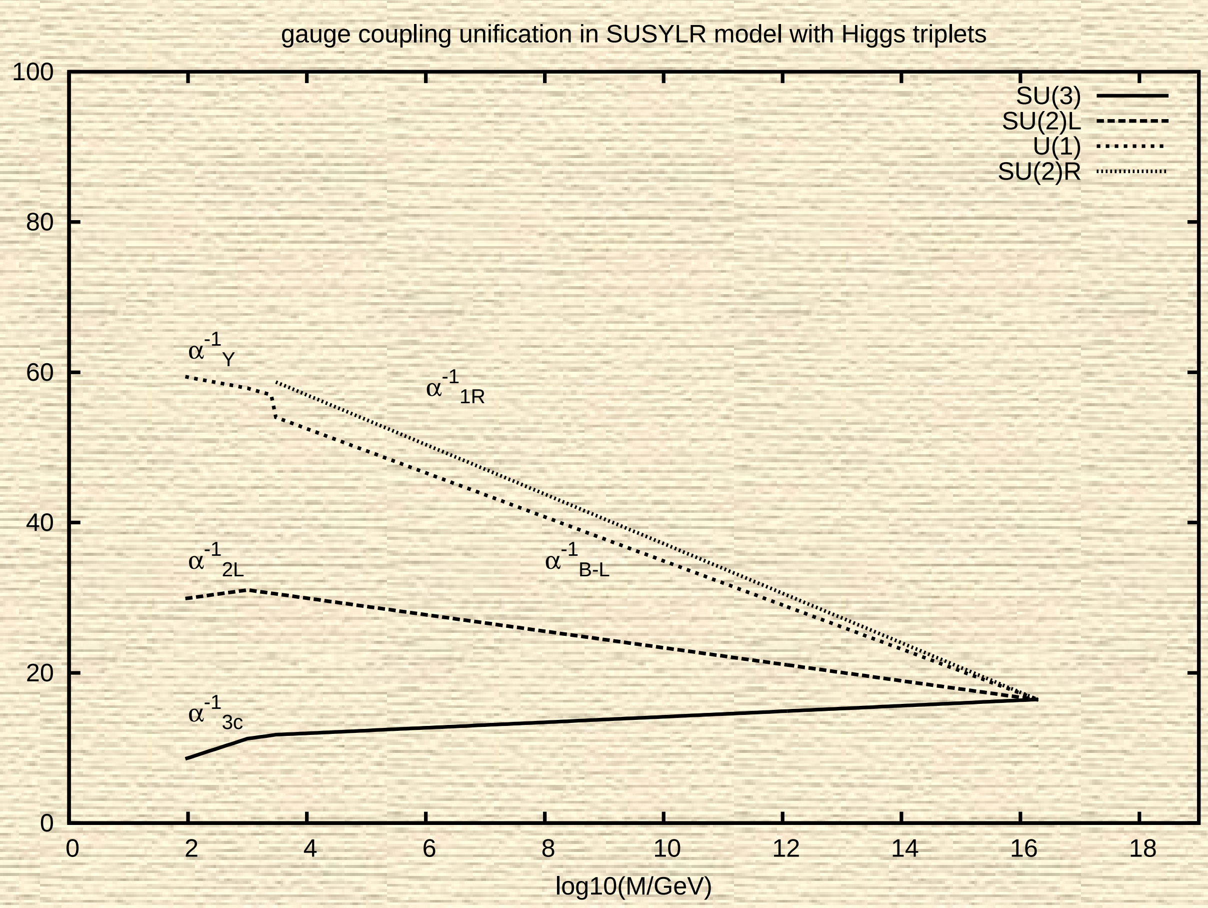
Table 2. Entries in this table are the values of the parameter $f(\gamma, \sigma)$, required to ensure wall disappearance at temperature T_D displayed in the header row. The table should be read in conjuction with table 1, with the rows corresponding to each other.

$m^2 - m'^2 \simeq 10^3\ (\mathrm{GeV})^2$ corresponding to high disintegration temperature T_D has a substantial region of parameter space available.

Lower T_D corresponding to $m^2 - m'^2 \simeq 10\ (\mathrm{GeV})^2$ viable but fine tuned.

Unification ... conditional

Aulakh-Bajc-Melfo-Rasin-Senjanovic model



Unification of coupling is achieved in this model (Debasish Borah & UAY PRD 2010)

- Breaking of $U(1)_{B-L}$ can be as low as 3 TeV

- Need to add new scalars at a higher scale. (Explored exhaustively–> Kopp, Lindner, Niro, Underwood 2009)

Excited leptons?

(Piyali Bannerjee, UAY PRD 2014)

- Cosmposite fermions? –> Flavor puzzle
- Rishon Model 1980's
- As of now fourth generation is ruled out –> no heavier chiral fermions
- Explore for excited leptons purely phenomenologically

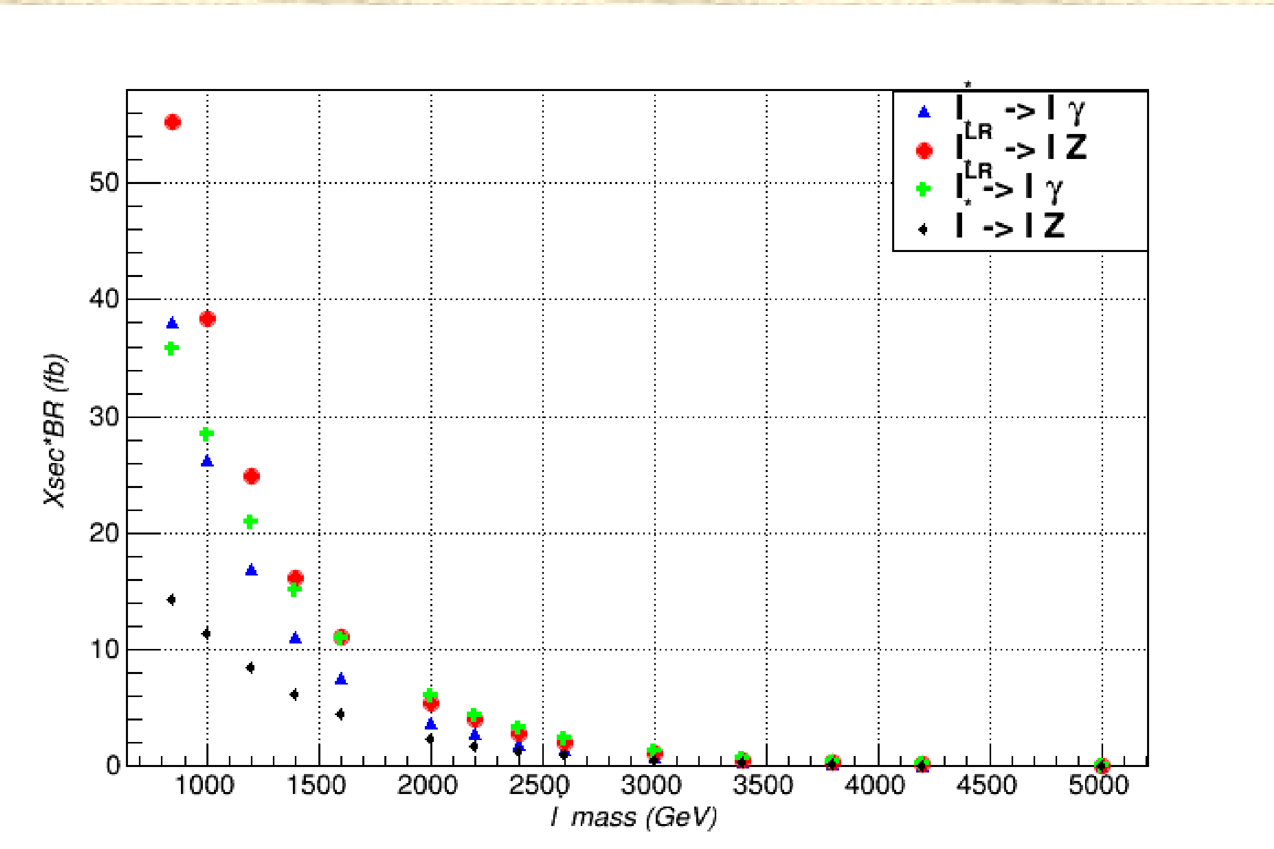
Baur, Spira, Zerwas (1990) SM with excited fermions.
In left-right symmetric version, we add

$$l_L^* = \begin{pmatrix} \nu_L^* \\ e_L^* \end{pmatrix} \sim l_R^* = \begin{pmatrix} \nu_R^* \\ e_R^* \end{pmatrix} \sim (1, 2, 1, -1)$$

and propose an effective "transition" interaction

$$\begin{aligned} \mathcal{L}_{\rm trans} \; &= \; \frac{1}{2\,\Lambda}\,\bar{l}_L^*\,\sigma^{\mu\nu}[g_s\,f_s\,\frac{\lambda^a}{2}\,G_{\mu\nu}^a + g_1\,f_1\,\frac{\tau}{2}\cdot\mathbf{W}_{\mu\nu}^L \\ &+ \; g_2\,f_2\,\frac{\tau}{2}\cdot\mathbf{W}_{\mu\nu}^R + g''\,f''\,\frac{B-L}{2}\,B_{\mu\nu}^{B-L}\Big]\,l_R + \text{H.c.} \end{aligned}$$

Cross section times branching ratio for excited muon decay into Z and photon channels in Standard Model and in left-right symmetric model with Z' mass 800 GeV



CMS limits on e^* and μ^* mass are at $\sqrt{s} = 7$ TeV with an integrated luminosity excluded $m_{l^*} < 1.9\,\mathrm{TeV}$ at 95% C.L the Z channel becomes a promising candidate to search for left-right symmetric excited leptons with masses above 1000 GeV

Conclusions and caveats

- Thermal leptogenesis is viable and appealing –> lives necessarily at high scale -:(
  - Tantalising possibility of accessing this high scale physics through see-saw constraints –> already making it difficult as an explanation

  Recommendation –> adopt SUSY L-R as JBSM Just Beyond SM at PeV scale
- Non-thermal leptogensis natural through domain walls
- Domain wall disappearance requirement constrains soft terms
- Link SUSY and Parity breaking, e.g., GMSB
- Excited lepton signature drastically modified in Z channel

–> Thanks page

Dankeshön!

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