Unified models for neutrinos

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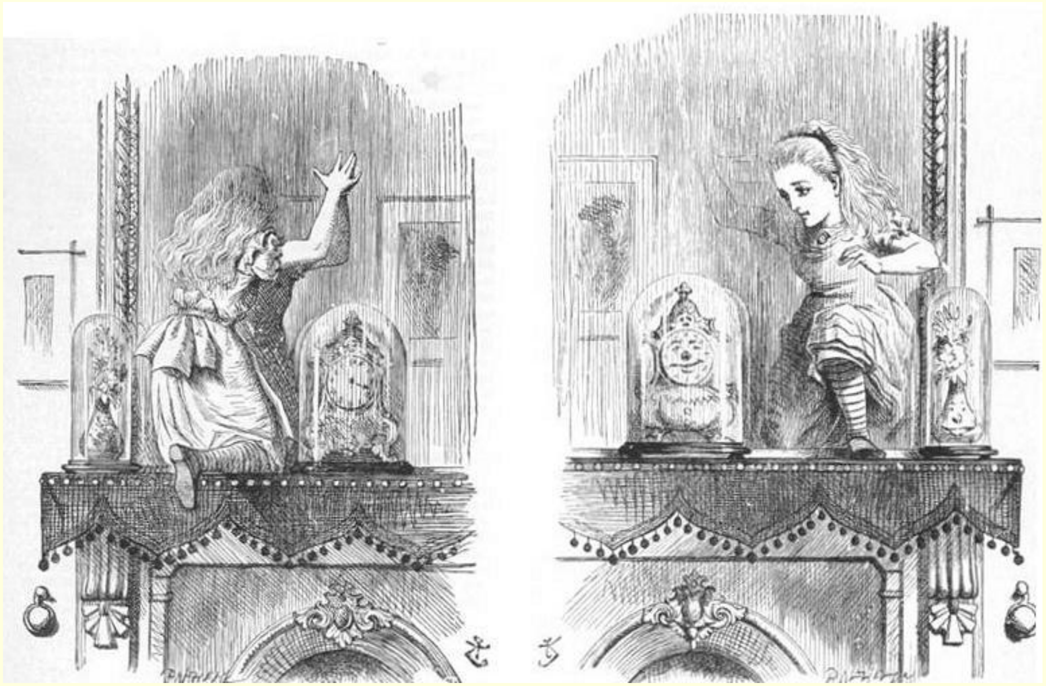
1 Neutrinos – the linkage between external and internal symmetries

Madam Wu's engimatic experiment

... Linakge between external and internal - 2

- Weak force : Four-Fermi theory
- Strong force : Yukawa's intermediate scalar bosons
- Weak force : Intermediate vector bosons Schwinger
- Weak force : $V - A$ structure Sudarshan and Marshak; Gell-Mann and Feynman; Sakuarai
  - universality
  - chirality

... Linkage between external and internal - 3



- Weak force : $\mathrm{SU}(2)$ becomes gauged Salam and Weinberg; based on Spontaneous Symmetry Breaking (Nambu, Goldstone, Higgs, Guralnik, Hagen, Kibble, Englert, Brout)
- Now we propose gauged interactions for Right Handed neutrino
  - ***Parity*** a space-time symmetry becomes *internal*
  - $B - L$ becomes *gauged* instead of *global* symmetry

1.1 From parity violation to the Standard Model

- $V - A$ structure
  - Chiral symmetry
  - Masless fermions
- Gauge symmetry
  - massless intermediate vector bosons
- "Chiral fermions"
  - Parity asymmetric multiplets
  - Parity asymmetric charge assignments

1.2 Standards set by the Standard Model

- No intrinsically massive vector bosons
- No vector - like fermions
- Fundamental scalars only for Higgs mechanism
- CP- volation only from
  - fermion flavor mixing
  - scalar potentials
  - scalar VEV's
- Singlets disfavored

$\rightarrow$ *should seek their embedding at a higher scale*

2 Overview of this presentation

- Unifying structures (See-saw paradigm)
  - Left- right symmetry
  - Supersymmetric version $\longrightarrow$ Just Beyond Standard Model
  - SO(10) and higher $\longrightarrow$ hierarchy? gravitino bound? Inflation?
- (Flavour – Auxiliary e.g. A_4 or E_6 partly embedded)
- Cosmology
  - phase transitions, Domain Wall $\longrightarrow$ consistecy conditions
  - cosmic strings at M_R scale (possible future discussion)
- Leptogenesis, Dark Matter, $0\nu\beta\beta$, Muon anomalous magnetic moment

3 Left-right as JBSM

$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes U(1)_X$

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
ν_L	$+\frac{1}{2}$	0	$-\frac{1}{2}$	0
e_L^-	$-\frac{1}{2}$	0	$-\frac{1}{2}$	-1
ν_R	0	$+\frac{1}{2}$	$-\frac{1}{2}$	0
e_R^-	0	$-\frac{1}{2}$	$-\frac{1}{2}$	-1

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
u_L	$+\frac{1}{2}$	0	$+\frac{1}{6}$	$+\frac{2}{3}$
d_L	$-\frac{1}{2}$	0	$+\frac{1}{6}$	$-\frac{1}{3}$
u_R	0	$+\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$
d_R	0	$-\frac{1}{2}$	$+\frac{1}{6}$	$-\frac{1}{3}$

- Need a new hypercharge X –> turns out to be exactly $B - L$
- $B - L$ ... the only conserved charge of SM which is not gauged!
- Exact left-right : $g_L = g_R$
- Higgs sector : Complex doublets; complex triplets ...
  - Triplets permit the see-saw (QFT implementation Type II)

3.0.1 Two possibilities for $L \leftrightarrow R$ symmetry

(Senjanovic)

$$P : \begin{cases} f_L \leftrightarrow f_R \\ \Phi \leftrightarrow \Phi^\dagger \\ \Delta_L \leftrightarrow \Delta_R \end{cases} \qquad C : \begin{cases} f_L \leftrightarrow (f_R)^c \\ \Phi \leftrightarrow \Phi^T \\ \Delta_L \leftrightarrow \Delta_R^* \end{cases}$$

The implications are to the fermion mass matrices; not covered here.

3.1 Minimal SUSY L-R Model – MSLRM

Just Beyond the Standard Model ...

- SUSY protects SSB scales
- $L - R$ could be just around the corner
  - the combined electroweak scale can be sequestered from GUT scale

Higgs superfields

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

– triplets doubled for anomaly cancellation.

- bidoublet doubling needed to accommodate CKM matrix.
- without the Ω's supersymmetric vacua necessarily break $U(1)_{EM}$ along with parity. (Kuchimanchi and Mohapatra)
- Alt fixes : non-renormalisable terms or singlets not pursued here.

Impose $\mathcal{C}$ type discrete parity,

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

The F-flat and D-flat SUSY vacua imply breaking to $\mathrm{SU}(2)_L \otimes U(1)_R \otimes U(1)_{B-L}$

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

This ensures spontaneous parity violation [Aulakh, Bajc, Melfo, Rasin, Senjanovic (1998 ...)] (called ABMSR in the following)

3.1.1 The Mass scale see-saw

- An R symmetry ensures Ω mass terms in superpotential are vanishing, no new spurious mass scale
- Usual R parity $(-1)^{3B-L+2s}$ preserved exactly
- Leads naturally to a see-saw relation

$$\boxed{M_{B-L}^2 = M_{EW} M_R}$$

- Leptogenesis postponed to a scale closer to M_{EW} *below* M_R !!
- Accelerator and non-accelerator signatures ... $M_{Z_R} \gtrsim \sqrt{3}\, M_{W_R}$

3.1.2 Exploratory extensions

As of writing,

- No accelerator hints of W_R, Z_R
- No hints of supersymmetry
- GERDA, KamLAND-Zen searches of $0\nu\beta\beta$ intensified
- Muon anomalous magnetic moment discrepancy as a hint

our group talks :

$\longrightarrow$ Prativa $g_L \neq g_R$ and extended inverse see-saw

$\longrightarrow$ Supriya $U(1)_{L_\mu - L_\tau}$ extension

$\longrightarrow$ Chayan doublet Higgs, embed in $\mathrm{SO}(10)$ GUT with ν_R as Dark Matter

4 Cosmology of LRSM - I

Exact symmetry and domain walls

How to have the discrete symmetry but not suffer its domain walls?

Make the gauge couplings of $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_R$ slightly different?

Make some fermion mass matrix asymmetric?

These are viable alternatives, but break the symmetry explicitly.

They beg the separate question, why the inexact symmetry exists, the elegant explantion as from a spontaneous choice is lost.

We have studied at least two possibilities, where the asymmetry in parity breaking can be bundled with some other similar partially answered problem :

i. Supersymmetry breaking hidden sector also communicates parity breaking

ii. Parity breaking accompanies supersymmetry breaking due to the choice of a metastable vacuum

4.1 Consistency of wall removal mechanism

"Wall removal" –> completion of the phase transition

- Assume P violation by higher dimensional operators, ie from unknown physics
- Using models of wall dynamics, obtain the time scale by which curvature tension relxes and walls become inert / non-oscillatory.
  - This is the epoch beyond which walls will come to dominate the total energy density
- Require this limiting curvature tension to be overcome by higher dimensional operators, thus removing the walls before they become dangerous.

5 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 :

- Supergravity – renormalisable terms couple separately to the left sector and right sector with no mixing terms.
- Gravitational instanton effects can affect discrete symmetry
- Effectivley assume breaking of parity in the hidden sector, communicated by gravity.
- Structure of the symmetry breaking terms determined by the Kahler potential formalism

5.1 Removal of domain walls – singlet scalar

Rai and Senjanovic (1994)

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

$$V_{eff} = \frac{C_5}{M_{Pl}} \phi^5 + \frac{C_6}{M_{Pl}^2} \phi^6 + \ldots \tag{3}$$

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 energy density of the domain walls goes as $\rho_W \sim (\sigma\, R^2 / R^3) \sim (\sigma / G\, t^3)^{1/2}$.

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

Domain wall dynamics : matter domination

[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

$\rho_W^{(in)} \sim \sigma H_i$

The corresponding temperature permits the estimate of the required pressure difference,

$$\delta\rho > M_R^4 \left(\frac{M_R}{M_{Pl}}\right)^{3/2} \tag{5}$$

A milder suppression factor than the radiation dominated case.

Planck scale terms in ABMRS model

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

and likewise $R \leftrightarrow L$. Hence,

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

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

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_{RD}^A to be $O(1)$ if the scale of M_R is an intermediate scale 10^{11}GeV.

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

Thus removal of domain walls imposes an upper bound on M_R and strongly suggests the scale is unrelated to GUT.

6 Cosmology of LRSM - II

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

- GUTs generically involve new gauge forces which mediate B violation
- Higgs scalars with interferance between diagrams provide a natural source of CP violation
- The Particle Physics rates and expansion rate of the Universe compete

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

Net baryon asymmetry

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

6.1 Leptogenesis

Thermal case Fukugita and Yanagida (1986)

A. Pilaftsis, T.E.J. Underwood / Nuclear Physics B 692 (2004) 303–345 305

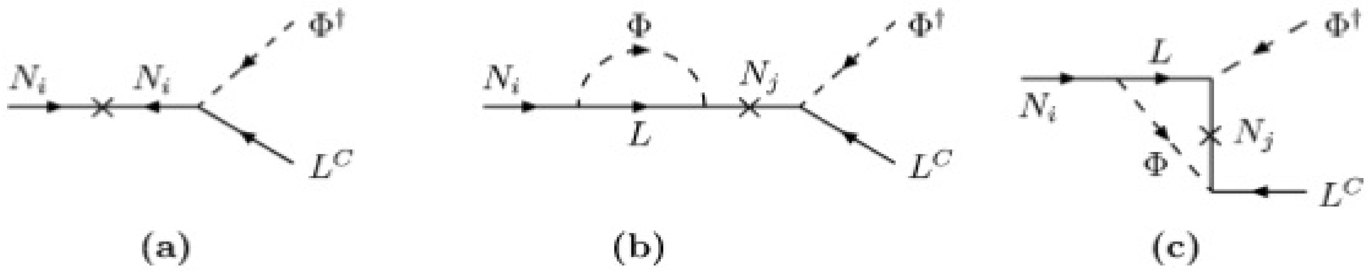
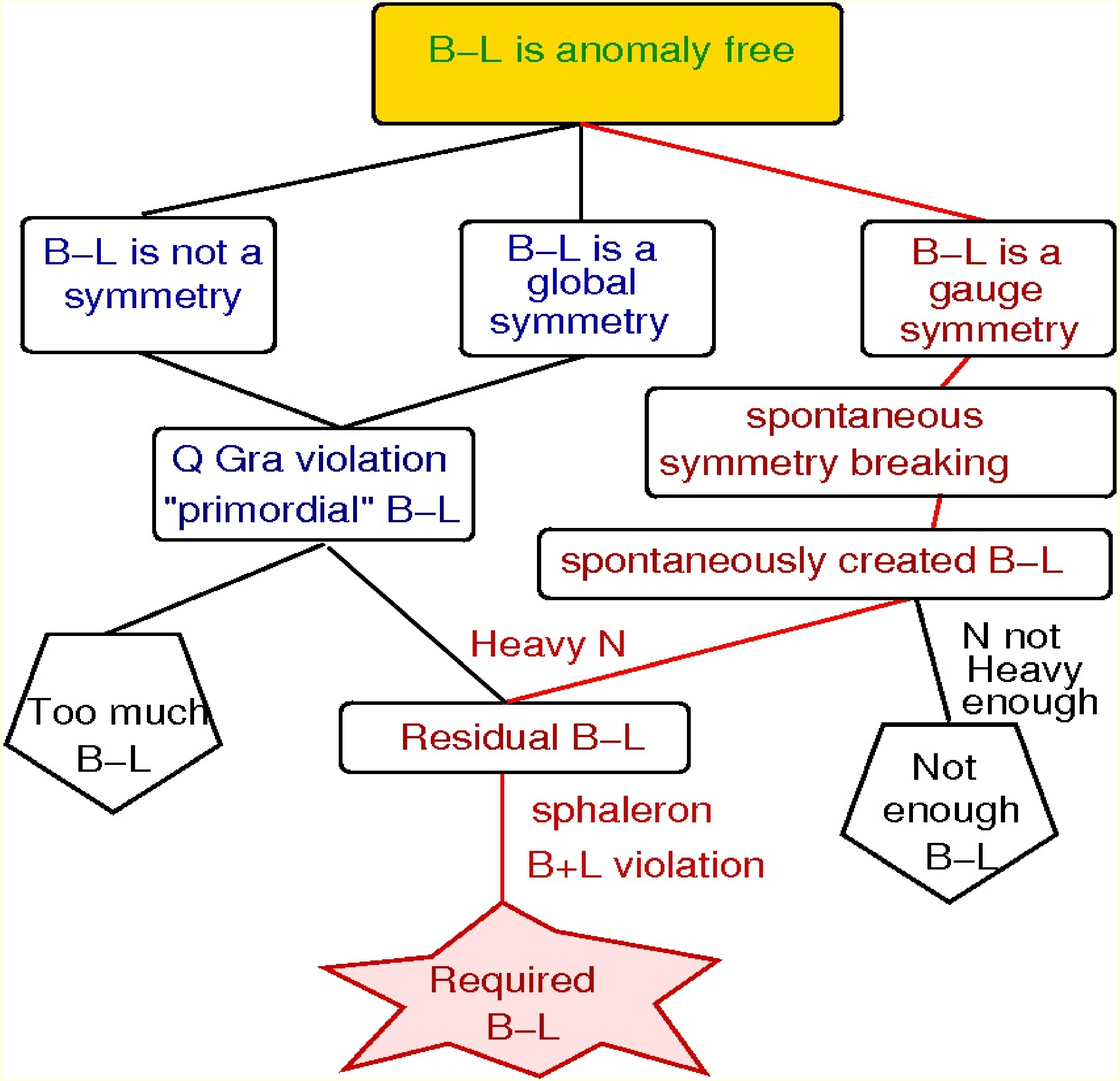


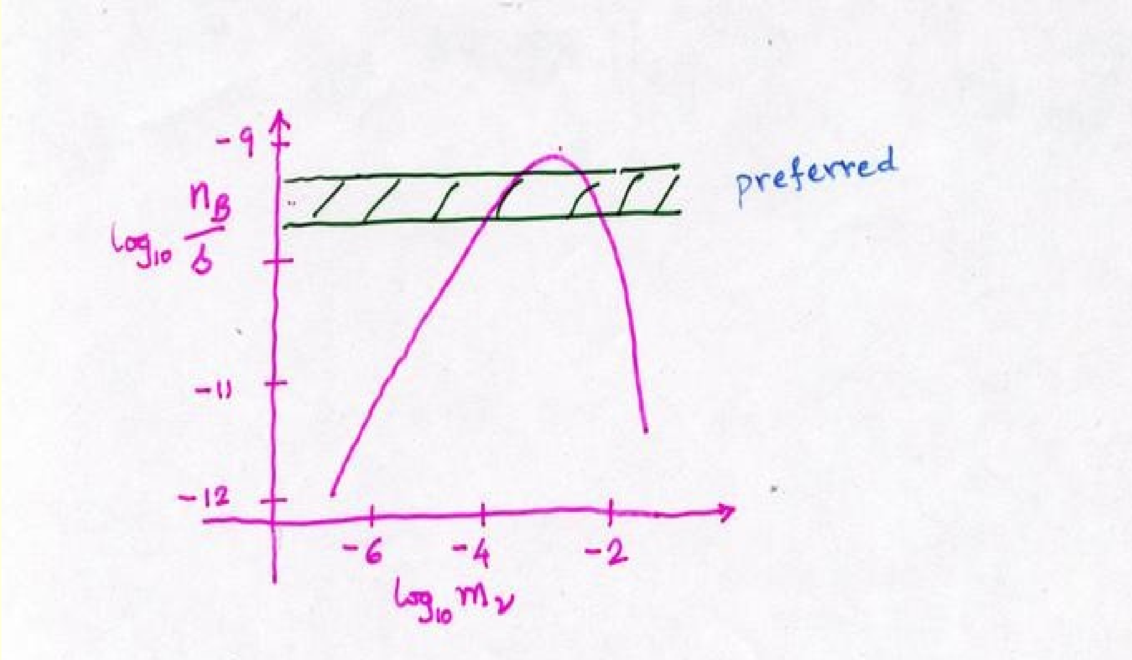
Fig. 1. Feynman diagrams contributing to the L-violating decays of heavy Majorana neutrinos, $N_i \to L^C \Phi^\dagger$, where L and Φ represent lepton and Higgs-boson iso-doublets, respectively: (a) tree-level graph, and one-loop (b) self-energy and (c) vertex graphs.

- Presence of heavy Majorana neutrino states violating L
- Scalar interactions as well as flavor mixing can be natural source of CP violation
- Requires competion between decay rates and Hubble value

6.2 What choices did der Alte have?



6.3 Difficulties of high scale leptogenesis - $\mathrm{SO}(10)$



Shaposhnikov; Di Bari, Buchmuller, Plumacher ... 2004-07

m_ν too small : Yukawa couplings too small to bring heavy N into equilibrium

m_ν too large : Erasure processes too efficient

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

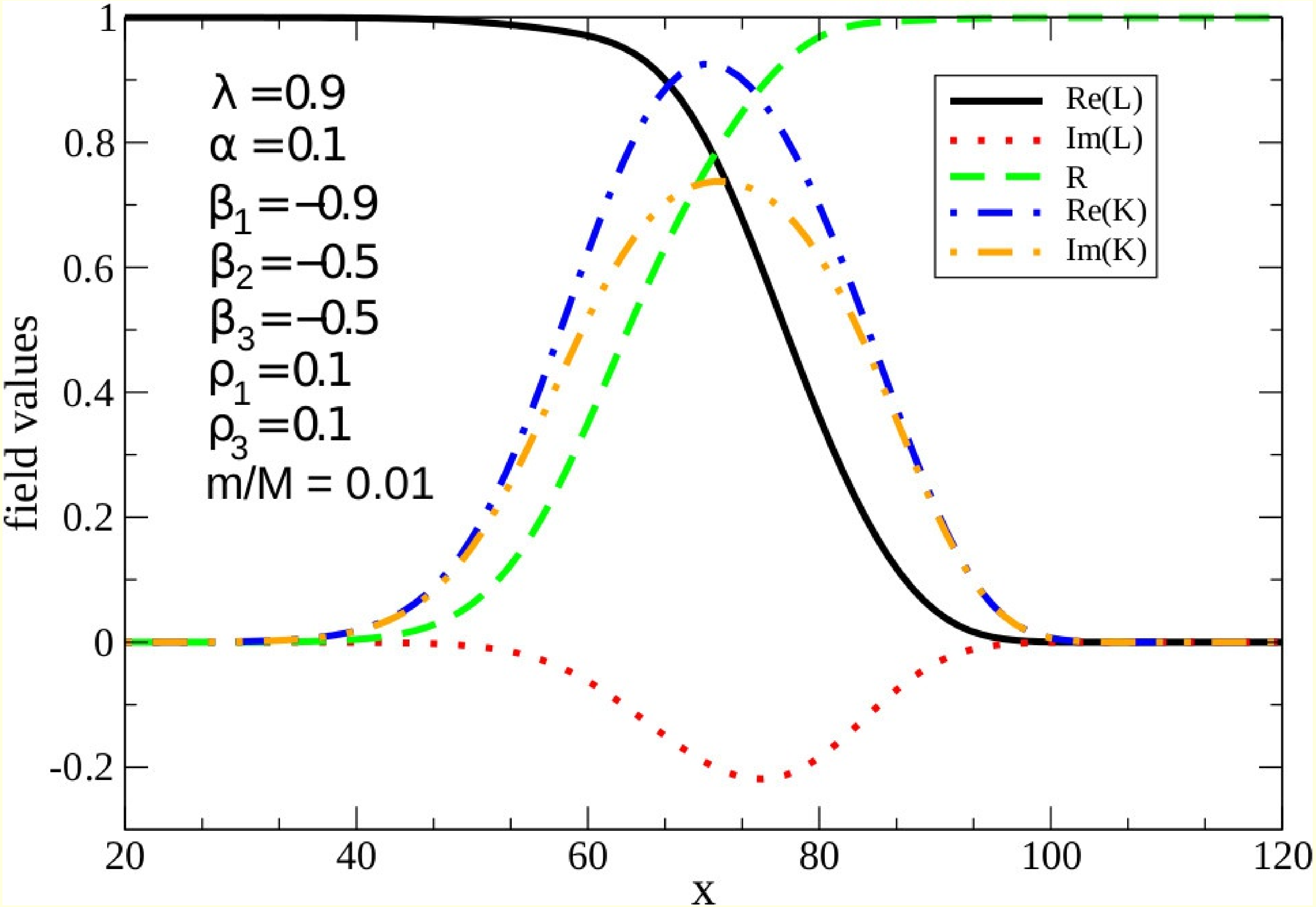
6.3.1 Linking to neutrino data

- Thus $M_N \gtrsim 10^9$ GeV
  - Conflicts with Supersymmetric unification –> gravitino overproduction
- Low energy neutrino mass differences are reasonably well constrained
- A careful examintion of see-saw formula with three generations taken into account show, for thermal leptogenesis,

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

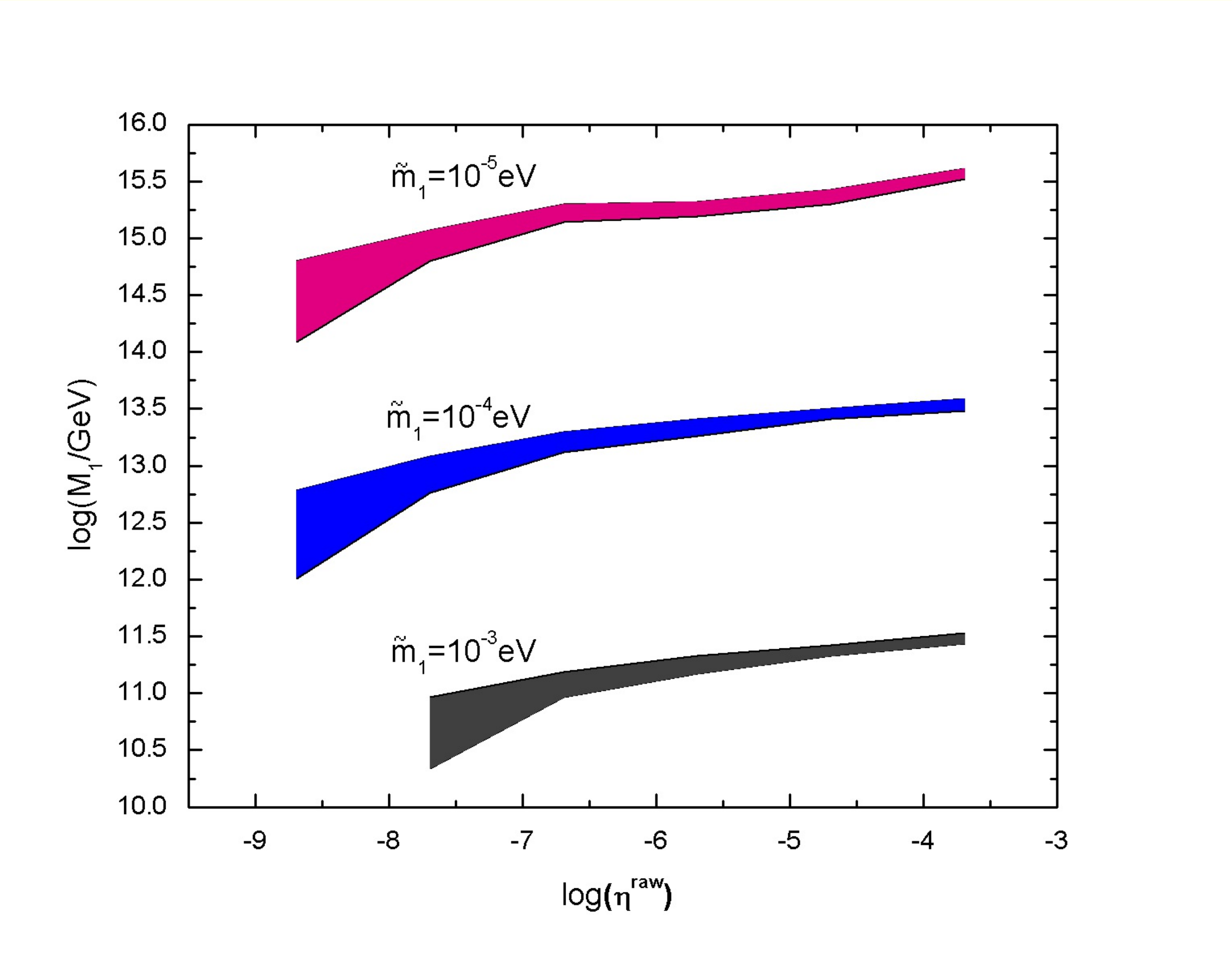
  (Davidson and Ybarra)
- This can be too small for producing the asymmetry

6.4 Non-thermal low scale leptogenesis



Left - Right breaking phase transition as robust source of Domain Walls
Cline, Das, Rabi, UAY (2002)

... viability of low scale leptogenesis

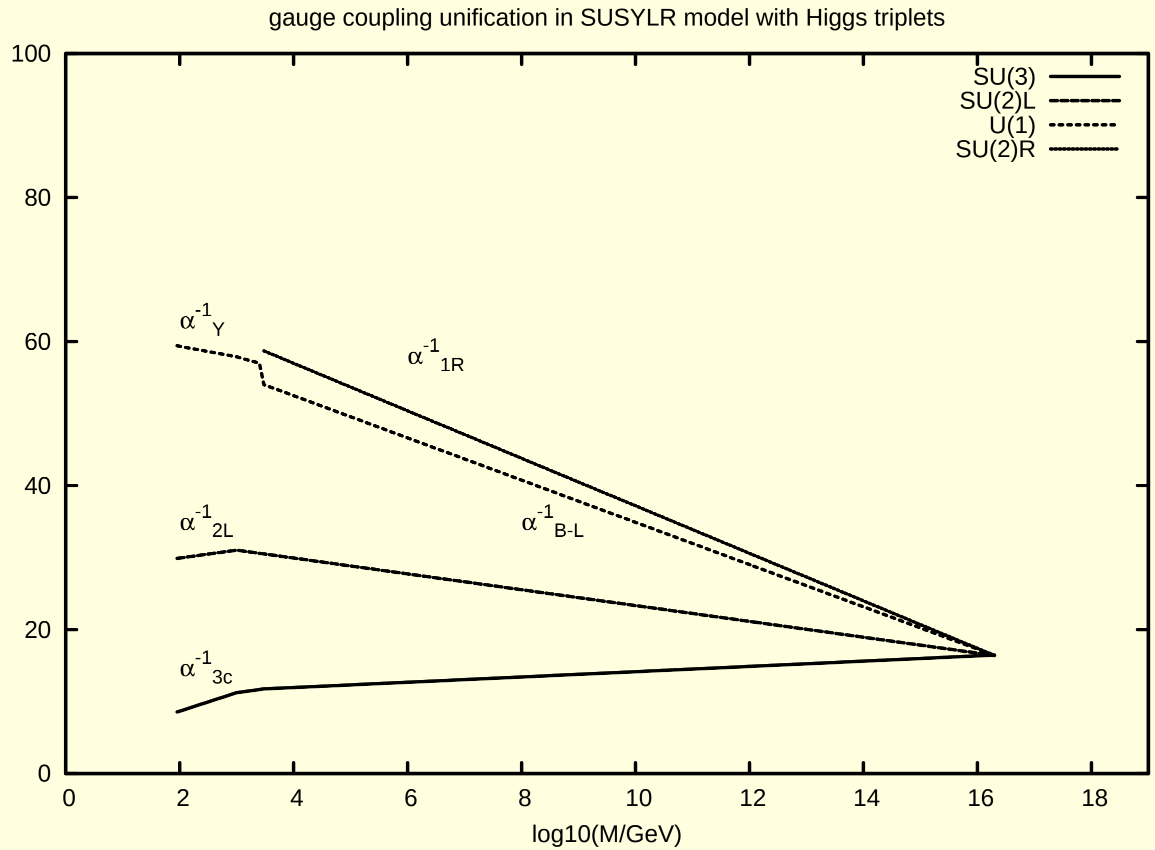


Allowed regions are open on the left

Sahu and UAY (2004)

Question : sufficient L asymmetry is generated by some mechanism, how low can N mass be and yet preserve the asymmetry? Answer : No lower bound.

6.5 Unification – conditional



Gauge coupling unification in the MSLRM (*Debasish Borah & UAY* 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)

7 Summary

→ SM construction as a guide to incporating massive neutrinos

→ $\mathrm{SO}(10)$ completion appealing

→ Intermediate Left-Right symmetry also elegant and accessible

- a viable SUSY version in ABMRS model

→ The issue of consistent cosmology with Domain Walls can be addressed

→ Tension of high scale Leptogenesis ameliorated by DW !

→ Cautious extensions to accommodate non-accelerator and low energy signatures : $U(1)_{L_\mu - L_\tau}$, modifications / extensions of the Higgs structure, extensions / alterations of the see-saw mechanism

- Importance of flavor sturcture to Leptogenesis

THANK YOU!

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