Gauged $B - L$ unification and cosmology

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Outline

- Motivation for gauged $B - L$
- The *real* constraint on heavy neutrino mass
- Domain walls in Left-Right symmetric model
- Cosmology of SUSY L-R model
- cosmological constraints on soft parameters
- implication and conclusions

Motivation

Status of *thermal* Leptogenesis

Net baryon asymmetry

$$Y_B = 0.55 \epsilon Y_{N_1} d \,,$$

- ϵ CP violation parameter
- Y_{N_1} abundance of the lightest of the heavy neutrinos at the L-violating scale
- d subsequent dilution.

Combining the observed bound on Baryon asymmetry from WMAP gives

$$M_1 \geq O(10^9)GeV \left(\frac{2.5 \times 10^{-3}}{Y_{N_1} d}\right) \left(\frac{0.05eV}{m_3}\right) .$$

Low energy neutrino data constrain ϵ to remain smaller than

$$|\epsilon| \leq 9.86 \times 10^{-8} \left(\frac{M_1}{10^9 GeV}\right) \left(\frac{m_3}{0.05eV}\right)$$

Problem

- Thermal Leptogenesis wants high scale $M_1 \sim 10^{12}$ GeV
  - Consistent with see-saw
  - highlights the hierarchy problem
- SUSY should control the hierarchy
  - Desirable on general grounds
  - Conflicts with the gravitino requirement on reheat temperature after inflation, $T_{RH} \leq 10^9 GeV$

Preserving the asymmetry

The presence of a heavy Majorana neutrino species (N) gives rise to processes depleting the existing lepton asymmetry in two ways.

1. Scattering processes (S) among the SM fermions and

2. Decay (D) and inverse decays (ID) of the heavy neutrinos.

Temperature dependent rates

$$\Gamma_D \sim \frac{h^2 M_1^2}{16\pi(4T^2 + M_1^2)^{1/2}} \quad \text{and} \quad \Gamma_S \sim \frac{h^4}{13\pi^3}\frac{T^3}{(9T^2 + M_1^2)},$$

where h is typical Dirac Yukawa coupling of the neutrino.

Possibilities for low scale L-genesis

Define dilution factor

$$10^{-d_B} \equiv \exp\left(-\int_{t_{B-L}}^{t_{EW}} \Gamma_S dt\right)$$

Here t_{B-L} is the time of the $(B-L)$-breaking phase transition and t_{EW} corresponds to the electroweak scale after which the sphalerons are ineffective.

Parametrically,

$$d_B \sim \; h^4 \frac{M_{Pl} T_{B-L}}{M_1^2}$$

Case 1 $M_1 > T_{B-L}$

Convert above constraint into an upper limit on the light neutrino masses

Using the canonical seesaw relation, including the effect of generation mixing, the parameter which appears in the thermal rates is

$$\tilde{m_1} \equiv \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

and is called the *effective neutrino mass* The constraint can then be recast as

$$m_\nu \sim \tilde{m_1} \lesssim \frac{180 v^2}{\sqrt{T_{B-L} M_{Pl}}} \left(\frac{d_B}{10}\right)^{1/2}$$

If a non-thermal mechanism produces $O(1)$ asymmetry, $d_B = 10$ and if we seek $T_{B-L} \sim$ 1TeV and $M_1 \sim$ 10TeV, this bound is academic in view of WMAP.

Given $m_\nu \approx 10^{-2}$eV, if we seek $T_{B-L} \sim$ 1TeV and $M_1 \sim$ 10TeV, with $h \approx 10^{-5} \approx m_e/v$ this bound can be read to imply that in fact d_B is vanishingly small.

Bake the cake and keep it too :
Low scale $B - L$ possible if we find a non-thermal mechanism for producing lepton asymmetry naturally in the range 10^{-10}.

Case 2 $M_1 < T_{B-L}$

Complete erasure is prevented provided dilution processes are slower than the expansion scale of the Universe for all $T > M_1$.

Suffices to require $\Gamma_D < H$ which also ensures that $\Gamma_S < H$.

$$m_\nu < m_* \equiv 4\pi g_*^{1/2} \frac{G_N^{1/2}}{\sqrt{2} G_F} = 6.5 \times 10^{-4} eV$$

Note m_* contains only universal couplings and g_*, and may be called the *cosmological neutrino mass*.

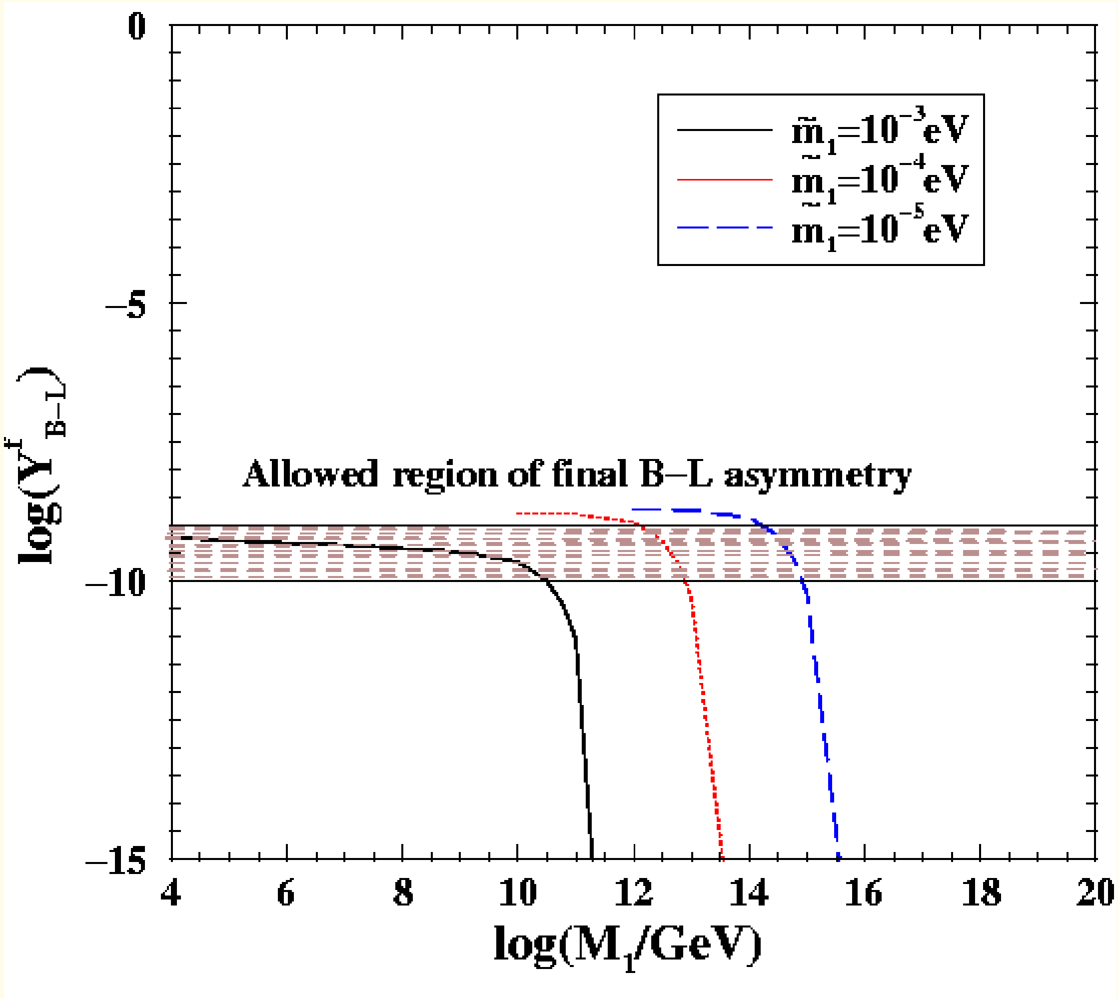
A scale for neutrino Dirac mass

Seesaw formula (details related to a particular texture)

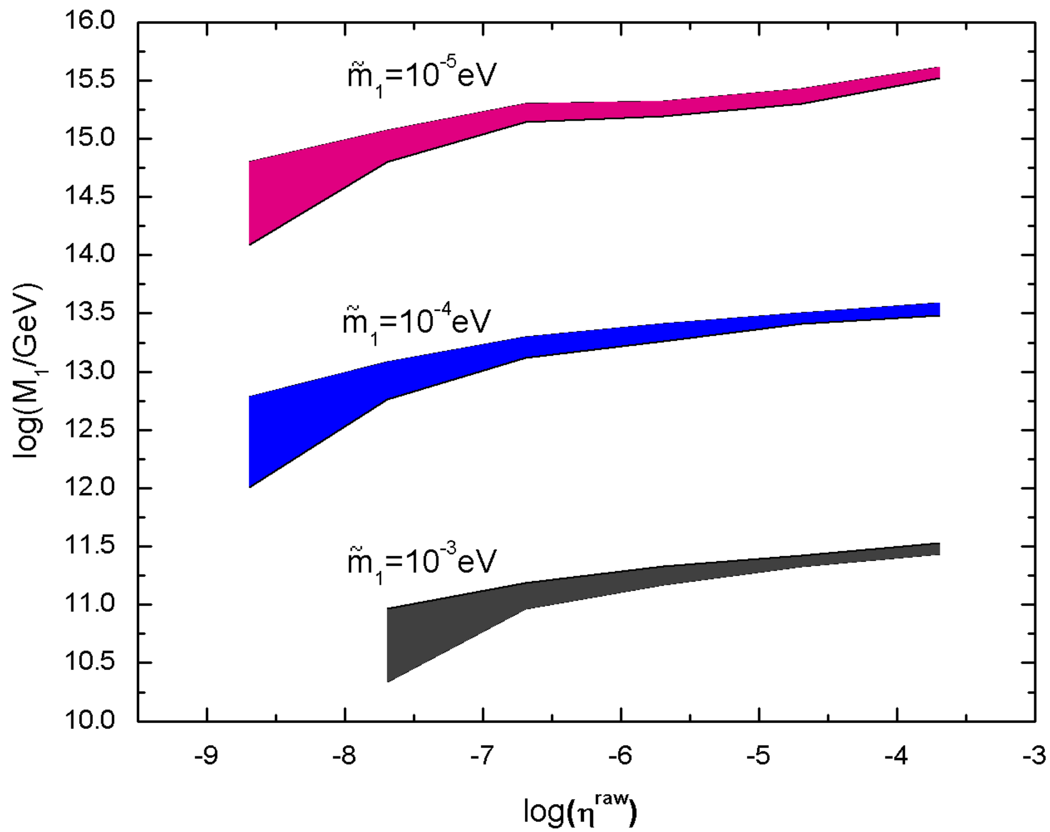
$$\tilde{m_1} = 4.16 \times 10^{-4} eV \left(\frac{10^8 GeV}{M_1} \right).$$

Front factor is $\propto m_D^2$ as in usual see-saw.
Thus with this texture of masses, the m_* bound is satisfied for $M_1 \gtrsim 10^8 GeV$.

But we want M_1 mass within the TeV range,
$\Longrightarrow$ Dirac mass scale of neutrinos smaller by 10^{-2} relative to the charged lepton mass scale



Narendra Sahu and UAY (PRD 2005)



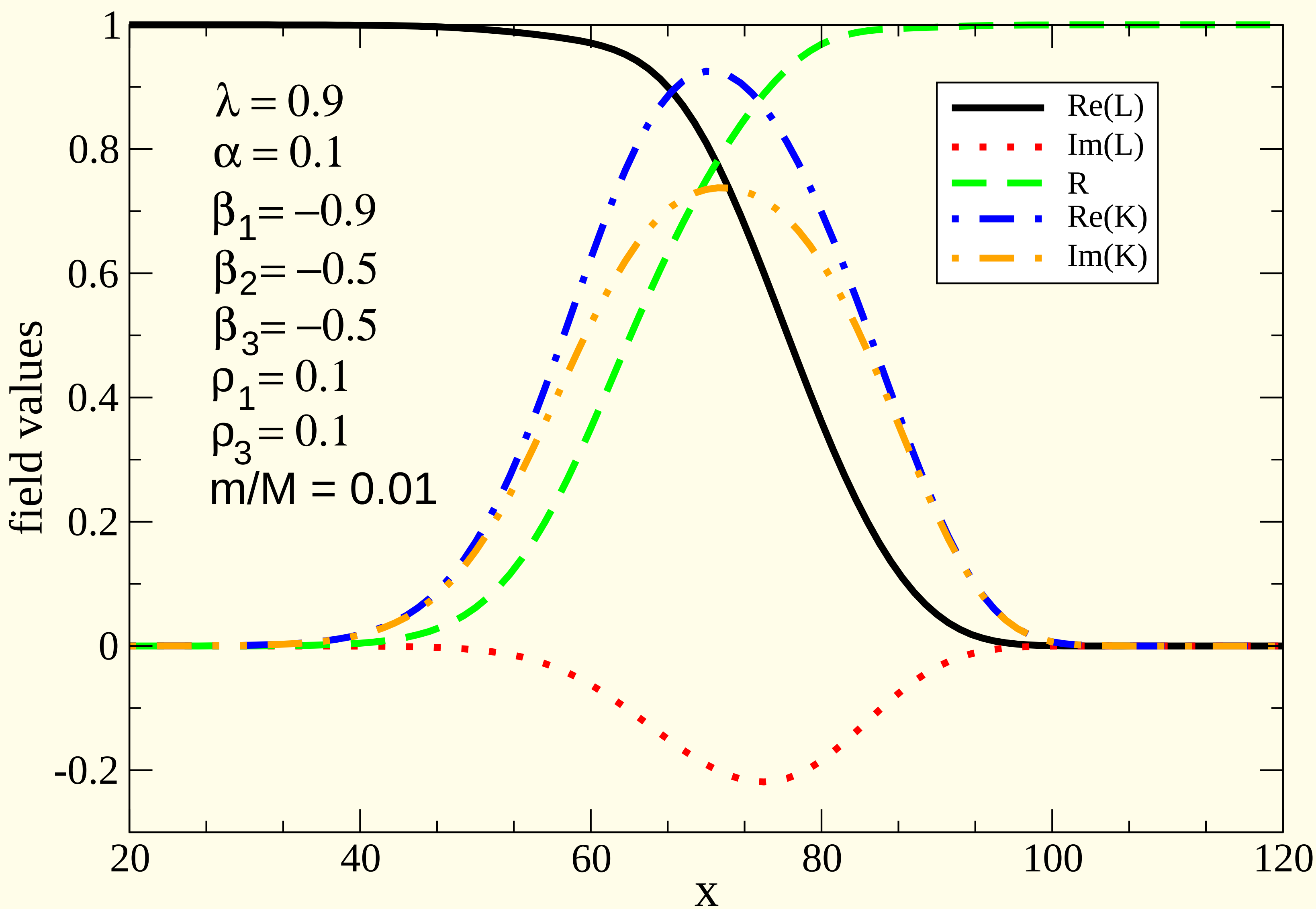
Narendra Sahu and UAY (PRD 2005)

Question : How to get large ”raw” L-asymmetry?

solution : Domain walls soon after the Left-Right symmetric phase (of SO(10)) allow non-thermal L-genesis.

Transient CP violation in the domain wall, similar to thick wall electroweak baryogenesis

J. Cline, UAY, Rabikumar and S. N. Nayak PRD (2002)



λ = 0.9
α = 0.1
β1 = –0.9
β2 = –0.5
β3 = –0.5
ρ1 = 0.1
ρ3 = 0.1
m/M = 0.01
Re(L)
Im(L)
R
Re(K)
Im(K)
field values
x
1
0.8
0.6
0.4
0.2
0
-0.2
20
40
60
80
100
120

Need for extension

- Hierarchy issue was not addressed. Can we obtain the same results with Supersymmetry?

- Can we tie up spontaneous parity breaking with SUSY breaking?

Gravitino & Moduli problem

T. Matsuda PLB (2000); M. Kawasaki F. Takahashi PLB (2005)

	Gravity mediated	Gauge mediated
Gravitino:	$m_{3/2} \sim 10^{2-3}\,\mathrm{GeV}$; Decays after BBN; photons produced disrupts the usual BBN	$m_{3/2} \sim 10\,\mathrm{eV} - 1\,\mathrm{GeV}$ Gravitino is stable; If $m_{3/2} > 1\,\mathrm{KeV}$, universe gets overclosed, unless gravitino is diluted
Moduli fields: Potential should be flat, raised by $m_\phi \sim m_{3/2}$	Decays after BBN; creates same problem as gravitino	Overcloses universe for $m_\phi < 100\,\mathrm{MeV}$; For $m_\phi \sim 10^{-1} - 10^4\,\mathrm{MeV}$, decay of moduli contributes in excess to γ - ray background spectrum

Supersymmetric Left-Right Model

Gauge group: $SO(10) \supset SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

Aulakh, Benakli and Senjanovic PRL (1997)

Quark and leptonic superfields:

$$Q = (3, 2, 1, 1/3), \qquad Q_c = (3^*, 1, 2, -1/3)$$
$$L = (1, 2, 1, -1), \qquad L_c = (1, 1, 2, 1)$$

Higgs sector:

$$\Phi_i = (1, 2, 2, 0), \qquad i = 1, 2$$
$$\Delta = (1, 3, 1, 2), \qquad \bar{\Delta} = (1, 3, 1, -2)$$
$$\Delta_c = (1, 1, 3, -2), \qquad \bar{\Delta}_c = (1, 1, 3, 2)$$

However, minimal supersymmetric model (MSSM) cannot break parity spontaneously.

Supersymmetric Left-Right Model

Way out: To break $SU(2)_R\,(SU(2)_L) \to U(1)_R\,(U(1)_L)$, without breaking $B - L$.

– Parity is spontaneously broken

– Electromagnetic charge preserved

To achieve this two extra Higgs fields are required

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

Supersymmetric Left-Right Model

F and D-flat conditions for the Lagrangian of the model suggest two types of vevs.

Type I: Left-handed field vev's are taken to vanish while the right-handed fields have vev's,

$$\langle \Delta \rangle = \langle \bar{\Delta} \rangle = \langle \Omega \rangle = \langle L \rangle = 0$$

$$\langle \Delta_c \rangle = \begin{pmatrix} 0 & 0 \\ d_c & 0 \end{pmatrix}, \langle \bar{\Delta}_c \rangle = \begin{pmatrix} 0 & \bar{d}_c \\ 0 & 0 \end{pmatrix}, \langle \Omega_c \rangle = \begin{pmatrix} \omega_c & 0 \\ 0 & -\omega_c \end{pmatrix}, \langle L_c \rangle = 0$$

Type II: Right-handed field vev's are taken to vanish while the left-handed fields have vev's,

$$\langle \Delta_c \rangle = \langle \bar{\Delta}_c \rangle = \langle \Omega_c \rangle = \langle L_c \rangle = 0$$

$$\langle \Delta \rangle = \begin{pmatrix} 0 & 0 \\ d & 0 \end{pmatrix}, \langle \bar{\Delta} \rangle = \begin{pmatrix} 0 & \bar{d} \\ 0 & 0 \end{pmatrix}, \langle \Omega \rangle = \begin{pmatrix} \omega & 0 \\ 0 & -\omega \end{pmatrix}, \langle L \rangle = 0$$

Supersymmetric Left-Right Model

According to the vev's the Higgs fields gets we can have,

Type I:

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$
$$\downarrow$$
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L}$$
$$\downarrow$$
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Type II:

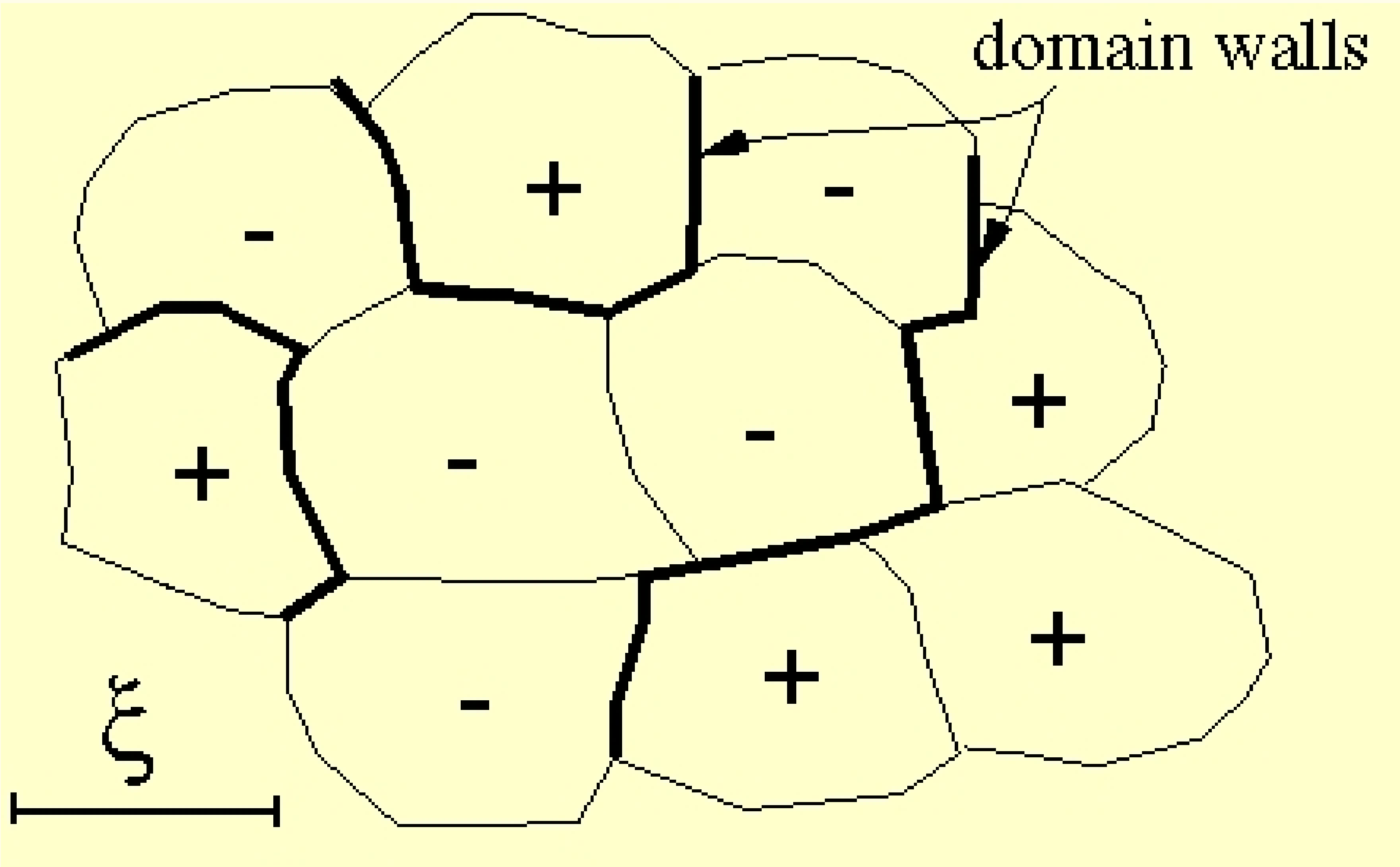
$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$
$$\downarrow$$
$$SU(3)_c \otimes U(1)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$
$$\downarrow$$
$$SU(3)_c \otimes SU(2)_R \otimes U(1)_Y$$

M_R = 1st stage of breaking $\sim 10^6$ GeV,

M_{B-L} = 2nd stage of breaking $\sim 10^4$ GeV

– Formation of Domain Walls at $\sim M_R$

– Domain Wall dominated Inflation


domain walls
+
-
ξ

Weak Inflation

The gravitino number density at low temp T_f is given by,

$$n_{3/2}(T_f) = 3.35 \times 10^{-12}\, T_9^{\rm max}\, T_f^3 \times (1 - 0.018 \ln T_9^{\rm max})$$

where, $T_9^{\rm max} = T/10^9\,{\rm GeV}$. At $T_f = 10^6\,{\rm GeV}$ we have,

$$n_{3/2}(T_f) = 3.35 \times 10^6 ({\rm G}eV)^3 \equiv n_{3/2}^{wb}$$

As $n \propto R^{-3}$ we have,

$$R_{we} = R_{wb}\left(\frac{n_{3/2}^{wb}}{n_{3/2}^{we}}\right)^{1/3}$$

where, R_{wb} (R_{we}) and $n_{3/2}^{wb}$ ($n_{3/2}^{we}$) are the scale factor and gravitino density at beginning (end) of weak inflation

Weak Inflation

The decay of gravitino into photons shouldn't disturb the balance of light nuclei. This constraint is given by, Ellis, Kim and Nanopoulos, PLB (1984)

$$\frac{m_{3/2} f \beta n_{3/2}}{n_e E_*} \lesssim 1$$

Putting the values $f = 0.8$, $\beta = 0.23$, $n_e = 7/8\ n_B$, $E_* = 100\ \mathrm{MeV}$ we have,

$$n_{3/2}^{we} \lesssim 1.66 \times 10^{-21} (\mathrm{GeV})^3$$

where, $\delta_B = n_B / n_\gamma$ at time of gravitino decay

Therefore the inflation required is,

$$R_{we} = R_{wb} \times 1.26 \times 10^9, \text{ for } \delta_B = 10^{-8}$$

Soft Terms & Parameters

Domain Walls themselves are not good news for cosmology. To remove them we introduce soft terms:

$$\begin{aligned}\mathcal{L}_{soft} = & \alpha_1 \mathrm{Tr}(\Delta\Omega\Delta^\dagger) + \alpha_2 \mathrm{Tr}(\bar{\Delta}\Omega\bar{\Delta}^\dagger) + \alpha_3 \mathrm{Tr}(\Delta_c\Omega_c\Delta_c^\dagger) \\ & + \alpha_4 \mathrm{Tr}(\bar{\Delta}_c\Omega_c\bar{\Delta}_c^\dagger) \\ & + m_1 \mathrm{Tr}(\Delta\Delta^\dagger) + m_2 \mathrm{Tr}(\bar{\Delta}\bar{\Delta}^\dagger) + m_3 \mathrm{Tr}(\Delta_c\Delta_c^\dagger) \\ & + m_4 \mathrm{Tr}(\bar{\Delta}_c\bar{\Delta}_c^\dagger) \\ & + \beta_1 \mathrm{Tr}(\Omega\Omega^\dagger) + \beta_2 \mathrm{Tr}(\Omega_c\Omega_c^\dagger)\end{aligned}$$

For the domain walls to collapse, the inequality between L & R sector of the soft terms (ϵ), should be of the same order as temperature of the domain walls (T_d)

$$\epsilon \sim T_d^4$$

Preskill Trivedi Wilczek Wise., NPB (1991); Kawasaki, Takahashi PLB (2005)

Soft Terms & Parameters

The asymmetry between the two sectors has to be tiny. Otherwise the symmetry is broken even at high scale

How small can the asymmetry be?
The value of T_d can vary between $100\ \mathrm{MeV} - 10\ \mathrm{GeV}$
For $T_d \sim 100\ \mathrm{MeV}$ we have $\epsilon \sim 10^{-4}\ \mathrm{GeV}$. Thus we have,

$$(m - m') \sim 10^{-12}\ \mathrm{GeV}^2$$

Here we have considered $m_1 \backsimeq m_2 \equiv m$, $m_3 \backsimeq m_4 \equiv m'$

Similarly, for $T_d \sim 1\ \mathrm{GeV}$ (say) we have,

$$(\beta_1 - \beta_2) \ \sim \ 10^{-12}\ \mathrm{GeV}^2$$

The $\Delta\Omega\Delta$ terms doesn't contribute to the asymmetry for $\alpha_1 \sim \alpha_2$, $\alpha_3 \sim \alpha_4$

Soft Terms & Parameters

For $m_1 \mathrm{Tr}(\Delta\Delta^\dagger) + m_2 \mathrm{Tr}(\bar{\Delta}\bar{\Delta}^\dagger) + m_3 \mathrm{Tr}(\Delta_c\Delta_c^\dagger) + m_4 \mathrm{Tr}(\bar{\Delta}_c\bar{\Delta}_c^\dagger)$:

$$
\begin{aligned}
(m - m') &\sim 10^{-4}\,\mathrm{GeV}^2 \quad \text{if } T_d \sim 10\ \mathrm{GeV}\\
(m - m') &\sim 10^{-8}\,\mathrm{GeV}^2 \quad \text{if } T_d \sim 1\ \mathrm{GeV}\\
(m - m') &\sim 10^{-12}\,\mathrm{GeV}^2 \quad \text{if } T_d \sim 100\ \mathrm{MeV}
\end{aligned}
$$

For $\beta_1 \mathrm{Tr}(\Omega\Omega^\dagger) + \beta_2 \mathrm{Tr}(\Omega_c\Omega_c^\dagger)$:

$$
\begin{aligned}
(\beta_1 - \beta_2) &\sim 10^{-8}\,\mathrm{GeV}^2 \quad \text{if } T_d \sim 10\ \mathrm{GeV}\\
(\beta_1 - \beta_2) &\sim 10^{-12}\,\mathrm{GeV}^2 \quad \text{if } T_d \sim 1\ \mathrm{GeV}
\end{aligned}
$$

Need to search origin of small differences in the hidden sector SUSY breaking potential thus relating the same to parity breakdown.

Conclusion

- Demonstrted low energy leptogenesis – model dependent but robust mechanism

- Extension to SUSY can relate SUSY breaking mechanism and parity breaking mechanism

- Domain walls can be put to good use

- Success of the mechanism provides constraints on the SUSY + parity breaking mechanism in sthe hidden sector