Cosmology with PeV scale gauged B-L symmetry

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Overview

- left-right symmetric models as JSBM
  - the renormalisable SUSY version
  - intermediate $U(1)_{B-L}$
- Constraint of exact Parity
  - Domain wall dynamics and successful Cosmology
  - Non-thermal leptogenesis
- SUSY breaking and Parity breaking – a study

Left-right as JBSM

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

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

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

- Need a new hypercharge X –> turns out to be exactly $B - L$
  ... the only global charge of SM waiting to be gauged!

Minimal SUSY L-R Model – MSLRM

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.

– alt fixes, non-renormalisable terms or singlets not pursued here.

Requirement of discrete parity,

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

The F-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 ...)]

The Mass scale see-saw

- An R symmetry ensures Ω mass terms in superpotential are vanishing, no new spurious mass scale
- Usual R parity preserved
- 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 !!

Genesis of baryogenesis

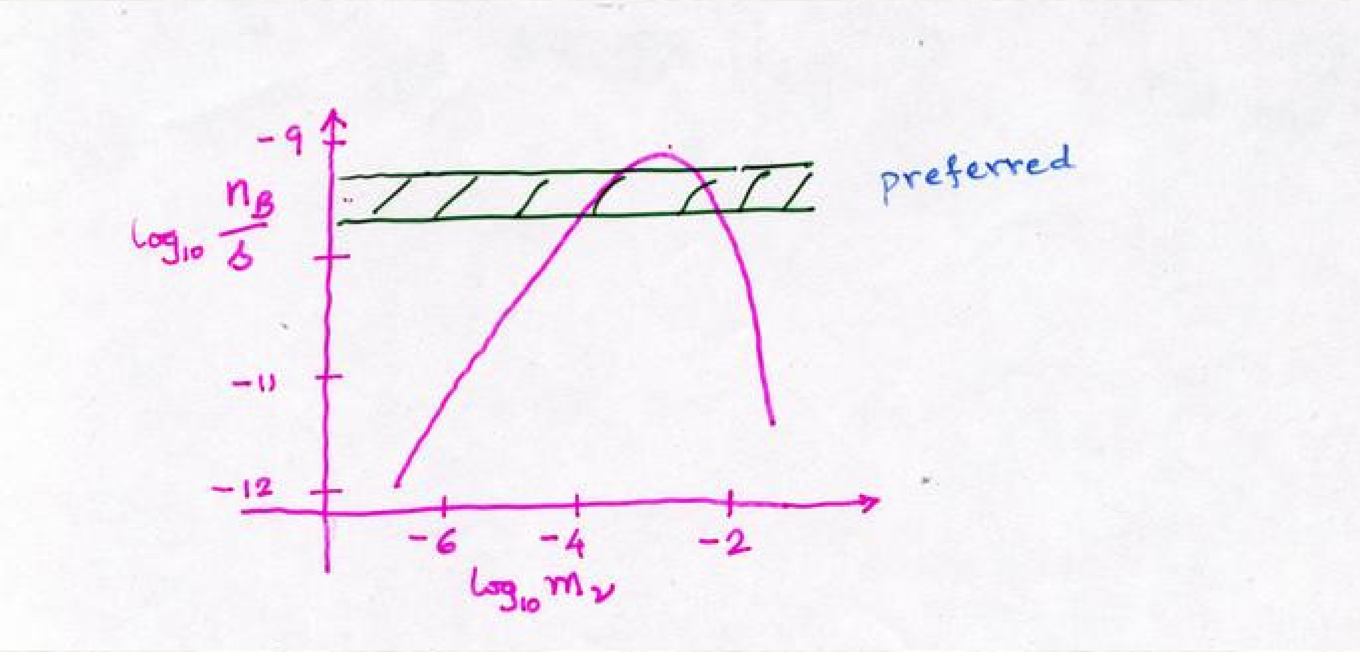
- CP violation discovery 1964
- CMBR discovery also 1965 ...
- The possibility of *dynamical origins* of baryon asymmetry

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

- Weinberg Brandeis lectures 1965; specific model Sakharov 1967

Leptogenesis - thermal case

Thermal leprogenesis in SO(10) (Buchmüller, Plümacher et al)



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

– Conflicts with Supersymmetric unification –> gravitino overproduction

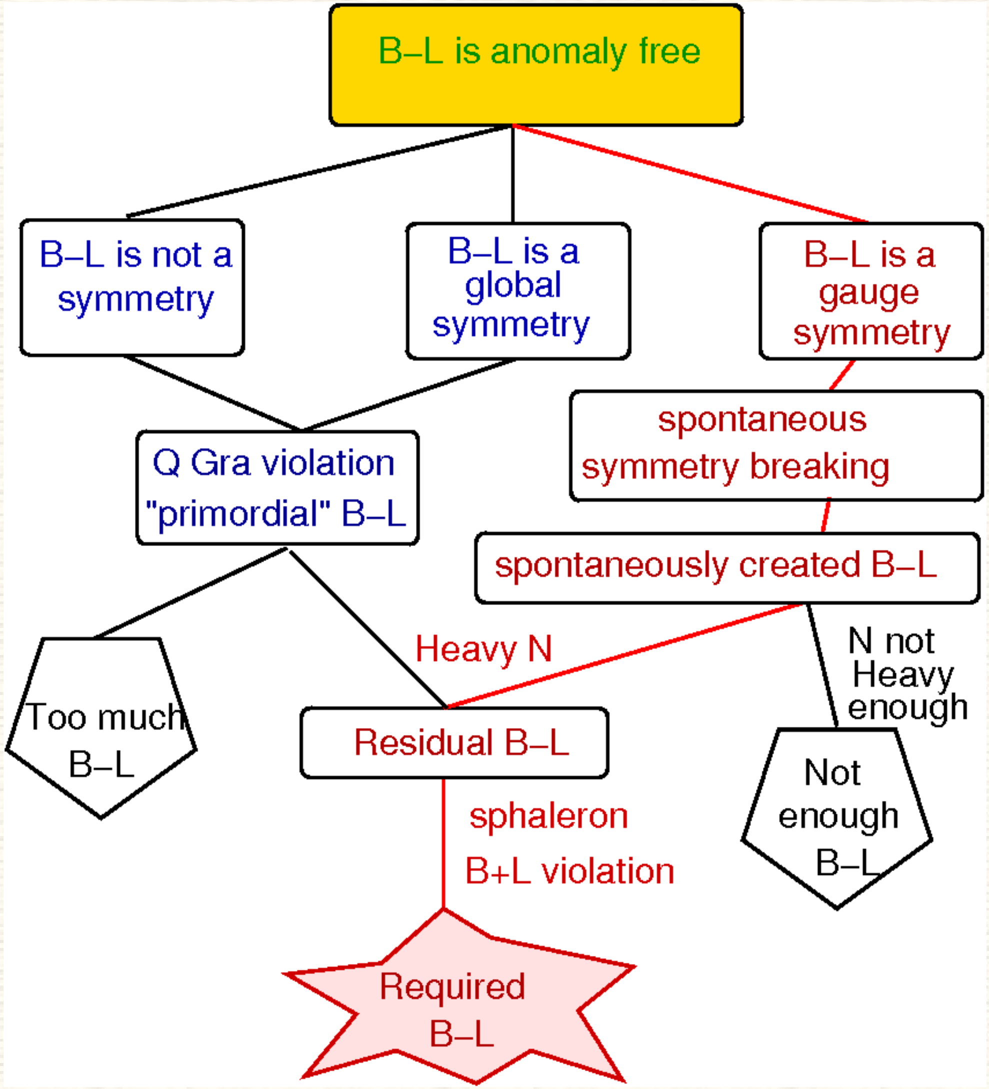
Neutrino mass and CP phase constraint

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

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

- Generically too small for producing the asymmetry

What choices did der Alte have?



Neutrino mass and (?) unification

How do we accommodate the neutrino mass?

- Higher order operator :

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

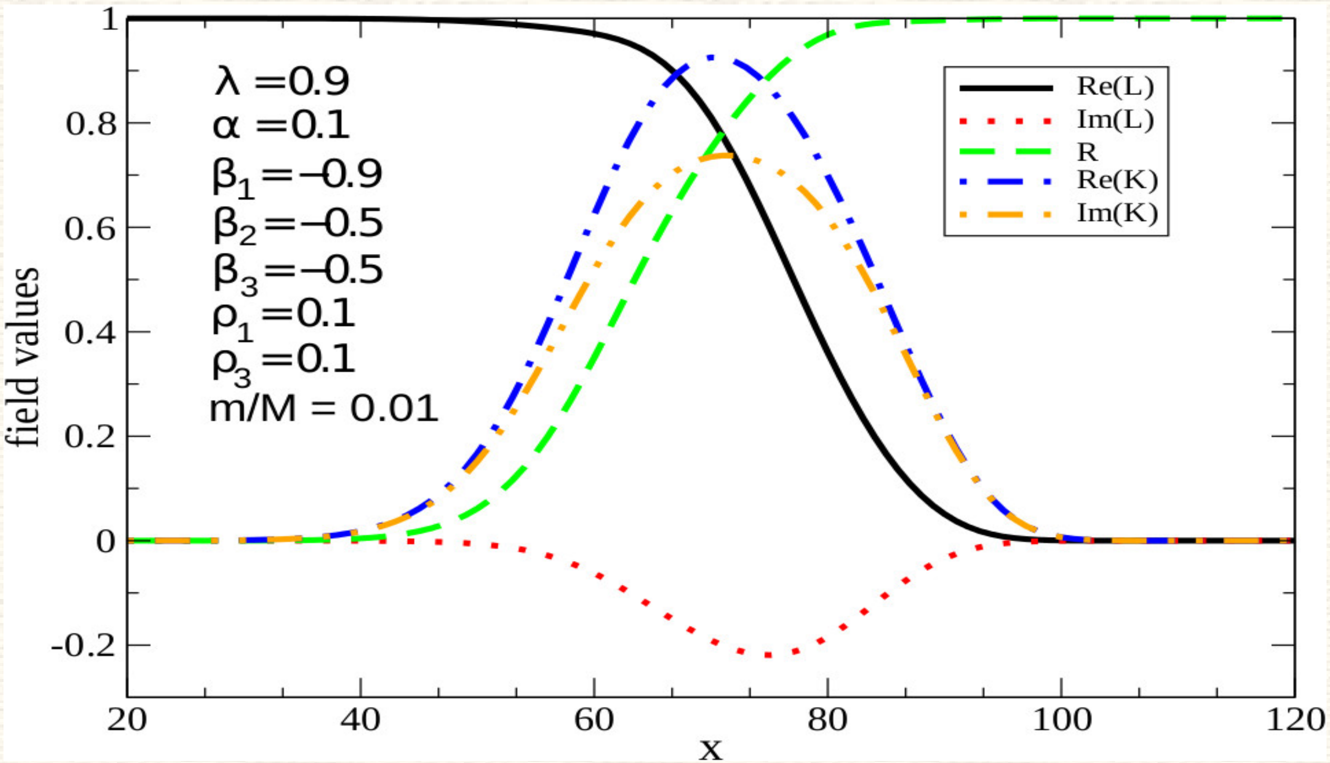
- Example : $m_\nu \sim O(0.1)$ eV $\Rightarrow \Lambda_\nu \sim O(10^{15})$ GeV
- We have not yet seen any sign of GUT scale
  - generically expect proton decay
- JBSM ideology ...
  - sequester majorana $M_{_N}$ from gauge coupling unification
  - Choose a convenient "pivot" for generic see-saw leptonic Dirac mass like m_τ or m_μ or m_e ... (words of stray wisdom)
  - $\Rightarrow M_{_N} \sim 10^{11}$GeV or $\sim 10^8$GeV or $\sim 10^4$ GeV respectively

Non-thermal leptogenesis

→ Parity breaking transition provides domain walls,

→ "First order" phase transition with bubble walls ensured

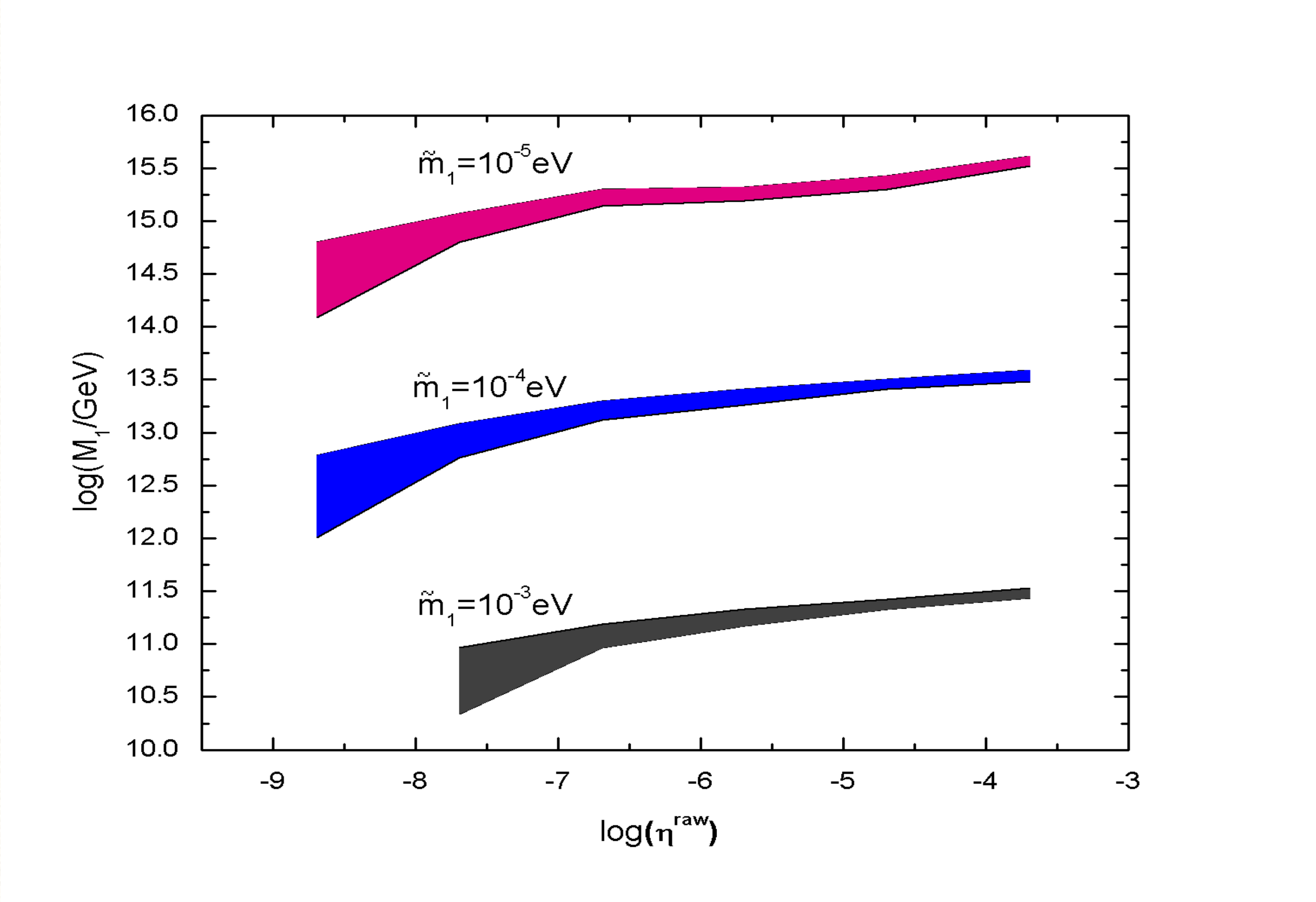
→ CP violating scalar condensate $\mathrm{Im}(\kappa)/\mathrm{Re}(\kappa)$



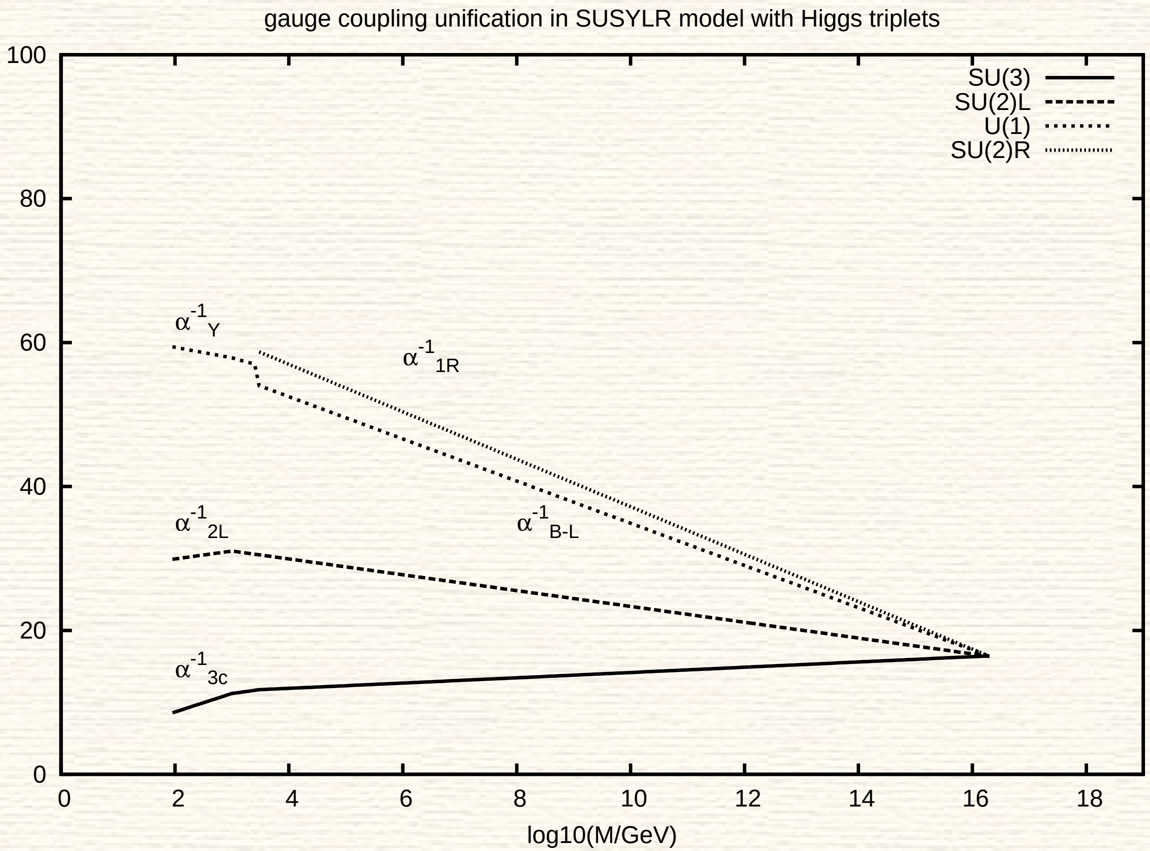
A simulated domain walls in a Left-Right symmetric model(A. Sarkar, UAY)

Can this lepton asymmetry with $M_{B-L} \ll M_R$ survive?

Yes! (Narendra Sahu and UAY 2005)



Unification ... conditional (eat the cake too)



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)

Parity breaking from Planck suppressed effects

Several caveats :

- Supergravity at the renormalisable level 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
  - However gravity horizons known to violate global symmetries
- Assume an unknown reason for (spontaneous) breaking of parity in the hidden sector, communicated by gravity.
- Use Kähler potential as the guide.

Removal of domain walls : baby version

For the theory of a generic neutral scalar field ϕ, the effective higher dimensional operators can be written as (Rai and Senjanovic)

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

In realistic theories, the structure of such terms conditioned by

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

Domain wall dynamics in radiation dominated phase

The dynamics of the walls is determined by two quantities :[Kibble; Vilenkin]

- *. 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.

Some dimensional analysis and "R2C2E[1]" yields,

$$\delta \rho \geq G \sigma^2 \approx \frac{M_R^6}{M_{Pl}^2} \sim M_R^4 \frac{M_R^2}{M_{Pl}^2} \quad (4)$$

1. "Reasoning too complicated to explain" in a short review; paraphrasing S. Rushdie, "Haroun and the Sea of Stories"

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 $\rho_W^{(in)} \sim \sigma H_i$
Let the temperature at which the domain walls are formed be $T \sim \sigma^{1/3}$. So

$$H_i^2 = \frac{8\pi}{3} G \sigma^{\frac{4}{3}} \sim \frac{\sigma^{\frac{4}{3}}}{M_{Pl}^2} \tag{5}$$

Thus we can set $M_{Pl}^{-2} T_D^4 \sim H_{eq}^2 \sim \sigma^{\frac{3}{4}} H_i^{\frac{1}{4}} M_{Pl}^{-3}$. The corresponding temperature permits the estimate of the required pressure difference,

$$\delta\rho > M_R^4 \left(\frac{M_R}{M_{Pl}}\right)^{3/2} \tag{6}$$

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

Planck scale terms in ABMRS model

[Sasmita Mishra and UAY 2010]

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

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 (gravitino constraint), $\kappa_{RD} \sim 10^{-4}$
– but $\kappa^A_{RD} \sim 10^8$ (highly unnatural) if $M_R \sim 10^{15}$GeV

For walls which live through MD era or era off oscillating inflaton,

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

– again, $M_R \sim 10^9$GeV $\Rightarrow \kappa_{MD} > 10^{5/2}$, unnatural and worse for GUT.

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

Conclusions and caveats

- Thermal leptogenesis is viable and appealing –> lives necessarily at high scale and in tension with other favorite themes
- JBSM Minimal SUSY Left-Right model as an appealing model to compare PeV scale phenomena against :
  - UV completion through SUSY / extra dimensions
  - Leptogenesis through L-R domain walls –> robust conclusion about the nature of phase transition
  - Domain wall removal provides upper bound on M_N
  - A very low $B - L$ scale possible
  - Acknowledgment : Narendra Sahu, Anjishnu Sarkar, Sasmita Mishra, Debasish Borah.

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Dankeshön!

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