Baryon asymmetry of the Universe and CP violation

BY U. A. YAJNIK, *IIT Bombay*

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Overview

- Three paradigms of baryogenesis :
  - GUT decay ... essentially thermal
  - TeV scale ... essentially non-thermal
  - Leptogenesis ... both possibilities
- Sphaleron physics
  - MSSM status
- Leptogenesis – the thermal case
  - ... very constrained
  - relation to light neutrino data
- Leptogenesis – the non-thermal case
  - ... lack of quantititve constraints
  - robust relation to spontaneous parity violation
- Some observational possibilities
  - Gravitational waves from bubble wall decays

Current status

From Nucleosynthesis calculations and

observed obundances of D, ^{3}He, ^{4}He and ^{7}Li,

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \cong 5 \times 10^{-10}\,; \qquad 0.017 < \Omega_B h^2 < 0.024$$
$$H_0 \equiv h 100\,\mathrm{km}/s/\mathrm{Mpc}; \qquad h \cong 0.7$$

Note from random fluctuations at the QCD scale, the residual η would be 10^{-17}

From WMAP data,

$$\Omega_B h^2 \cong 0.022$$

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; esp. Sakharov 1967 proposes :

GUT scale baryogenesis

(Sakharov 1967; Yoshimura; Weinberg 1978)

1. There should exist baryon number B violating interaction

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

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

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

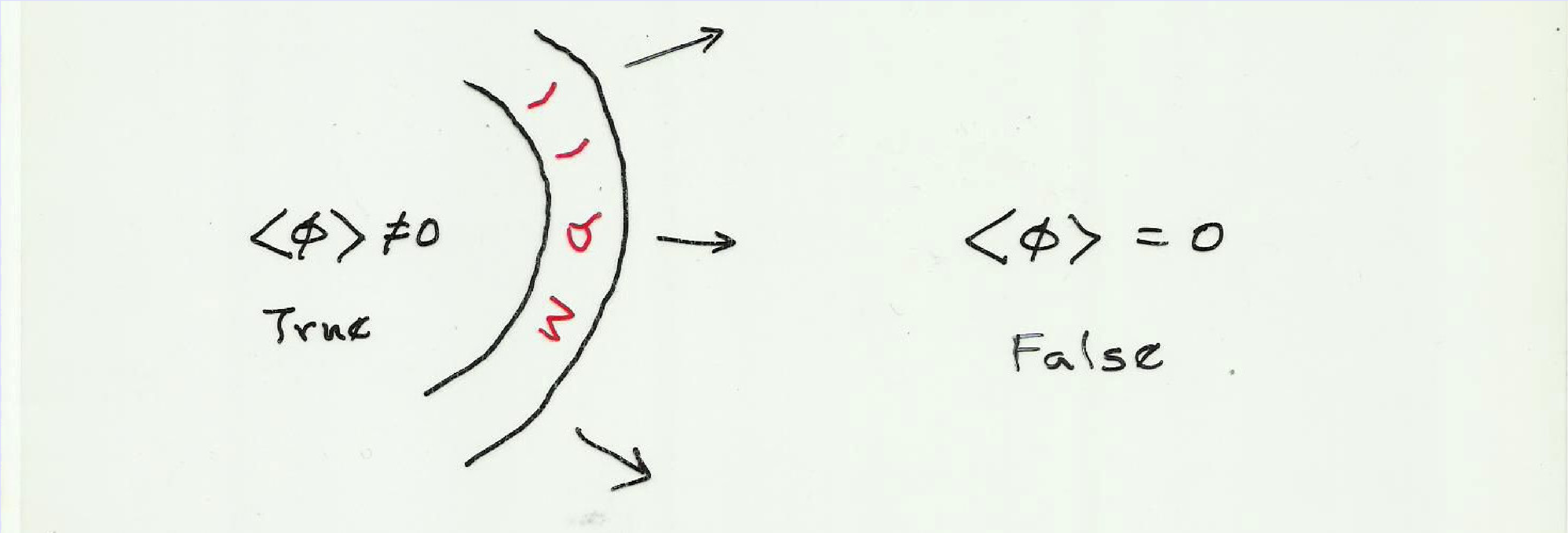
However, rather startling additional inputs appear from global apects of SM gauge group.

TeV scale baryogenesis

- 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
- Expansion rate H too slow at electroweak scale – need another source of out of equilibrium conditions –> First Order Phase Transition (FOPT)
- First order phase transition in SM requires Higgs mass to be $\lesssim 90$GeV



– 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

In either case we need to go beyond the SM :

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

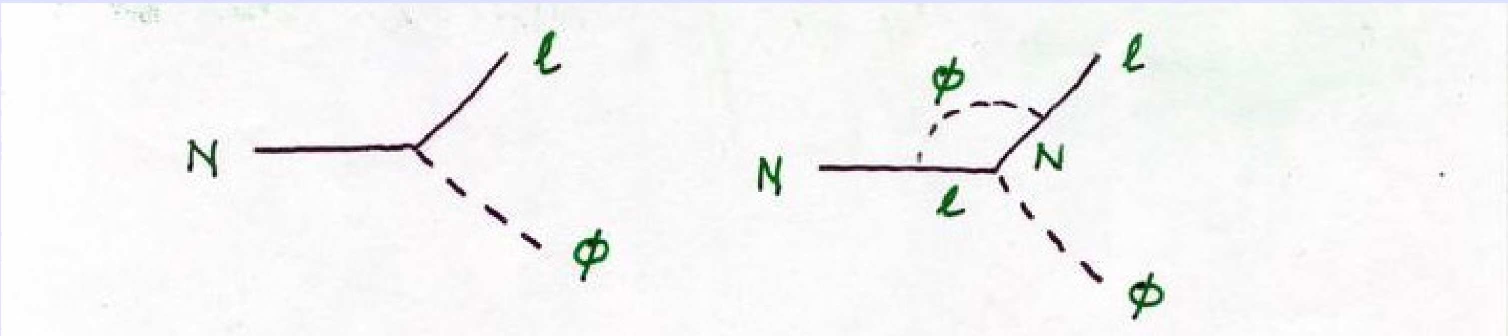
→ At least two scalars as order parameters of the phase transition. Minimal model : 2 Higgs Doublets

→ MSSM as realistic and adequate (summary later)

Leptogenesis

(Fukugita and Yanagida 1986)

- Out of equilibrium decay of heavy Majorana neutrinos

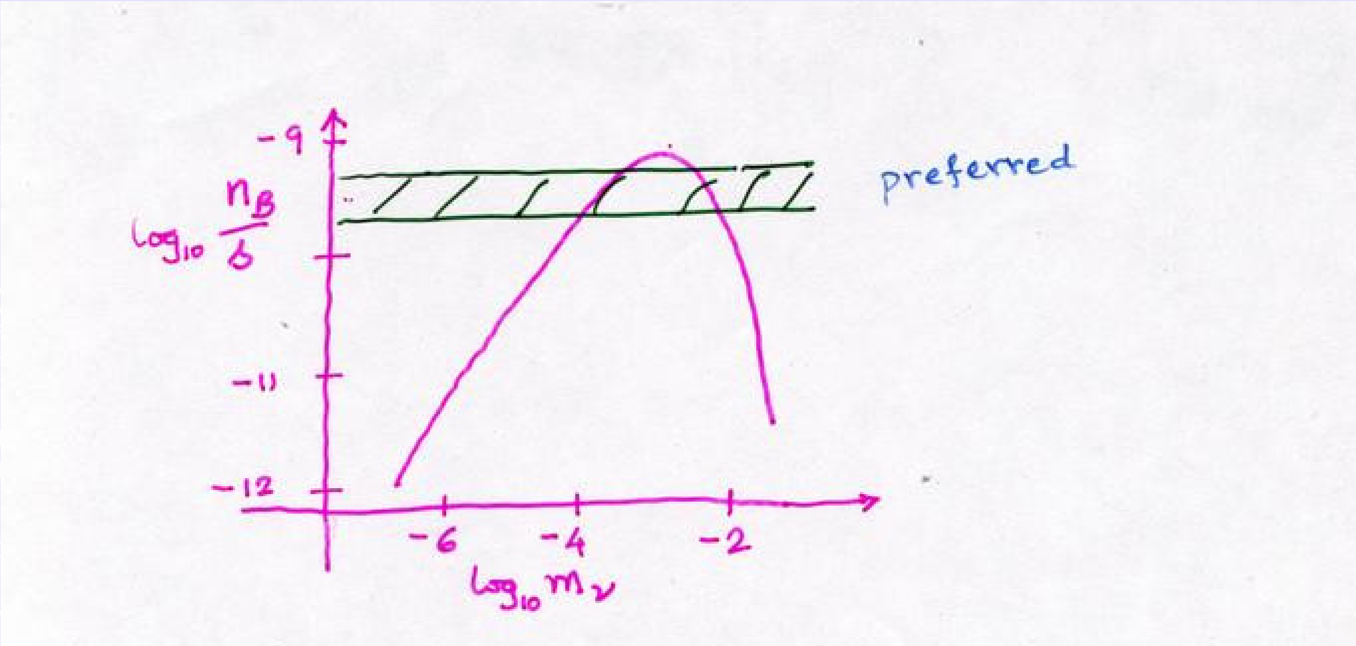


- Easy to arrange CP violation due to complex vacuum expectation values of scalar fields producing the mass

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

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

Thermal leprogenesis in SO(10) (Buchmuller, Plumacher et al)



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

m_ν too large : Erasure processes too efficient

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

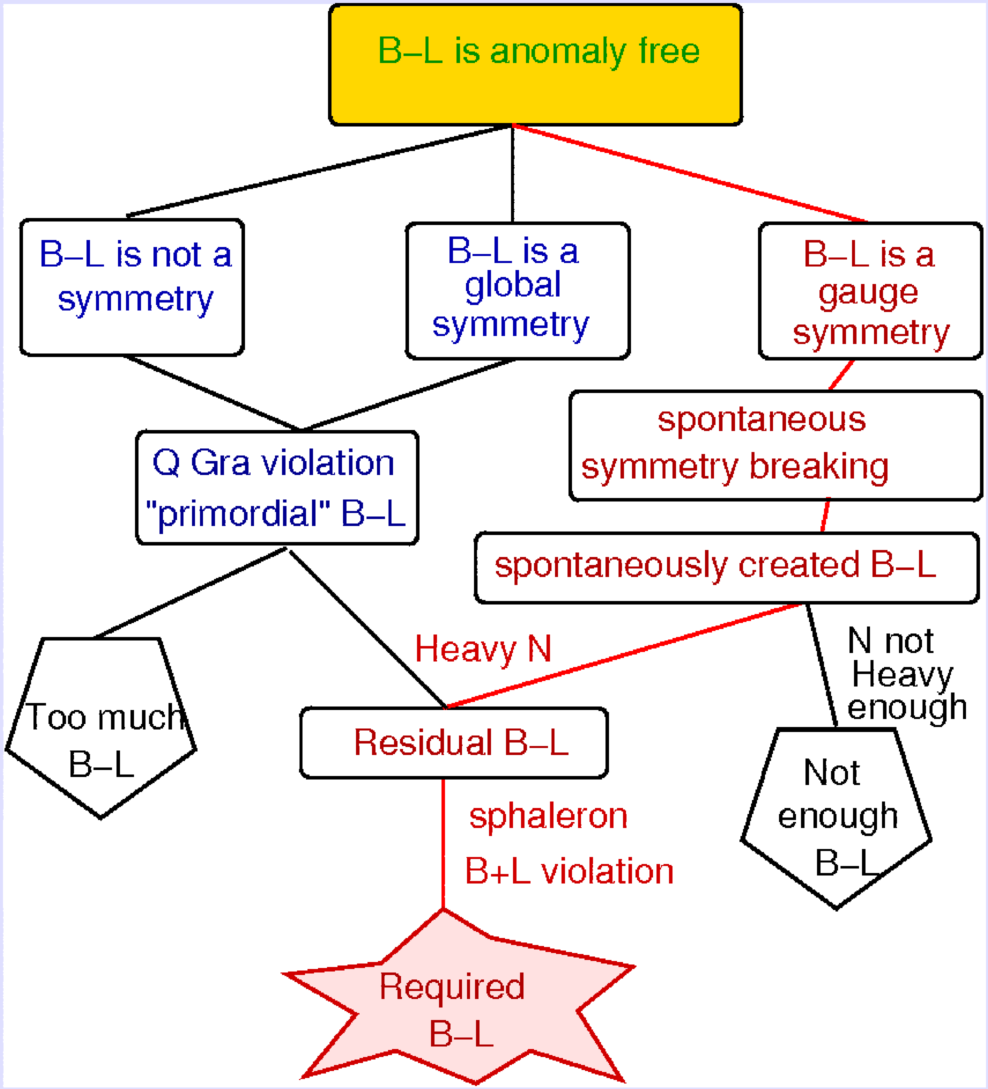
More on Leptogenesis

- $M_N \gtrsim 10^9$ GeV – does not sit well with hierarchy in non-SUSY case
  - Conflicts with Supersymmetric unification –> gravitino overproduction
- Low energy neutrino mass differences are reasonably well constrained
- Analysis of see-saw formula with three generations taken into account show, for thermal leptogenesis, (Davidson and Ybarra)

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

- This can be too small for producing the asymmetry

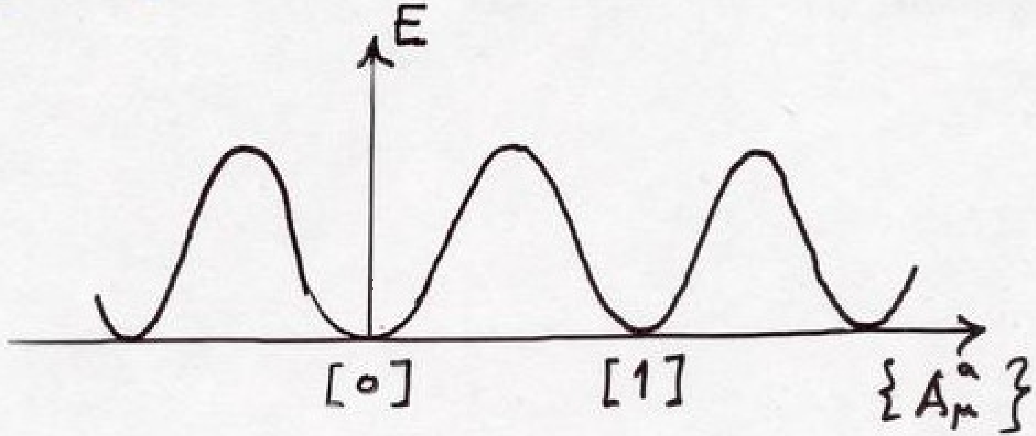
What choices did god have?



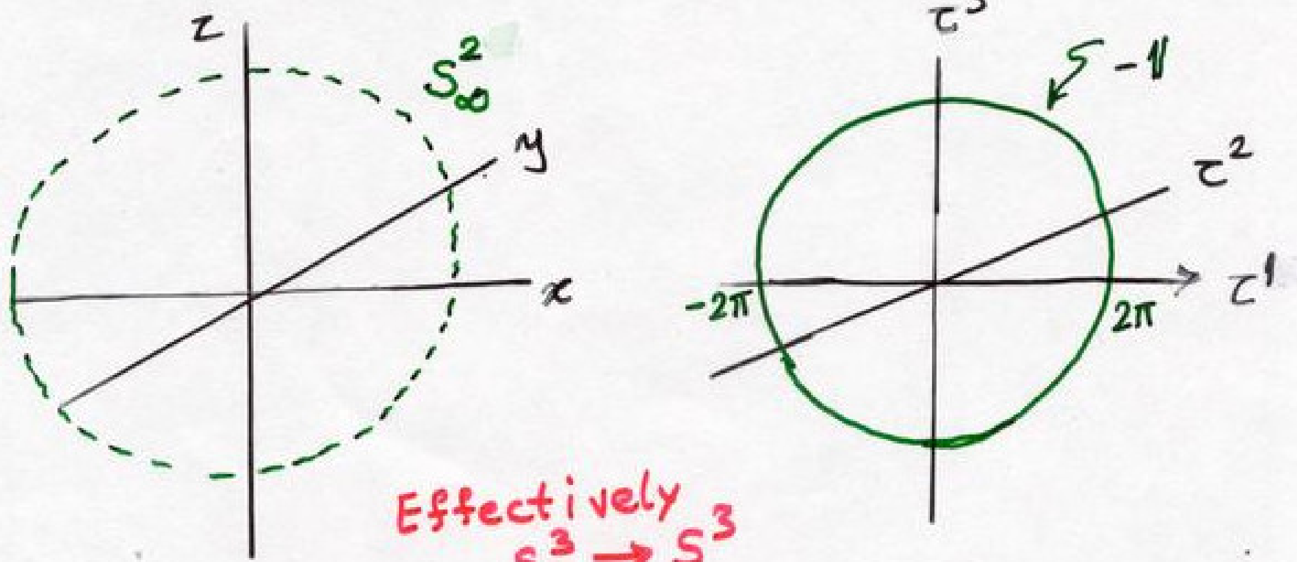
Details of : Anomalous violation of $B + L$

- Gauge theories are non-linear and possess a non-trivial vacuum structure (Jackiw-Rebbi 1973; Klimkhammer-Manton; Soni 1984)

"Large" gauge transformations



$$U_{J\text{-}R}^{[1]} = \frac{\lambda^2 - r^2}{\lambda^2 + r^2} + i\,\frac{2\,\vec{\tau}\cdot\vec{r}\,\lambda}{\lambda^2 + r^2}$$



Effectively
$S^3 \rightarrow S^3$

Each vacuum characterised by

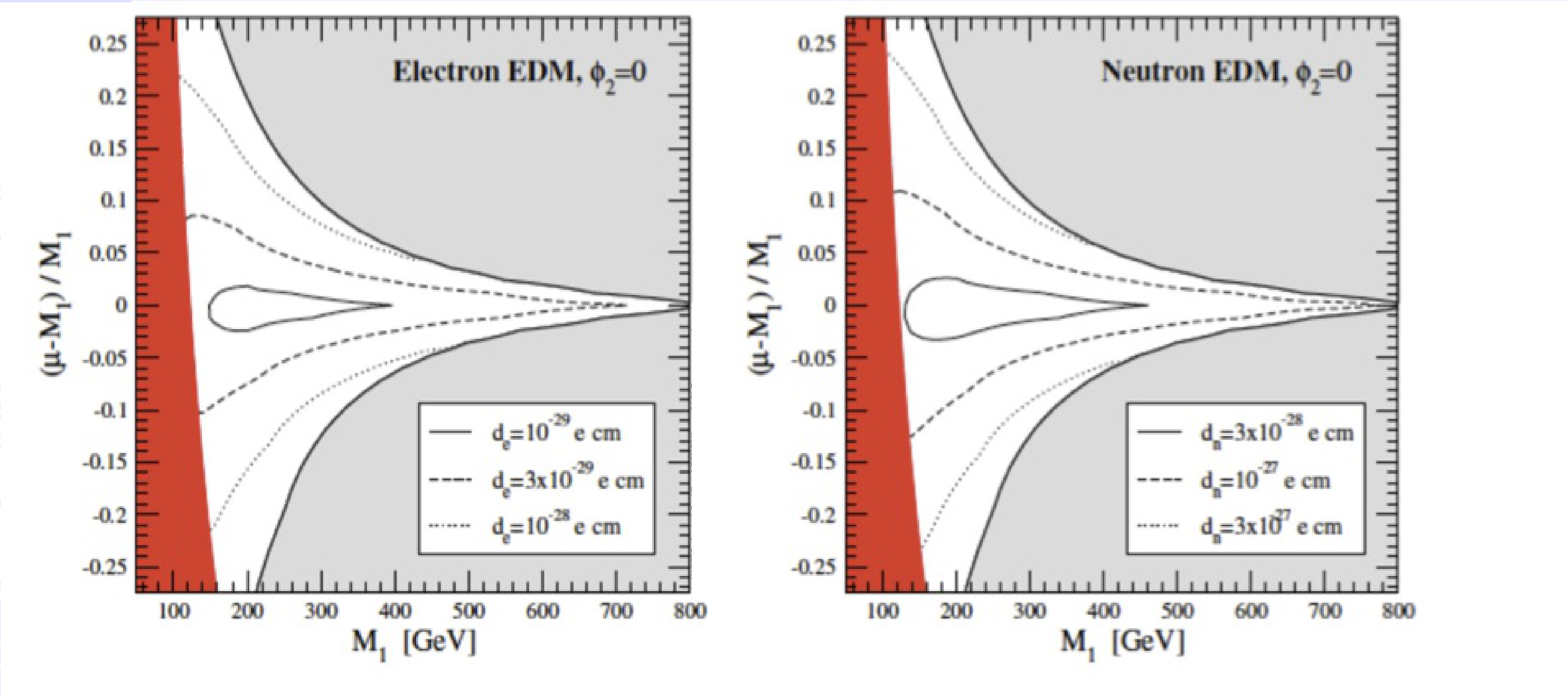
$$N_g = \int d^3x \, K^0$$

where

$$K^\mu = \mathrm{Tr}\, \varepsilon^{\mu\nu\rho\sigma} \left(A_\nu \partial_\rho A_\sigma - \frac{2}{3} A_\nu A_\rho A_\sigma \right)$$

Interestingly, if there are chiral fermions coupled to this gauge field, then their axial current turns out to be anomalous in QFT, resulting in

$$\Delta N_F = \Delta N_g$$



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.

Neutrino mass and after

How do we accommodate the neutrino mass?

- $M_L \overline{\nu_L^C} \nu_L$ violates the $\mathrm{SU}(2)_L$ invariance.

- Higher order operator :

$$\mathcal{L} \sim \frac{c_1}{\Lambda_\nu} \mathrm{Tr}\left(\phi \tilde{\phi}^\dagger l_L \bar{l_L^C} \right) \sim \frac{c_1}{\Lambda_\nu} \overline{\nu_L^C} \langle \phi \rangle^2 \nu_L$$

- 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.

→ It did, provided $m_D \approx 100$GeV. (Still $M_{\rm GUT} \sim 10^{16}$GeV, $M_N \sim 10^{12}$GeV)

→ The only guide to neutrino Dirac mass m_D could be charged fermions mass.

→ Unfortunately m_D values for charged fermions are scattered from 175GeV to 1 MeV.

→ Unfortunately also, light neutrino mass differences (known since 1998) imply an order of magnitude variation in m_2 values.

Left-right as JBSM

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

Gauged $B - L$

	τ_L^3	τ_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

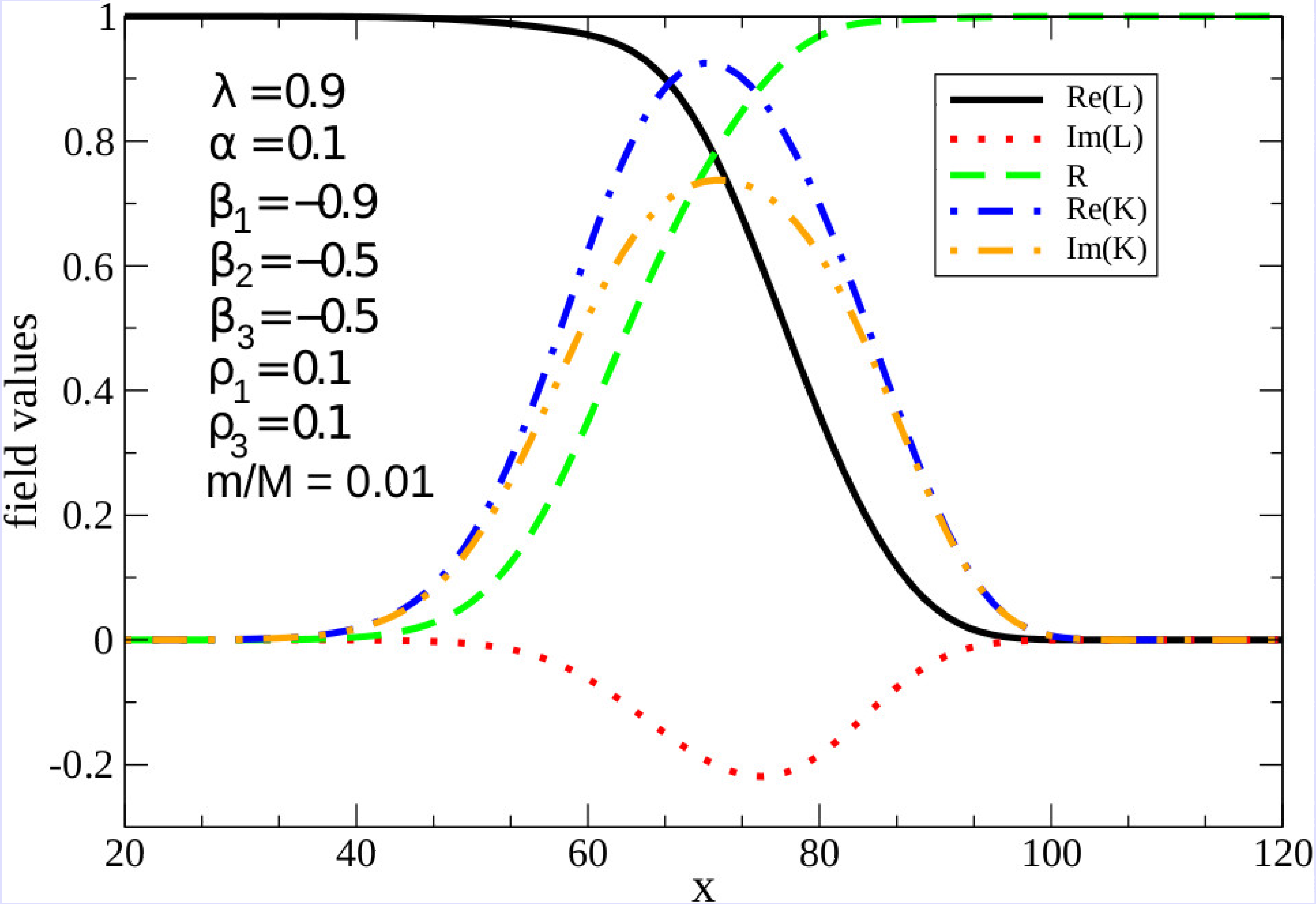
	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
$\lceil u_L \rceil$	$+\frac{1}{2}$	0	$+\frac{1}{6}$	$+\frac{2}{3}$
$\lfloor d_L \rfloor$	$-\frac{1}{2}$	0	$+\frac{1}{6}$	$-\frac{1}{3}$
$\lceil u_R \rceil$	0	$+\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$
$\lfloor d_R \rfloor$	0	$-\frac{1}{2}$	$+\frac{1}{6}$	$-\frac{1}{3}$

- Introduced new species ν_R –> as a partner to e^-_R
- New gauge symmetry $\mathrm{SU}(2)_R$
- Need a new hypercharge X –> turns out to be exactly $B - L$
- In praise of $B - L$ ... the only conserved charge of SM which is not gauged! –> Hereby it gains the status of being gauged

Non-thermal leptogenesis

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. (Sarkar, UAY 2003)

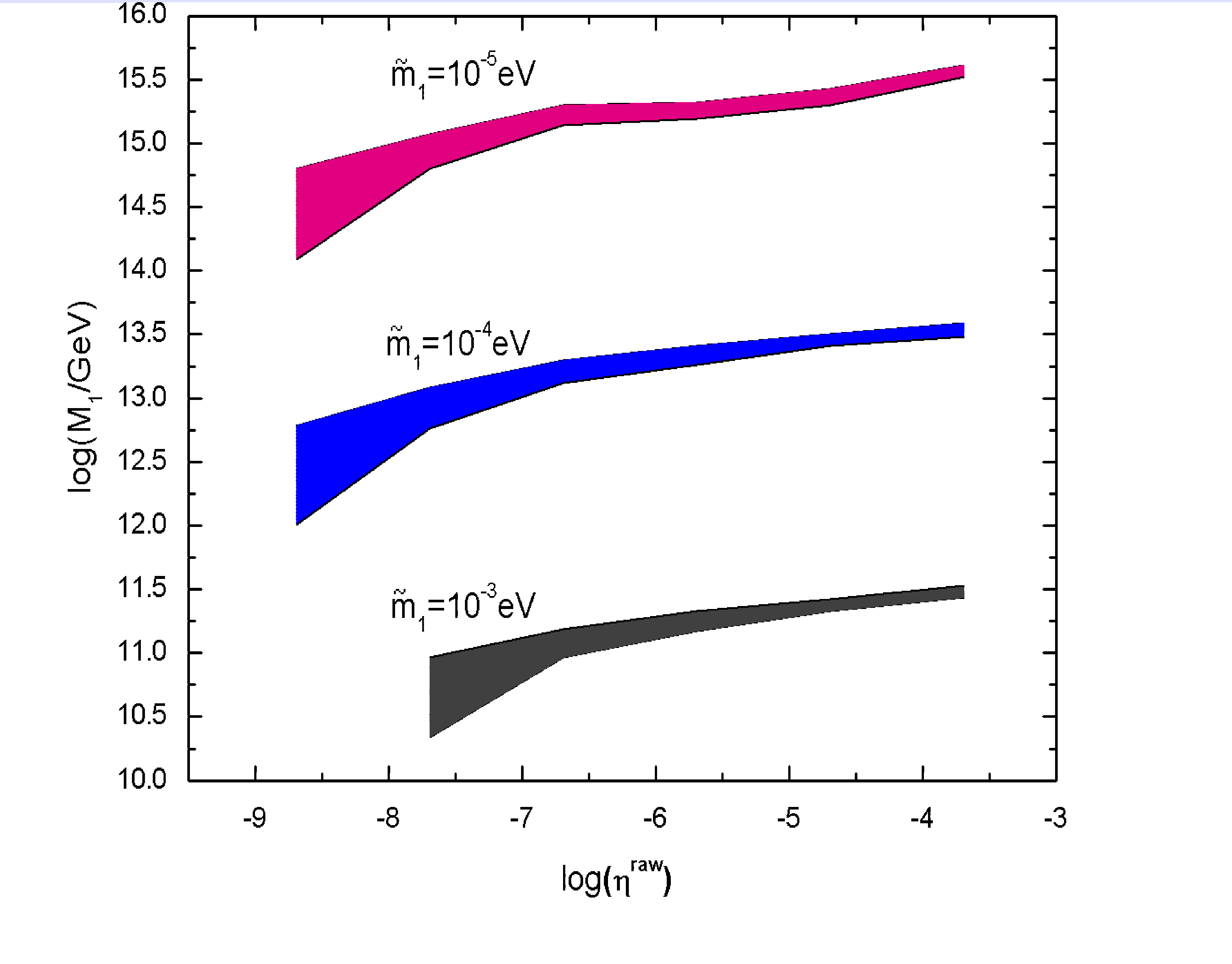
- The left-right symmetric model has domain walls, with sufficient CP violation provided by the scalar condensates to produce lepton number at a low scale.
- The effect is the same as having bubble walls



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

Can this lepton asymmetry survive?

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



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
log(M1/GeV)
m̃1=10-5eV
m̃1=10-4eV
m̃1=10-3eV
-9
-8
-7
-6
-5
-4
-3
log(ηraw)

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

- MSSM baryogenesis is severely constrained

  - Also unclear whether the CP phase can be ascertained in LHC

- Our recommendation : Believe in JBSM Left-Right model

  - UV completion through SUSY / extra dimensions

  - Leptogenesis through L-R domain walls –> robust conclusion about the nature of phase transition

  - Main problem of JBSM : how to get rid of the domain walls after they did their job. (Narendra Sahu, Anjishnu Sarkar, Sasmita Mishra, Debasish Borah).

THANK YOU