Leptogenesis with Left-Right domain walls

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- Motivations
- Message from "Electroweak B-gen"
- Salient features of L-R
- Calculations
- Results

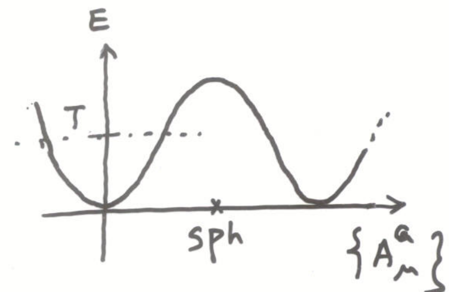
PASCOS Jan '03

Implications of the sphaleron

Zero temp. tunnelling governed by instanton rate $\sim e^{-1/g^2}$

Sphaleron is the smallest barrier height separating neighbouring vacua.

At $T \neq 0$, states in the left well are occupied as $e^{-\beta E}$



For $0 \ll E \ll E_{sph}$

estimate crossing rate $\sim \langle p\,\Theta(p)\,\delta(x_{bar})\rangle_T$

Arnold - Mclerran formula

$$\Gamma = A\,\kappa\,(\mathcal{N}\mathcal{V})_0\,T^4\,e^{-E_{sph}(T)/T}$$

sphaleron zero-mode volume

other fluctations

valid for $M_W \ll T \ll M_W/\alpha_W$

Higgs mass bound

$\Gamma \sim \alpha_W^5 T^4 \qquad T \gg M_W \quad ; \quad T \lesssim 10^{12}\,\mathrm{GeV}$

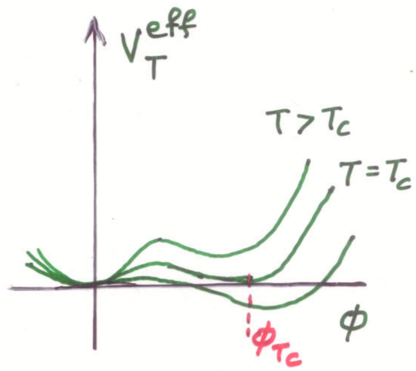
Rapid depletion of GUT generated B+L

Electroweak B-genesis

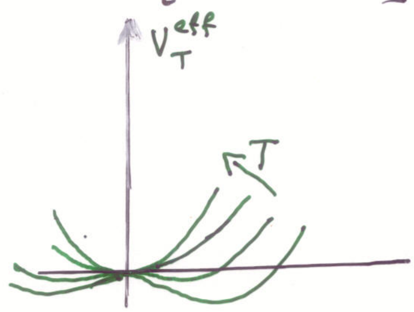
[KRS] optimism

$\cancel{B}$, $\cancel{C}$, $\cancel{CP}$ all present in SM

Out-of-equil. conditions result from first order phase transition [F.O.P.T.]



F. O. P. T.



spinodal decomposition

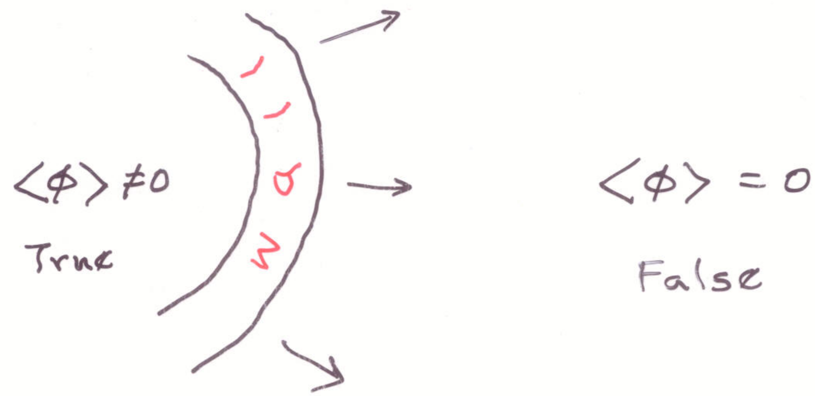
In F.O.P.T. bubbles of true vacuum nucleate for $T < T_c$

Expansion of bubble walls is the required irreversible process.

Crucial requirements

- FOPT
- sufficient $\cancel{CP}$
- prevent washout

Typical B-genesis scenario



Mechanisms relying on

1. dynamics of the scalar field(s) in the bubble walls (McLerran, Shapo. (Turok, Zadrozny, Voloshin

   requires adiabatic conditions
   i.e. wall thickness $\gg \underbrace{10\, T_c^{-1}}_{\sim \text{inverse plasma masses}}$

2. dynamics of fermions scattering from the wall (Cohen, Kaplan, Nelson

   class I : thin walls
   class II : thick walls

Thick walls or thin walls?

Left - Right symmetric model

q - L symmetry

	T_3^L	$\frac{1}{2}Y$
ν	$1/2$	$-1/2$
e^-	$-1/2$	

$$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \quad \begin{array}{c} 1/2 \\ -1/2 \end{array} \left.\vphantom{\begin{array}{c} 1 \\ 1 \end{array}}\right\} -1/2$$

ν_R	0	0
e^-_R	0	-1

Left - Right symmetric model

q - L symmetry

	T_3^L	$\frac{1}{2}Y$	T_3^R	$\frac{1}{2}X$
ν_L	$1/2$	$-1/2$	0	$-1/2$
e^-_L	$-1/2$	$-1/2$	0	$-1/2$
ν_R	0	0	$1/2$	$-1/2$
e^-_R	0	-1	$-1/2$	$-1/2$

s.t. $\frac{1}{2}Y = T_3^R + \frac{1}{2}X$

$X = \frac{1}{2}(B-L)$

Higgs structure

$\Delta_L : (3, 0, 1) \qquad \Delta_L \longrightarrow u_L \Delta_L u_L^\dagger$

$\Delta_R : (0, 3, 1) \qquad \Delta_R \longrightarrow u_R \Delta_R u_R^\dagger$

$\Phi : (2, 2, 0) \qquad \Phi \rightarrow u_L \Phi u_R^\dagger$

Yukawa couplings

$$\mathcal{L}_Y = h \bar{\Psi}_L \Phi \Psi_R + \tilde{h} \bar{\Psi}_L \tilde{\Phi} \Psi_R$$
$$+ f \left(\Psi_L^T C^{-1} \tau_2 \Delta_L \Psi_L + \Psi_R^T C^{-1} \tau_2 \Delta_R \Psi_R \right) + h.c.$$

Salient effects in L-R model

- Natural source of majorana mass at high scale v_R
- Weak hypercharge descends from B-L which now becomes gauged.

$$SU(2)_L \otimes \underbrace{SU(2)_R \otimes U(1)_{B-L}}$$

$$\Big\downarrow v_R \qquad \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R e^{i\theta} & 0 \end{pmatrix}$$

$$(0,1,1)$$

$$\underbrace{SU(2)_L \otimes U(1)_Y}$$

$$\Big\downarrow v_L \qquad \langle \phi \rangle = \begin{pmatrix} \kappa_1 e^{i\alpha} & 0 \\ 0 & \kappa_2 \end{pmatrix}$$

$$(1/2, 1/2, 0)$$

$$\langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix}$$

$$U(1)_{EM} \qquad (1,0,1)$$

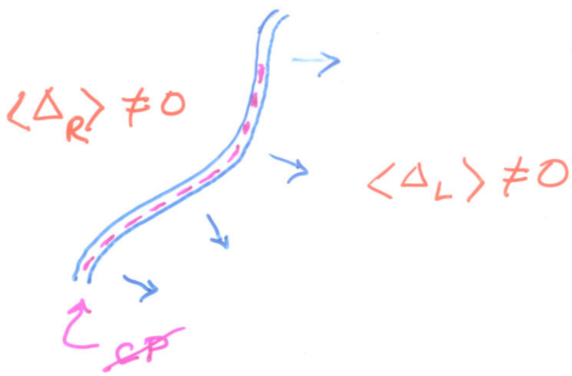
$$v_{electroweak} \simeq \kappa_1 \sim \sqrt{v_R v_L}$$

Exact L-R symm : $g_L = g_R$; $(\text{Field})_L \leftrightarrow (\text{Field})_R$

Milder req. : $\Delta_L \leftrightarrow \Delta_R$ ... with mild breaking

L-R domain walls and L-genesis

Cline &UAY; Nayak
WHEPP VI (2000)



- L violating condensate
- CP asymmetry
  $\Rightarrow$ Asymm. in transmission coeff.s for ν_R and $\overline{\nu_R^c}$
- Preferred direction of wall motion

Next...

- Study Higgs sector for domain walls
- Establish $\cancel{CP}$ within walls
  ... spatially varying CP phase
- Calculate asymm. between transmissions of ν_L & ν_L^c
  .... Net L-number accumulation in the preferred phase
- Subsequent evolution
  - Δn_L relaxation due to heavy N_u processes
  - Conversion of Δn_L into Δn_B by sphalerons

Scalar potential in the L-R model

$$V_\phi = -\mu^2 \phi^2 + \lambda \phi^4 \qquad \begin{array}{l} \mu_i^2 : 1, 2 \\ \lambda_i : 1, .. 4 \end{array}$$

$$V_\Delta = -\mu_3^2 \Delta^2 + [\rho_1, \rho_2] \Delta^4 + [\rho_3, \rho_4] \Delta^2 \Delta^2$$

$$V_{\phi-\Delta} = [\alpha_1, \alpha_2, \alpha_3] \phi \phi \Delta \Delta$$
$$+ [\beta_1 \ \beta_2 \ \beta_3] \phi \Delta \phi \Delta$$

Term to note

$$\alpha_2 \left(\mathrm{Tr}\, \tilde{\phi}^\dagger \phi \ \mathrm{Tr}\, \Delta_L \Delta_L^\dagger + \mathrm{Tr}\, \tilde{\phi} \phi^\dagger \ \mathrm{Tr}\, \Delta_R \Delta_R^\dagger \right)$$
$$+ \alpha_2^* \left(\mathrm{Tr}\, \tilde{\phi}^\dagger \phi \ \mathrm{Tr}\, \Delta_R \Delta_R^\dagger + \mathrm{Tr}\, \tilde{\phi} \phi^\dagger \ \mathrm{Tr}\, \Delta_L \Delta_L^\dagger \right)$$

DGKO
PRD 44 (1991)

Imposition of $\Delta_L \leftrightarrow \Delta_R$ symmetry allows only α_2 to be complex.

--- explicit CP violation

Spontaneous CP violation from the fate of the α, θ phases

Cosmic Strings :

$$U^{\infty}(\theta) = \exp\left\{ i \frac{\theta}{2} \left(T^3_R - \tfrac{1}{2}(B-L) \right) \right\}$$

$$\langle \Delta_R \rangle (r \to \infty, \theta) = U^{\infty}(\theta) \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} U^{\infty\dagger}(\theta)$$

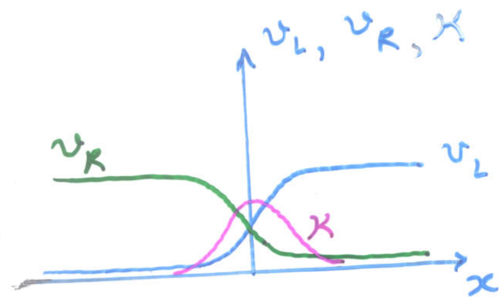
$$= \begin{pmatrix} 0 & 0 \\ e^{i\theta} v_R & 0 \end{pmatrix}$$

Domain Walls :

① $v_R(x) = \sigma(x) \cos \xi(x)$

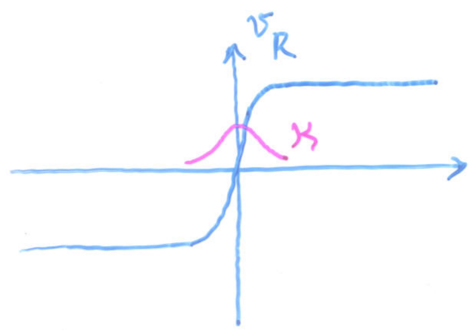
$v_L(x) = \sigma(x) \sin \xi(x)$

$\kappa(x) = f(x)$



② $v_R(x) = R(x)$

$\kappa(x) = f(x)$



UAY, Widyan, Mukherjee
Mahajan & Choudhuri
PRD 59 (1999)

Fate of κ and α

$$-\kappa'' + \alpha'^2\kappa + [\mu^2]\kappa + [\alpha](v_L^2+v_R^2)\kappa$$
$$+ [\beta]\, v_L v_R \kappa + [\lambda]\kappa^3 = 0$$

Transl. inv. vacua

$$\kappa^2 = -\frac{1}{[\lambda]}\left([\mu^2] + [\alpha](v_L^2+v_R^2) + [\beta]\, v_L v_R\right)$$

$$\xrightarrow{x\to\infty} \; -\frac{1}{[\lambda]}\left([\mu^2] + [\alpha]\, v_\infty^2\right)$$

$$\xrightarrow{x\to 0} \; -\frac{1}{[\lambda]}\left([\mu^2] + 2[\alpha]\, v_0^2 + [\beta]\, v_0^2\right)$$

$$\frac{\partial^2 V}{\partial \kappa^2} \xrightarrow{x\to\infty} \begin{cases} \boxed{[\mu^2] + [\alpha]\, v_\infty^2 > 0} & k = 0 \\ -2\left([\mu^2] + [\alpha]\, v_\infty^2\right) & k \neq 0 \end{cases}$$

$$\frac{\partial^2 V}{\partial \kappa^2} \xrightarrow{x\to 0} \begin{cases} [\mu^2] + \left(2[\alpha] + [\beta]\right) v_0^2 & k = 0 \\ \boxed{-2\left\{[\mu^2] + \left(2[\alpha] + [\beta]\right) v_0^2\right\}} & k \neq 0 \end{cases}$$

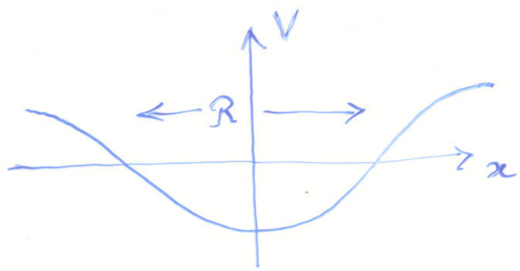
Need $\boxed{\cdots\cdots} > 0$

Amounts to $[\beta] < 0$

Existence of a solution:

Instability of the trivial vacuum

$$\int_{\mathcal{R}} \left(-[\mu^2] + [\alpha](v_L^2+v_R^2) - [\beta]\, v_L v_R\right)^{1/2} > \frac{\pi}{2}$$



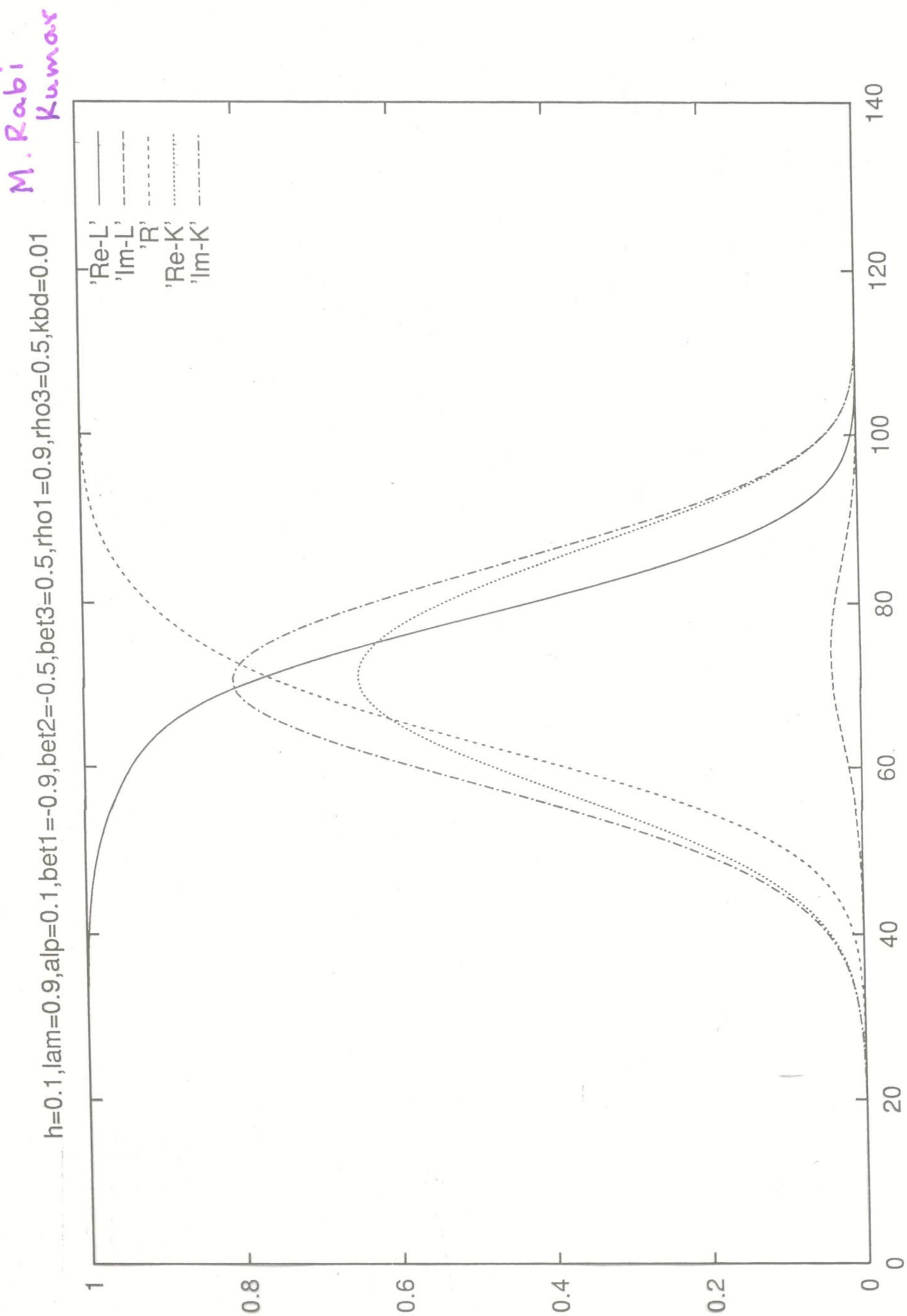
$$\int_{\mathcal{R}} \sqrt{E_n - V(x)} = (n+\tfrac{1}{2})\pi$$

Effective hamiltonian:

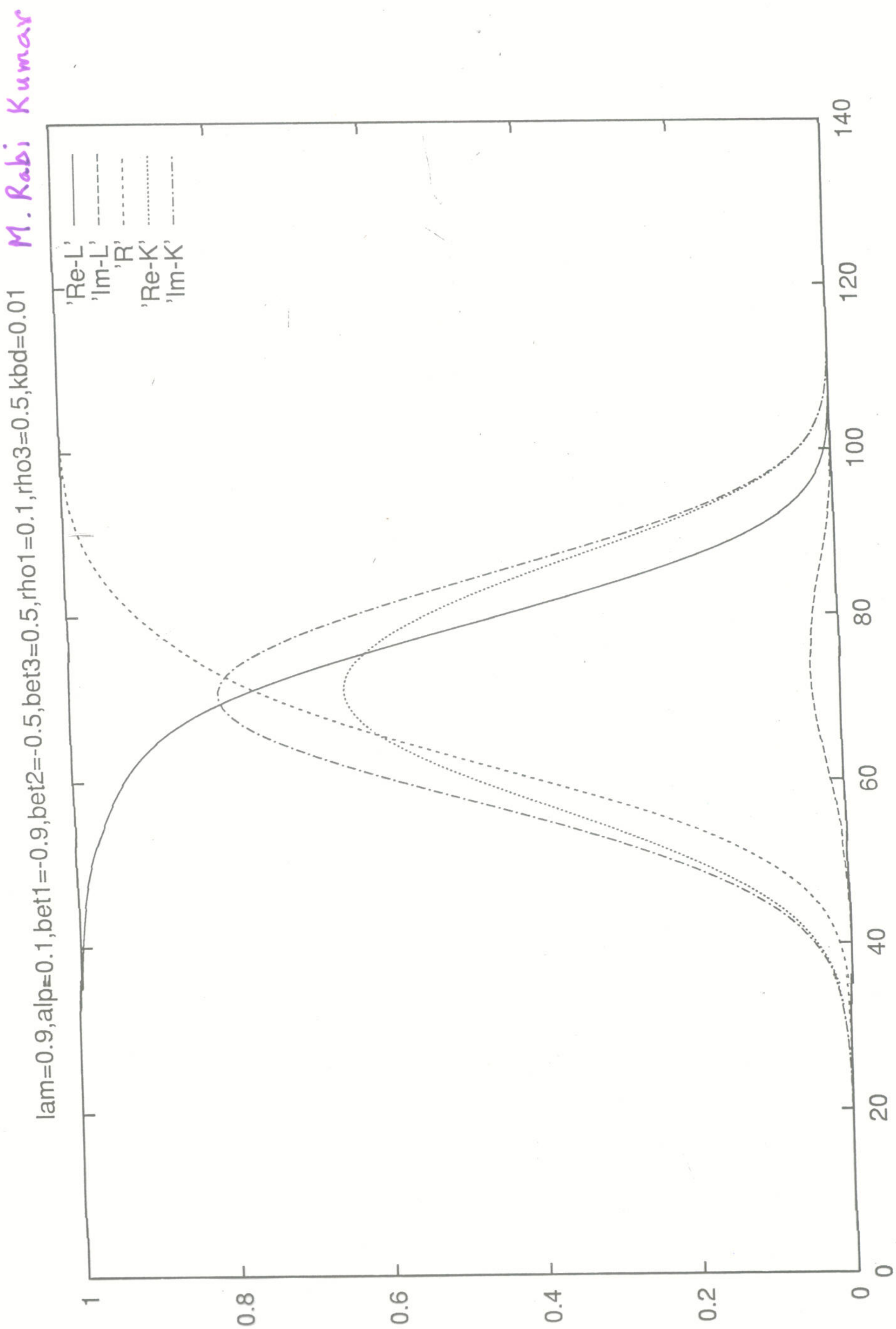
$$\begin{aligned} H = \int dx \Big\{ & \frac{1}{2}\left|\frac{dL}{dx}\right|^2 + \frac{1}{4}\rho_1 |L|^2 (|L|-M)^2 \\ & + \frac{1}{2}\left(\frac{dR}{dx}\right)^2 + \frac{1}{4}\rho_1 R^2 (R-M)^2 + \rho_3 |L|^2 R^2 \\ & + \frac{1}{2}\left|\frac{dK}{dx}\right|^2 + \frac{1}{4}\lambda (|K|^2 + m^2)^2 \\ & + \alpha |K|^2 (|L|^2 + R^2) + \beta_1 |K|^2 (\mathrm{Re} L) R \\ & + \beta_2 |K| \,\mathrm{Re}(KL) R + \beta_3 \,\mathrm{Re}(K^2 L) R \Big\} \end{aligned}$$

$$L = L(x) e^{i\theta(x)} \qquad K = K(x) e^{i\alpha(x)} \qquad R = R(x)$$

$$\frac{m^2}{M^2} \equiv \text{“kbd”} \sim \left(\frac{m_{W_L}}{m_{W_R}}\right)^2$$



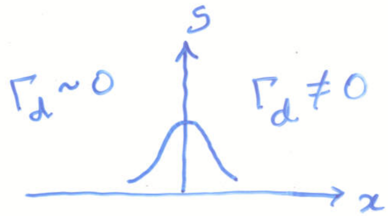
M. Rabi Kumar
h=0.1,lam=0.9,alp=0.1,bet1=-0.9,bet2=-0.5,bet3=0.5,rho1=0.9,rho3=0.5,kbd=0.01
'Re-L'
'Im-L'
'R'
'Re-K'
'Im-K'
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
120
140

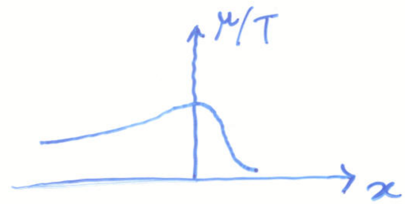

lam=0.9,alp=0.1,bet1=-0.9,bet2=-0.5,bet3=0.5,rho1=0.1,rho3=0.5,kbd=0.01
M. Rabi Kumar
'Re-L'
'Im-L'
'R'
'Re-K'
'Im-K'
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140

Diffusion eqn. for μ_L

$$-D_\nu \left(\frac{\mu}{T}\right)'' - v_w \left(\frac{\mu}{T}\right)' + \Gamma_d \left(\frac{\mu}{T}\right) = S(x)$$

where $S(x) = \dfrac{v_w}{\langle \vec{v}^{\,2}\rangle} \dfrac{D_\nu}{T} \left\langle \dfrac{p}{E} \dfrac{(m_\nu^2\, \alpha')'}{4E^2} \right\rangle_T'$





wall frame of ref.

$$\frac{\mu(x)}{T} = \int_{-\infty}^{\infty} dy\; G(x-y)\, S(y)$$

$$\Delta n_L(x) = \frac{1}{6}\mu_L(x)\, T^2$$

Parametrically,

$$\Delta n_L \sim \frac{1}{T} h^2 \lambda \langle \Delta_R \rangle_T^2 \langle \phi \rangle_T^2 \Big|_{wall}$$

$$\sim \lambda^3 h^2 \rho^2 T^3$$

so that $\dfrac{\Delta n_L}{s} \sim \dfrac{\lambda^3 h^2 \rho^2}{g_*}$

Finally, $\Delta n_B = \dfrac{28}{79} \Delta n_{B-L} = -\dfrac{28}{51} \Delta n_L$

$$\eta_L^{raw} \equiv \frac{\Delta n_L}{s_\gamma} \simeq 0.01\, v_w \frac{\alpha_0}{g_*} \left(\frac{\langle\Delta\rangle_T}{T}\right)^5 f^4 \sqrt{\rho_{eff}}$$

from $M_N^4 / T^2 \Delta_W$

↑ Majorana Yuk. coup.

Sphaleronic redistribution:

$$\Delta n_B = \frac{28}{79} \Delta n_{B-L} = -\frac{28}{51} \Delta n_L$$

If all η_L survives and redistributes,

we need $\left(\frac{\langle\Delta_T\rangle}{T}\right)^5 f^4 \approx 10^{-7}$

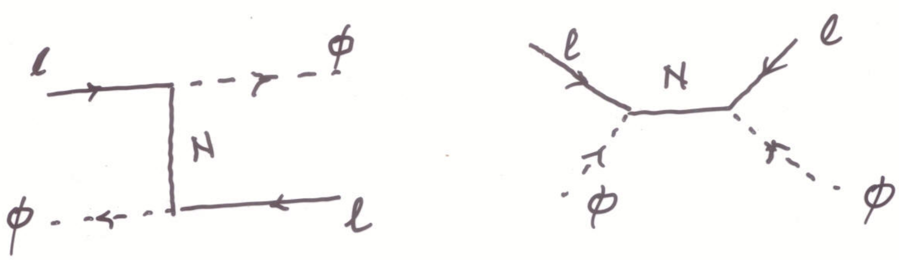
i.e. $M_N \gtrsim 10^{-2}\, v_R$

otherwise the mechanism is not important

Post-processing:

$$\Gamma_D \sim \frac{h^2 M_N^2}{(M_N^2+T^2)^{1/2}} \qquad \Gamma_S \sim \frac{h^4}{\pi^2}\frac{T^3 M_N^2}{(T^2+M_N^2)^2}$$

h - Dirac Yukawa ; f - Majorana Yukawa



$M_N > T_{LR} \longleftarrow \mid \longrightarrow M_N < T_{LR}$

	$T < T_{EW}$	$T_{EW} < T < M_N$	$M_N < T < T_{LR}$
1 N decays	✗	✗ ✓	✓
2 N mediated scattering	✓	✓	✓
3 sphaleronic redistrib.	✗	✓	✓

$\downarrow$ n_B frozen

For dissipation of original η^{raw} by 10^{-d_B}

$$m_\nu \lesssim \frac{180\,(174\,\mathrm{GeV})^2}{\sqrt{T_{LR} M_{PL}}}\left(\frac{d_B}{10}\right)^{1/2}$$

or,
$$T_{LR} \lesssim 10^{13}\,\mathrm{GeV} \times \left(\frac{\mathrm{eV}}{m_\nu}\right)^2 \times \left(\frac{d_B}{10}\right)$$

If $M_N < T_{BL}$, decay processes are important. In this case

$$m_\nu < 0.3\,\text{eV} \times \left(\frac{d_B}{10}\right)$$

PR D66 (2002)

Summary:

- L-R model possesses novel (unique?) mechanism for L-genesis
- Robustness? exact L-R symm. of Higgs sector.
  - Generalisable?
- Brings together η, M_N and m_ν
- Could also constrain mixing angles.