Through the looking glass : mere mirage or road not taken?

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Outline

- Parity, chirality and all that
- Symmetries of the Standard Model
- Cosmology mandate 1 : sphaleron and after – baryon asymmetry
- Cosmology mandate 2 : useful vs. dangerous relics
- Constraining the scale of unification and of new physics

Parity and chirality

Dirac equation

$$i\gamma^0\frac{\partial\psi}{\partial t}+i\vec{\gamma}\cdot\nabla\psi-m\psi=0$$

with the requirement that

$$(\gamma^0)^2=2I\,,\qquad \gamma^0\gamma^i+\gamma^i\gamma^0=0,\qquad \gamma^i\gamma^j+\gamma^j\gamma^i=-2I\delta^{ij}$$

A minimum four component equation and 4×4 γ- matrices are required.
The Lagrangian density needed to obtain this equation is

$$\mathcal{L}=i\bar{\psi}\gamma^\mu\partial_\mu\psi-m\bar{\psi}\psi$$

But for $m=0$ we get two separate equations, the Weyl equations

$$i\frac{\partial\psi}{\partial t}-i\vec{\boldsymbol{\sigma}}\cdot\nabla\psi=0\ \ \text{(eq.1), and}\ \ i\frac{\partial\psi}{\partial t}+i\vec{\boldsymbol{\sigma}}\cdot\nabla\psi=0\ \text{(eq.2)}$$

Chirality

- Auxiliary matrix $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$; $\gamma^\mu\gamma^5 + \gamma^5\gamma^\mu = 0$
- Two component fermions from 4-component function ψ,

$$\psi_{_L} = \frac{I - \gamma^5}{2}\psi \quad \text{and} \qquad \psi_{_R} = \frac{I + \gamma^5}{2}\psi$$

  - $\psi_{_L}$ satisfies (eq.1) while $\psi_{_R}$ satisfies (eq.2)
- Chirality is defined as the ratio $\frac{\text{sgn(energy)}}{\text{sgn}(\vec{S} \cdot \vec{p}\,)}$
- Thus $\psi_{_L}$ contains left handed particles and right handed anti-particles

  $\psi_{_R}$ contains right handed particles and left handed anti-particles
- For $m = 0$, each doublet is a complete representation of Lorentz group

Dirac mass and Majorana mass

Note that the mass term in the Dirac lagrangian is of the form

$$\mathcal{L}_{DM} = m_D \bar{\psi}\psi = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

Both chiralities needed to make up a massive spin-$1/2$ particle.
Majorana fermions are self-charge-conjugate like photons.
Starting with a Weyl fermion ψ_L define

$$\psi_L^C \equiv \mathcal{C}\psi_L^* \sim \chi_R$$

which transforms under the Lorentz group as some χ_R.

$$\mathcal{L}_{\rm Maj} = M\left(\overline{\psi_L^C}\psi_L + \overline{\psi_L}\psi_L^C\right)$$

The price we pay is that the fermion current is not conserved :

$$\frac{\partial}{\partial x^\mu}(\overline{\psi_L}\gamma^\mu\psi_L) = 2M\overline{\psi_L^C}\psi_L \text{ (check)}$$

Madam Wu's experiment (1956)

Neutrino is massless and only one chirality has been singled out in nature
(Sudarshan and Marshak; Feynman and Gell-Mann; Salam(-Pauli))

The Standard Model

The gauge group is $\mathrm{SU}(2)_L \otimes U(1)_Y$

Left handed electron and (in 1967 the only known) left-handed neutrino are placed in a doublet Ψ_L of $\mathrm{SU}(2)_L$, while the right handed electron remains singlet under $\mathrm{SU}(2)_L$.

$$\begin{array}{cccc}
 & \tau^3_L & \frac{1}{2}Y & Q \\
\left\lceil \;\nu_L\; \right\rceil & +\frac{1}{2} & -\frac{1}{2} & 0 \\
\left\lfloor \;e^-_L\; \right\rfloor & -\frac{1}{2} & -\frac{1}{2} & -1 \\
e^-_R & 0 & -1 & -1
\end{array}$$

The building blocks of the Lagrangian are the covariant derivatives

$$D_\mu \Psi_L \equiv \left(\frac{\partial}{\partial x^\mu} + i g \tau^a W^a_\mu + i\,(-1) g' B_\mu\right)\Psi_L$$

$$D_\mu \psi_R \equiv \left(\frac{\partial}{\partial x^\mu} + i(-2)\,g' B_\mu\right)\psi_R$$

In the case of quarks, both chiralities of each of up and down quarks occurs.

But only the left handed ones form a doublet under $\mathrm{SU}(2)_L$, while the right handed components remain singlets

$$\begin{array}{llll}
 & \tau_L^3 & \frac{1}{2}Y & Q \\
\left[\begin{array}{l} u_L \\ d_L \end{array}\right] & \begin{array}{l} +\frac{1}{2} \\ -\frac{1}{2} \end{array} & \begin{array}{l} \frac{1}{6} \\ \frac{1}{6} \end{array} & \begin{array}{l} +\frac{2}{3} \\ -\frac{1}{3} \end{array} \\
u_R & 0 & +\frac{2}{3} & +\frac{2}{3} \\
d_R & 0 & -\frac{1}{3} & -\frac{1}{3}
\end{array}$$

This symmetry breaks at low energies to $U(1)_{EM}$

No mass terms permitted

An important automatic ingredient of this construction :

$\overline{\psi_L}\,\psi_R$ is not gauge invariant

Left handed and right handed components of fermions have different gauge charges.

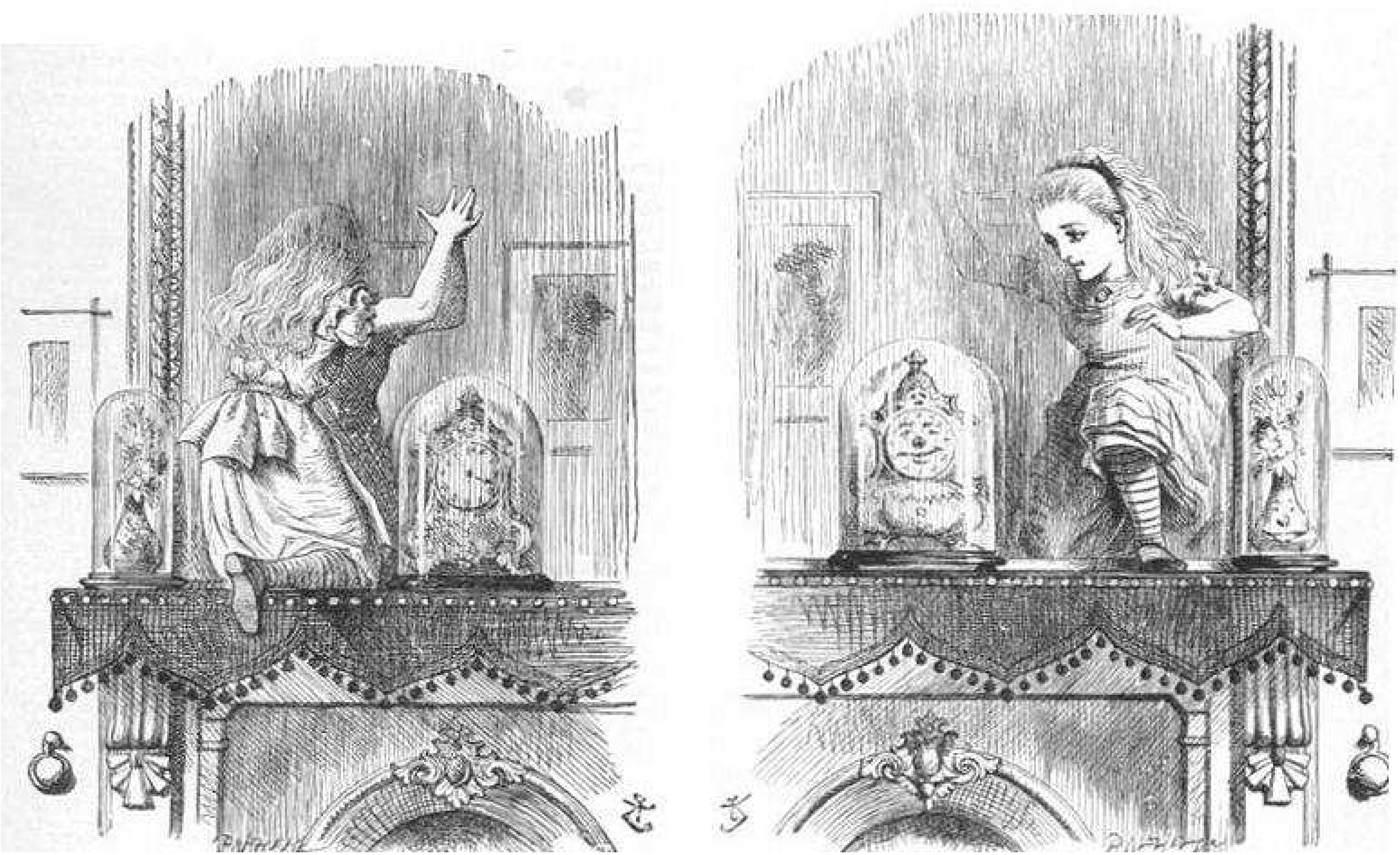
Solution : Introduce a scalar doublet field, the Higgs,

– with just the right charges,
– which allows interaction terms,
– which after symmetry breaking become effective mass terms

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &\sim h\,\overline{\Psi}_{_L}\,\phi e^-_{_R} \\ &\longrightarrow h\left(\;\bar{\nu}_{_L}\;\overline{e^-_{_L}}\;\right)\left(\begin{array}{c}\phi^+\\ \phi^0\end{array}\right)e^-_{_R} \\ &\longrightarrow h\left(\;\bar{\nu}_{_L}\;\overline{e^-_{_L}}\;\right)\left(\begin{array}{c}0\\ v\end{array}\right)e^-_{_R} \end{aligned}$$

Have ones symmetry and get masses too, (in the broken symmetry phase).

The central point of this talk :



The central point of this talk :

- Chirality is an elegant concept naturally embedded in the Quantum realistion of Lorentz Group –> spontaneous generation of mass.
- But that does not necessarily mean imbalance in Parity ie simple mirror reflection –> The world of quarks is both chiral and parity balanced.
- The observed P violation –> could be a spontaneously generated imbalance between right chiral and left chiral species
- This symmetry breaks in the early Universe
  - forming domains of opposite preferred chiralities
  - the world we see is one of the two alternatives our Universe chose

General mass matrix – the "see-saw" mechanism

In the general case where fermion number is not conserved (only neutrino sector so far), we need to diagonalise the mass matrix :

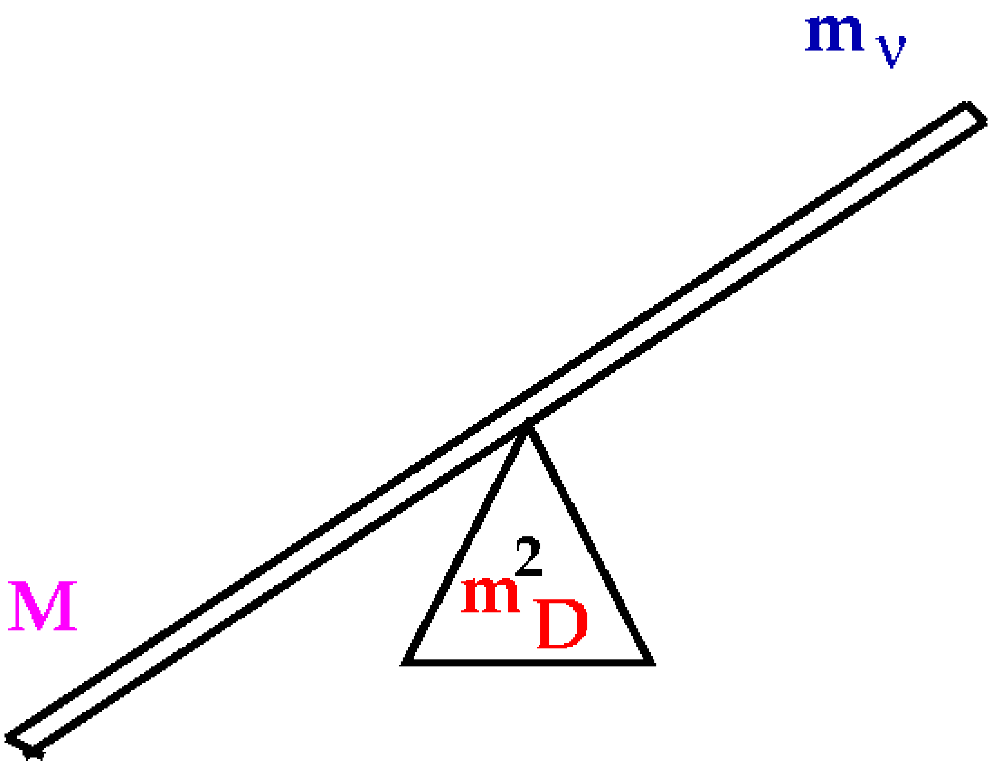
$$\begin{array}{cc} & \begin{array}{cc}\psi_L & \psi_R\end{array} \\ \begin{array}{c}\overline{\psi_L} \\ \overline{\psi_R}\end{array} & \left(\begin{array}{cc}\mathcal{C}m_L & m_D \\ m_D & \mathcal{C}M_R\end{array}\right)\end{array}$$

The relevance of the case $m_L \ll M_R$

(Gell-Mann, Ramond and Slansky 1978) :

The eigenvalues are

$$m_1 \simeq M_R ; \quad m_2 \simeq -\frac{m_D^2}{M_R}$$


m_ν
M
m^2_D

Beyond the SM

1. Through gauge coupling unification –> running couplings unite
2. Through fermion masses –> the M_R scale

GUT orthodoxy (almost heresy now) assumed naturalness of 1, and M_R was expected to fit in.

→ It did, provided $m_D \approx 100$GeV.

→ The only guide to neutrino Dirac mass 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.

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 :

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

- 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

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
$\lceil \ \nu_L \ \rceil$	$+\frac{1}{2}$	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 $\nu_{_R}$ –> 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

Cosmology input 1 : baryogenesis

GUT scale 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

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

$$\Gamma_{_X} \cong \alpha_{_X} m_{_X}^2 / T; \qquad H \cong g_{_*}^{1/2} T^2 / M_{_{\rm Pl}}$$

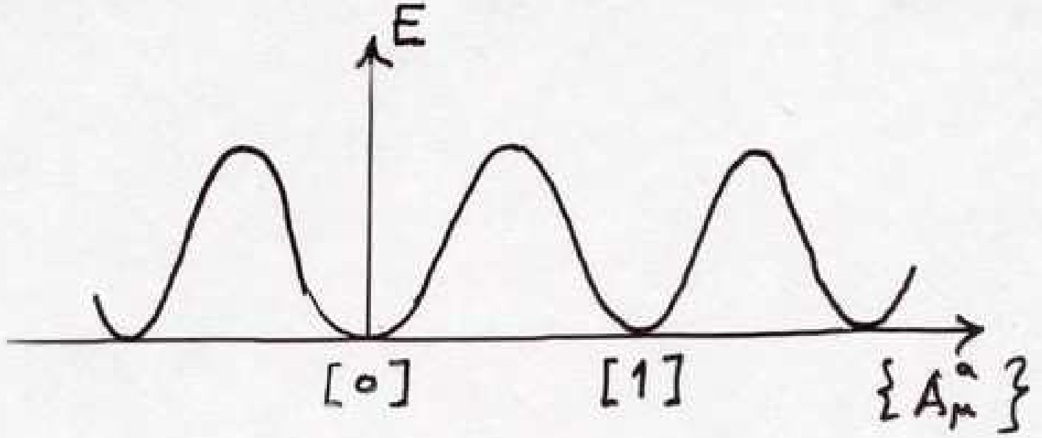
However, rather startling additional inputs appear from global apects of SM gauge group.

Anomalous violation of $B + L$

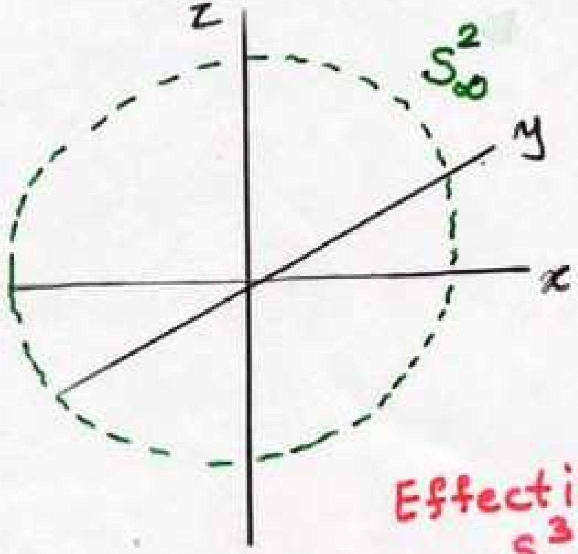
- Gauge theories are non-linear and possess a non-trivial vacuum structure

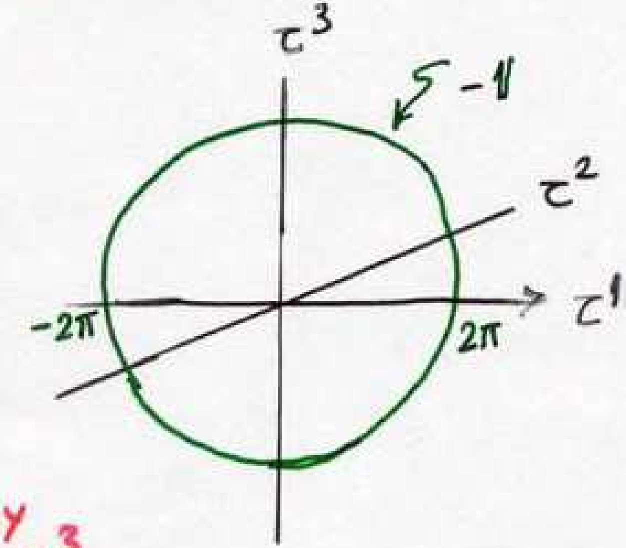
  (Jackiw-Rebbi 1973; Klimkhammer-Manton; Soni 1984)

"Large" gauge transformations



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





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

$$\Delta N_F = \Delta N_g$$

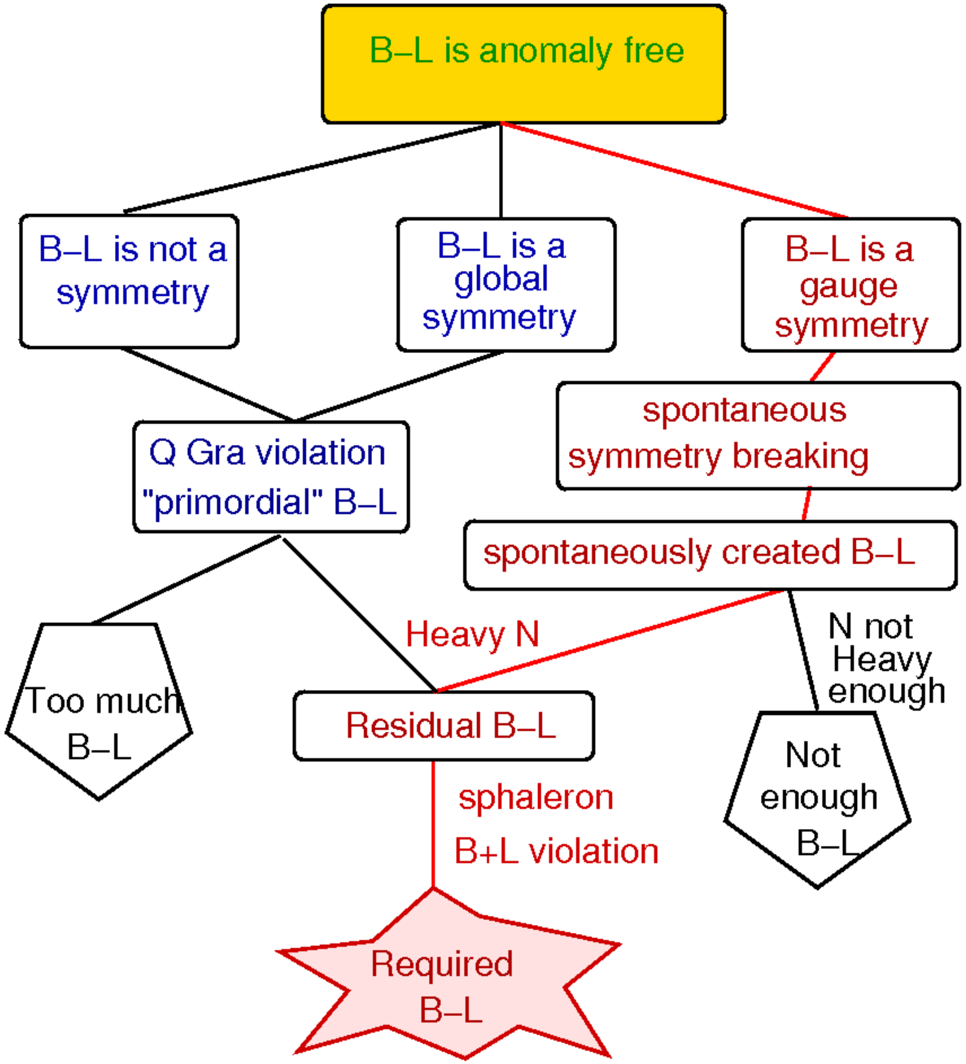
Sphaleron

- In the Standard Model, the anomalous axial current of the fermions coupled to the $\mathrm{SU}(2)_L$ turns out to be $B + L$.
- Further, the Higgs vacuum expecatation value sets a scale for the height of the barrier separating vacua with differing N_g.
- At $T \gg M_W$, the barrier is irrelevant, and $B + L$ is ill-defined.
  - Any baryon asymmetry B produced by GUT mechanism would be re-distributed into net B and L.
- B and L are accidentally conserved tree level quantum numbers in the SM (aside from lepton flavours).
- Due to the anomaly, $B - L$ number is the only number of non-trivial significance to the Universe which remains global.

Gauged $B - L$

- Quantum Gravity has god's license to violate any global quantum numbers
  - any global number passing a hoizon is lost for ever
  - Quantum Gravity era domainated by strong fluctuations in spce-time metric will leave behind random residue of a global charge
- Gauged $B - L$ ensures Quantum Gravity cannot leave behind unpredictable residue
  - $U(1)_{B-L}$ we get in Left-Right symmetric model is a minimal and natural implementation
- Any mechanism that can exploit $B + L$ violation through the anomaly can generate net baryon asymmetry from verifiable Particle Physics (Kuzmin-Rubakob-Shaposhnikov 1987

What choices did (Einstein's) god have?

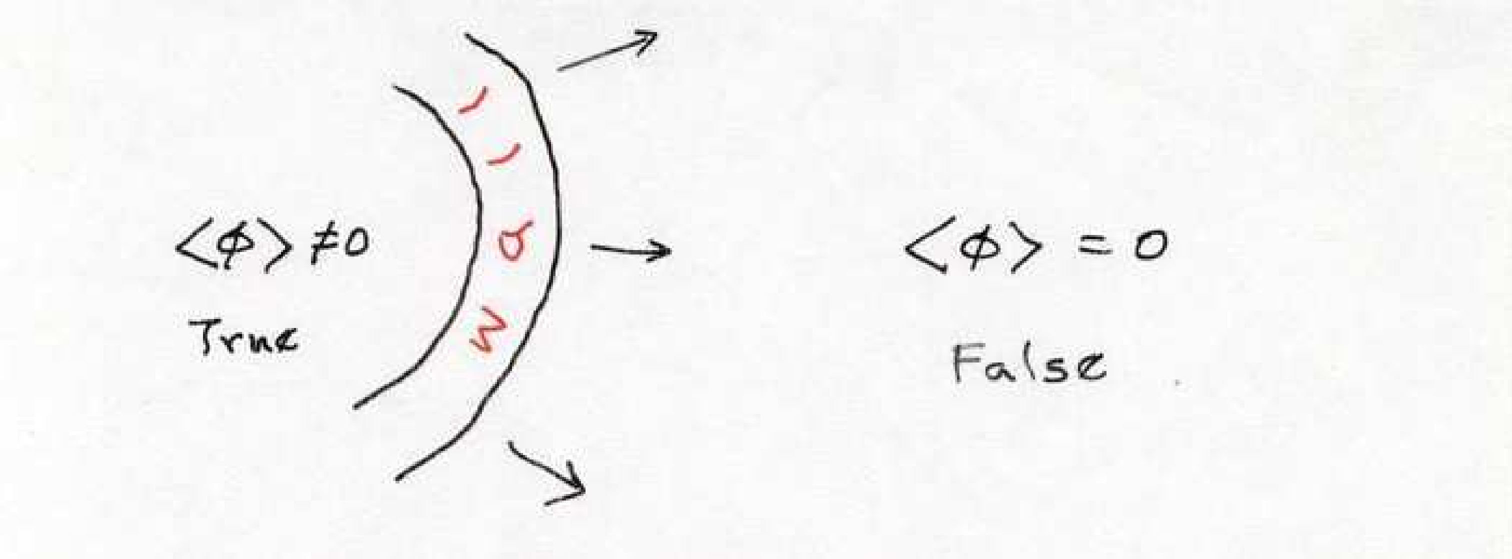


Phase transition and Higgs mass

- Expansion rate of the Universe too slow at lower scales

$$H^2 = \frac{8\pi}{3} G\rho \approx \frac{T^4}{M^2_{Pl}};$$

- Out of equilibrium conditions can arise at phase transitions



- First order phase transition in SM requires Higgs mass to be $\lesssim 90$GeV

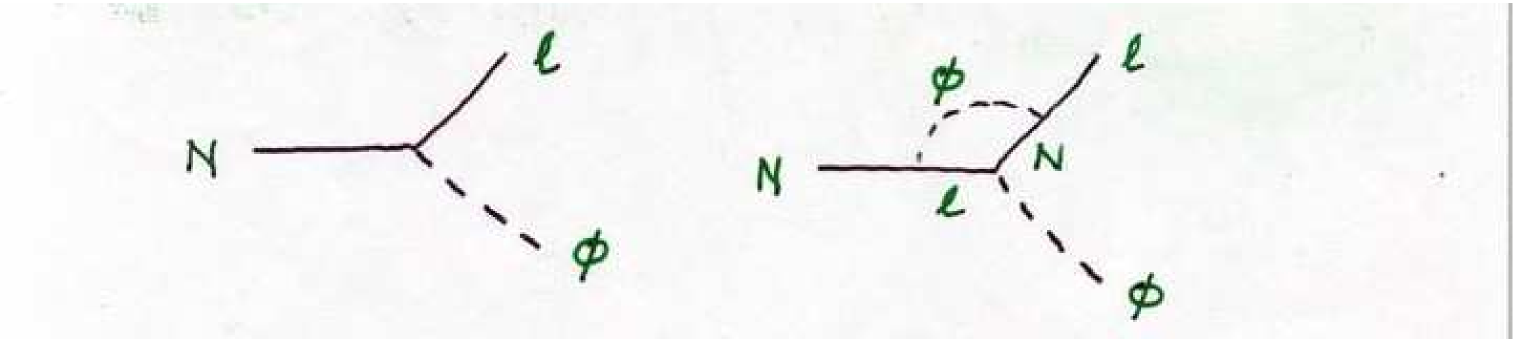
- SM Higgs will not suffice
- Need new physics, both for
  1. CP violation effects
  2. To ensure first order phase transition
- Rough answer : given enough scalar fields, can achieve both

Challenge : To identify all the required scalars with those automatically provided by other compulsions within Particle Physics.

Leptogenesis

(Fukugita and Yanagida 1986)

- Out of equilibrium decay of heavy Majorana neutrinos

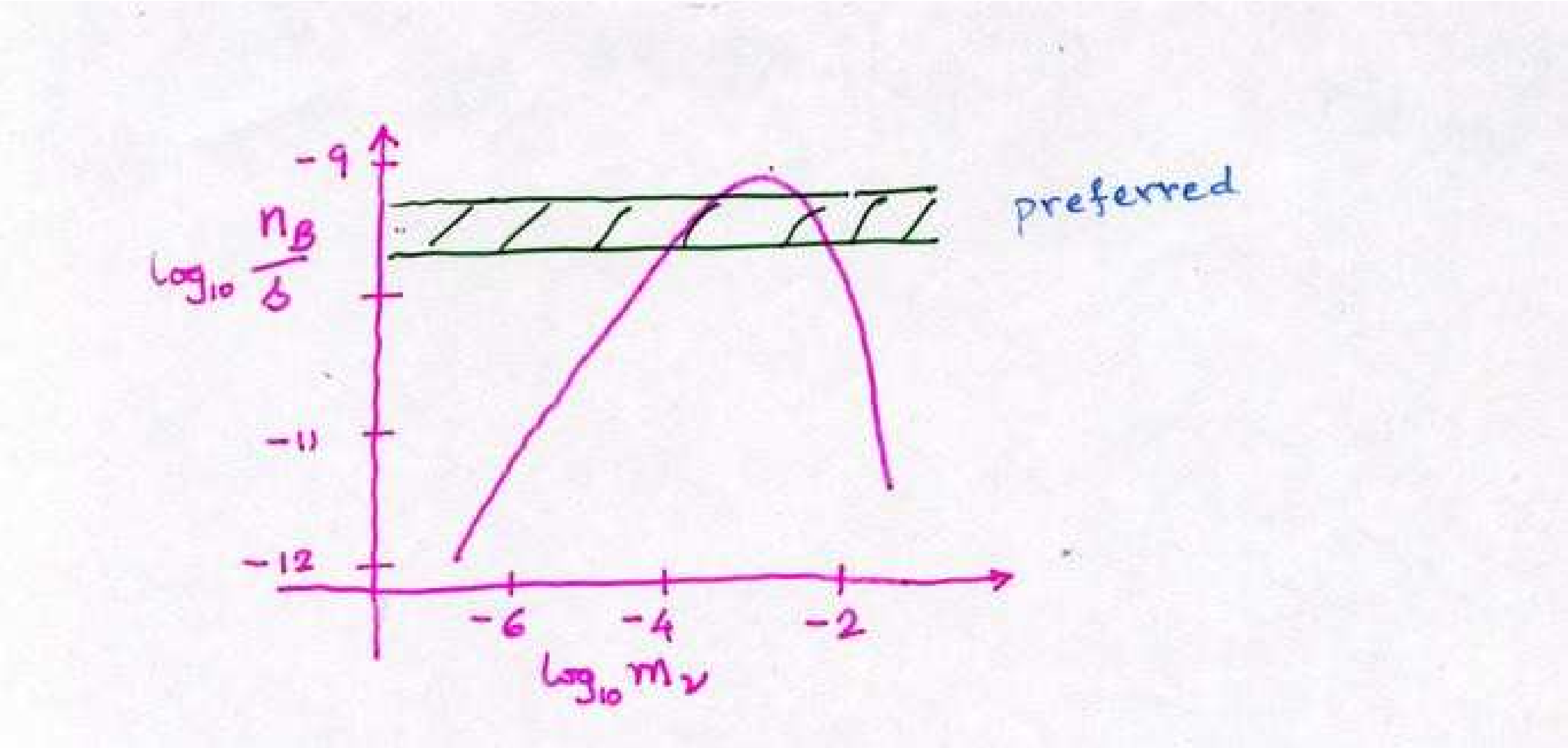


- Easy to arrange CP violation due to complex vacuum expectation values of scalar fields producing the mass

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

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

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



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

News from the front

- 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,

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

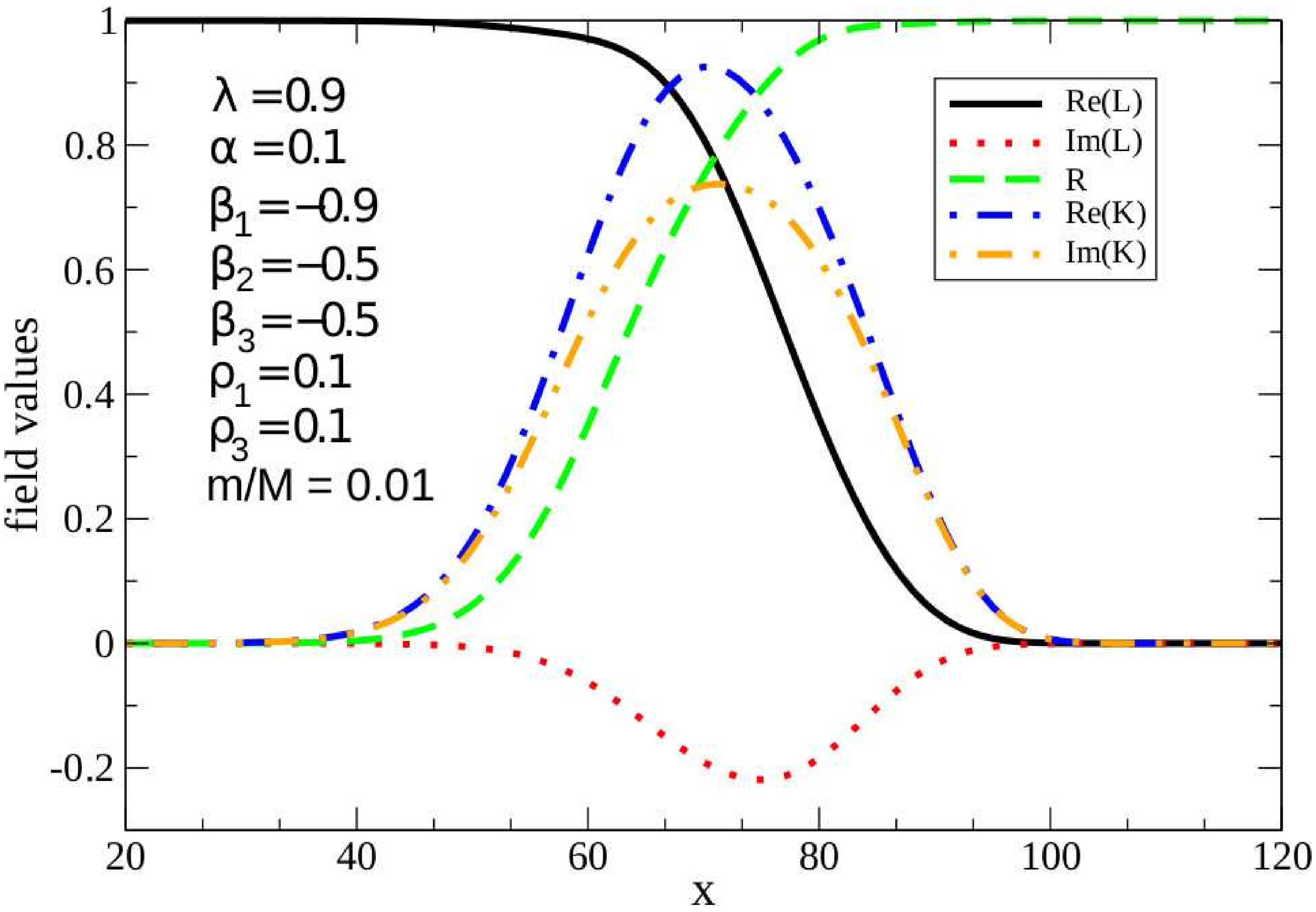
- This can be too small for producing the asymmetry

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)

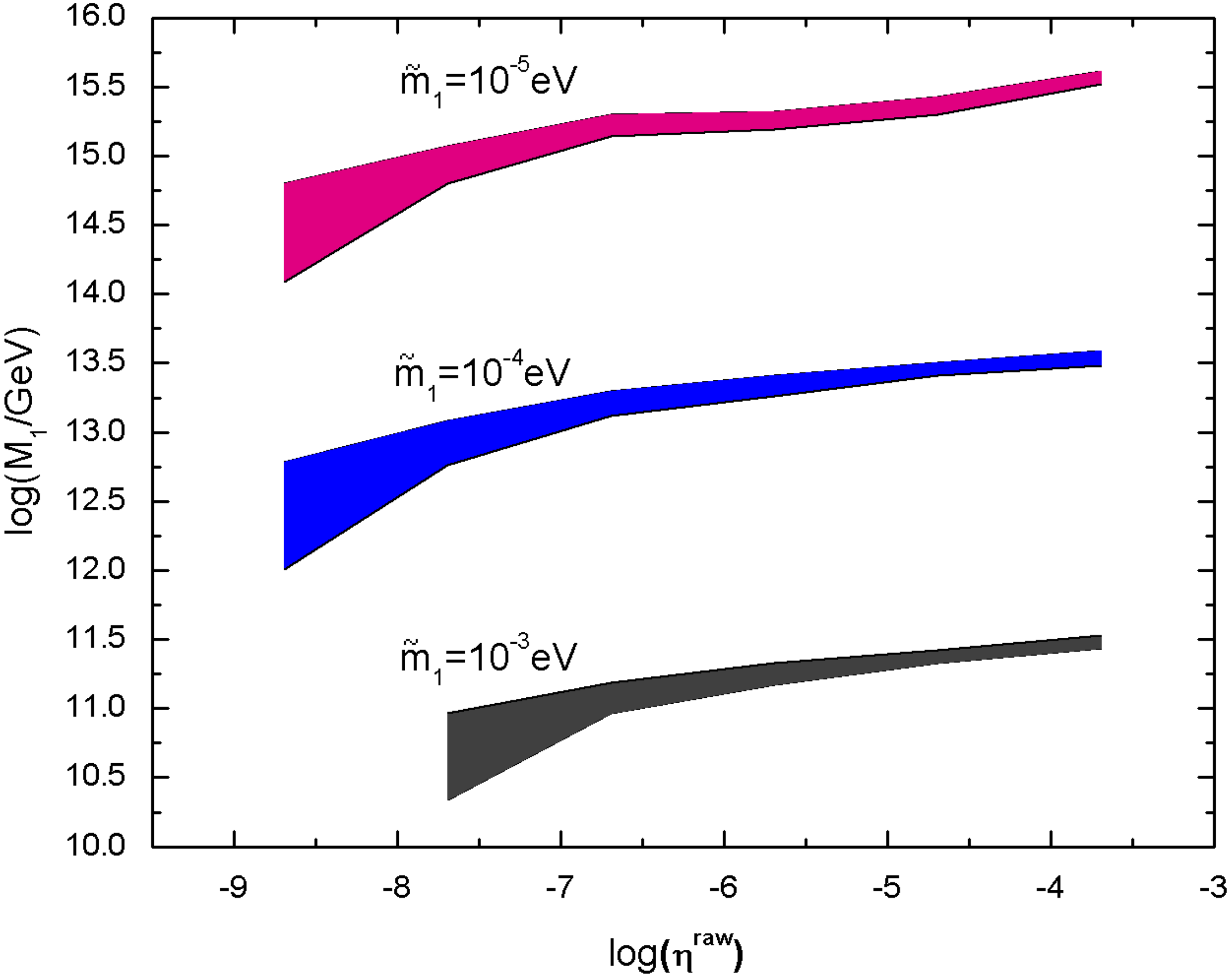
- The left-right symmetric model has domain walls, with sufficient CP violation provided by the scalar condensates to produce lepton number at a low scale.
- The effect is the same as having bubble walls



λ =0.9
α =0.1
β_1=–0.9
β_2=–0.5
β_3=–0.5
ρ_1=0.1
ρ_3=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

Can this lepton asymmetry survive?

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


$\tilde{m}_1=10^{-5}$eV
$\tilde{m}_1=10^{-4}$eV
$\tilde{m}_1=10^{-3}$eV
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(M_1/GeV)
-9
-8
-7
-6
-5
-4
-3
log(η^{raw})

Summary so far : invoking the “h”-word

It is unclear from Quantum Field Theory what would keep the electroweak scale 250GeV secluded from the Planck scale 10^{19}GeV.

Such a hierarchy of scales is striking because there are no symmetries protecting it. A vector boson or a fermion has reasons of symmtry to remain light; the scalar Higgs boson has no such symmtries.

Majorana neutrinos seem to rescue the situation of absence of proton decay. But pitch the value for the masses in the intermediate range.

What do we make of the intermediate range mass $10^9 - 10^{11}$GeV for the Majorana neutrino? Neither GUT scale $10^{14} - 10^{17}$GeV nor electroweak.

Supersymmetry at the TeV scale can stabilise the hierarchy, also legitimise the intermediate scale.

But Supersymmtry predicts gavitions and then the required Majorana mass to produce baryon asymmery is too high or too finely tuned.

Mechanisms – invoking extra dimensions – are of two types :

I. Construe the high value of Planck scale as a chimera – volume factor of compactified dimensions fatten it up.

II. An exponentially varying “warped” metric value in the fifth dimension.

In the following I present some investigations to see how low can the $M_{_N}$ scale be. If it can be within two or three orders of magnitude of the electroweak scale – a “JBSM”, then any of the above three mechanisms can explain the hierarchy, whereas all the cosmological issues can be addressed by Physics upto the PeV (10^6GeV) scale.

Cosmology 2 : Scale of M_N

One lacuna and many solutions

Summary and the issue

- The $\nu_{_R}$ states fit within an elegant gauge structure if left-right symmetry is invoked
- $B - L$ becomes a gauged symmtry enabling a dynamical explanation for baryon asymmtry
- Spontaneous breaking of parity symmetry results in domains of opposite chirality, separated by domain walls
- Domain walls have the property that they provide a more dominant energy contribution to the Universe – conflict wih cosmological histroy for epochs after the Big Bang Nucleosynthesis (BBN)

How to have the discrete symmtry 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 asymmtry in parity breaking can be bundled with some other similar partially answered problem :

i. Supersymmtry breaking hidden sector also communicates prity breaking
ii. Parity breaking accompanies supersymmetry breaking due to the choice of a metastable vacuum

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.

Supersymmetric Left-Right model

Minimal SUSY L-R Model – MSLRM

The minimal set of Higgs superfields required is,

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

where the bidoublet is doubled so that the model has non-vanishing Cabibo-Kobayashi-Maskawa matrix. The number of triplets is doubled to have anomaly cancellation.

Supersymmetric minima breaking $\mathrm{SU}(2)_R$ symmetry are signaled by the ansatz

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

Mass scale see-saw

- A new mass scale $\omega = \langle\Omega\rangle$ gets introduced.
- Demand that Ω mass terms in superpotential are vanishing.
- Leads to enhanced R symmetry.
- Leads naturally to a see-saw relation

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

  - This means Leptogenesis is postponed to a lower energy scale closer to M_{EW}.
  - Low scale violation of $B-L$ natural, not a high scale like $10^9 - 10^{14}$ GeV

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 :

- However, the structure of supergravity ensures that at the renormalisable level gravity 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
- Thus effectivley we have to assume an unknown reason for absence of parity or its spontaneous breaking in the hidden sector, communicated by gravity.

- Regardless of their origin, the structure of the symmetry breaking terms in the scalar potential will be the same as what can be derived from the Kahler potential formalism

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

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

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 dynamics of the walls is determined by two quantities :

- $*.$ 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.

The two get balanced at time $t_R \sim R/\beta$ being the time scale by which the wall portions that started with radius of curvature scale R straighten out.
Scaling law for the growth of the scale $R(t)$ on which the wall complex is smoothed out.

$$R(t) \approx (G\,\sigma)^{1/2}\,t^{3/2} \tag{4}$$

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

In radiation dominated era this ρ_W becomes comparable to the energy density of the Universe $(\rho \sim 1/(G\ t^2))$ around time $t_0 \sim 1/(G\,\sigma)$.

Next, we consider destabilization of walls due to pressure difference $\delta\rho$ arising from small asymmetry in the conditions on the two sides. This effect competes with the two quantities mentioned above. Since $f_F \sim 1/(G\ t^2)$ and $f_T \sim (\sigma/(G\ t^3))^{1/2}$, it is clear that at some point of time, $\delta\rho$ would exceed either the force due to tension or the force due to friction. For either of these requirements to be satisfied before $t_0 \sim 1/(G\,\sigma)$ we get

$$\delta\,\rho \geq G\,\sigma^2 \approx \frac{M_R^6}{M_{Pl}^2} \sim M_R^4\,\frac{M_R^2}{M_{Pl}^2} \tag{5}$$

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

$$H_i^2 = \frac{8\,\pi}{3}\, G\, \sigma^{\frac{4}{3}} \sim \frac{\sigma^{\frac{4}{3}}}{M_{Pl}^2} \tag{6}$$

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,

$$\delta\,\rho > M_R^4 \left(\frac{M_R}{M_{Pl}} \right)^{3/2} \tag{7}$$

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

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

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 needed to avoid gravitino problem after reheating at the end of inflation, $\kappa_{RD} \sim 10^{-4}$, a reasonable constraint. but requires κ^A_{RD} to be $O(1)$ if the scale of M_R is an intermediate scale 10^{11}GeV.

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

which seems to be a modest requirement, but taking $M_R \sim 10^9$GeV being the temperature scale required to have thermal leptogenesis without the undesirable gravitino production, leads to $\kappa_{MD} > 10^{5/2}$.

Conclusion

- The discovery of neutrino mass opens up new challenges and new hopes
- Challenge : how the ν_R states fit into the gauge structure
- Hopes : easy ways of producing baryon asymmetry
- Dynamical explanation of B-asymmetry natural for gauged $B - L$.
- Thermal leptogenesis is highly constrained, again by neutrino data
- But routes through non-thermal processes naturally included in gauged $B - L$ models.
- The new bogey raised by exact P symmetry, domain walls, can be used in reverse to put upper bounds on M_R scale, again consistent with Leptogenesis being non-thermal

Thank You!