Baryogenesis - Leptogenesis : seeking supersymmetry connection

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1 What are the issues?

- Need for CP violation
- Need for
  - either Out-of-Equilibrium (O-o-Eq) decays
  - or First order phase transition (PT)
- These are unavailable in the SM
- They are easily available in TeV scale SUSY
- but SUSY does not demand this nor regulate it generically (compare DM)
- Non-supersymmtric models serve just as well
  - SUSY will feature in this talk as "now you see it now you don't"
- "Elegant" solutions may not have easy signatures !!

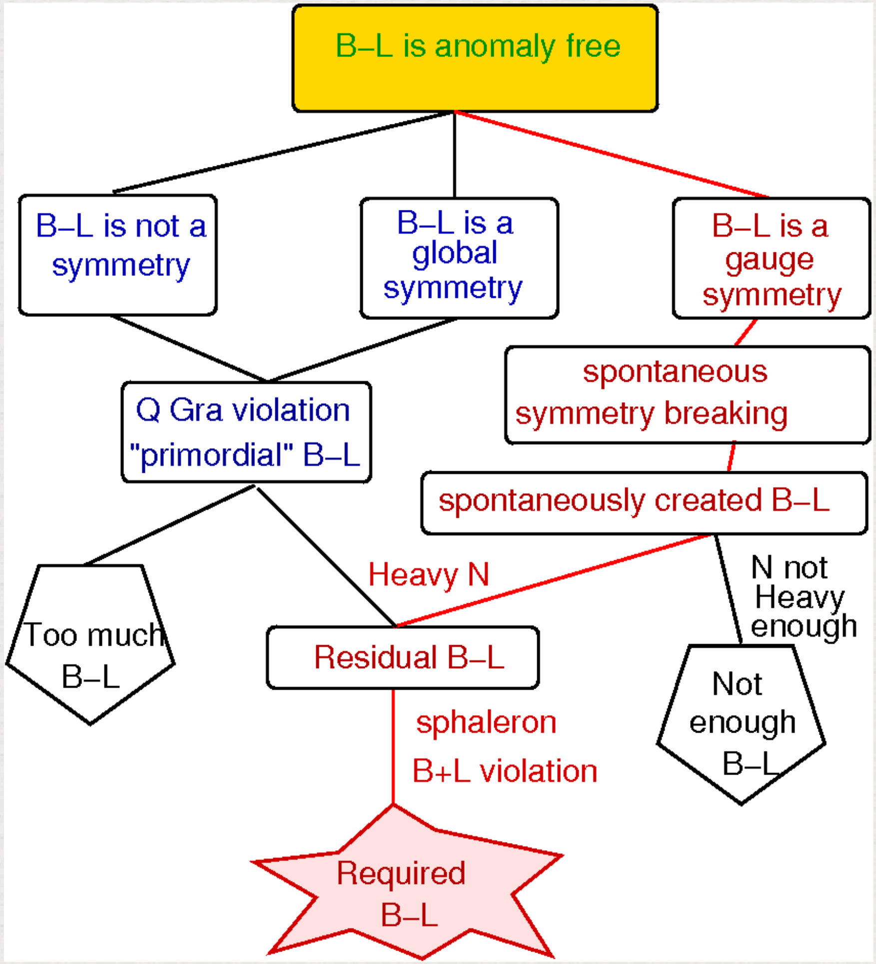
1.1 Current status

- → High scale O-o-Eq mechanisms disfavoured – neutrino data
- → Affleck-Dine an intrinsically SUSY mechanism viable, but too generic to be predictive
- → SM, LHC + non-accelerator effects show no signs of accommodating CP requirement naturally
- → Solutions which "work" provide no easy signatures (der Alte threw the key into a dark house)
  - – Light majorana neutirnos work just fine, but too weakly coupled to provide collatatal signature
  - – D-parity domain walls work but few signatures
- → Flavour effects, sterile neutrinos promise observable signatures.
- → Gravitational waves have energy scale limitation in confirming domain wall scenarios

2 Essential mechanisms - B and L symmetries

B and L are accidental symmetries of SM

What choices did der Alte have?



2.1 Classic B-genesis

Discovery of CMB 1964 and of CP violation 1964
Sakharov (1967) Yoshimura (1979)
Weinberg (Brandeis Lecturess1964), (1979)

→ Particle Physics rates and expansion rate of the Universe compete

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

→ *CP* violation due to interferance of diagrams

$$r_1 = \frac{\Gamma(X \to qq)}{\Gamma_1 + \Gamma_2} \neq \frac{\bar{\Gamma}(\bar{X} \to \bar{q}\bar{q})}{\bar{\Gamma}_1 + \bar{\Gamma}_2} = \bar{r}_1$$

2.1.1 Classic L-genesis

Fukugita and Yanagida (1986)

See saw mechanism –> (i) Majorana neutrinos (ii) High scale

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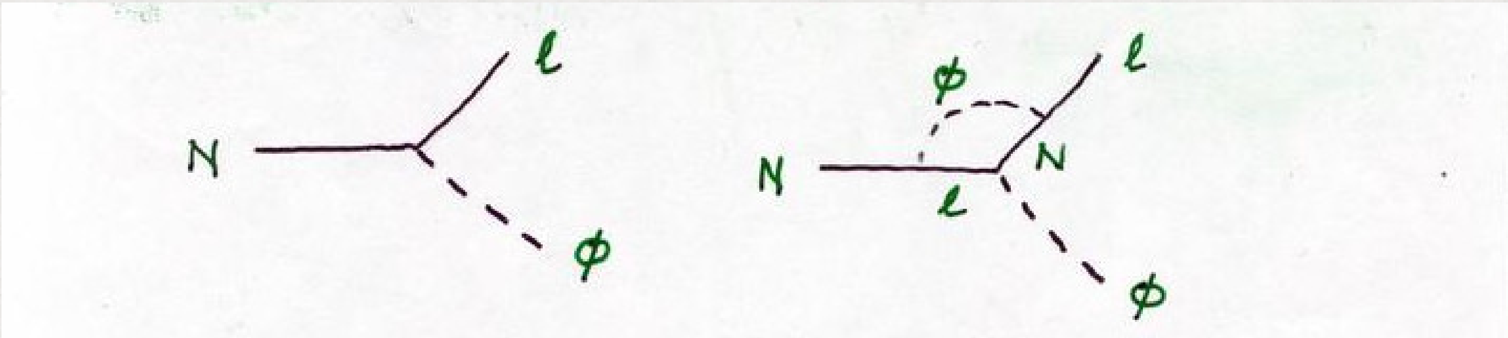

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→ Out of equilibrium decay of heavy Majorana neutrinos

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

$$\frac{r-\bar{r}}{r} \sim \frac{1}{v^2 m_D^2} \mathrm{Im}\left(m_D^\dagger m_D\right)^2$$

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

2.2 Sphalerons and the anomaly

- B and L are known to be accidental symmetries of SM at tree level
- $SU(2)_L \otimes U(1)_Y$ anomaly of lepton sector exactly equals that of the baryon sector.
- Hence $B + L$ turns out to be anomalous while $B - L$ remains anomaly free
- Anomalous processes can proceed by tunneling (Klinkhammer and Manton 1983)

$$\Gamma_{\text{sphaleron}} \sim \exp\{-S^E_{\text{sphaleron}}\}$$

at a finite temperature at a rate

$$\Gamma^T_{\text{sphaleron}} \sim \exp\{-E_{\text{sphaleron}} / kT\}$$

- where

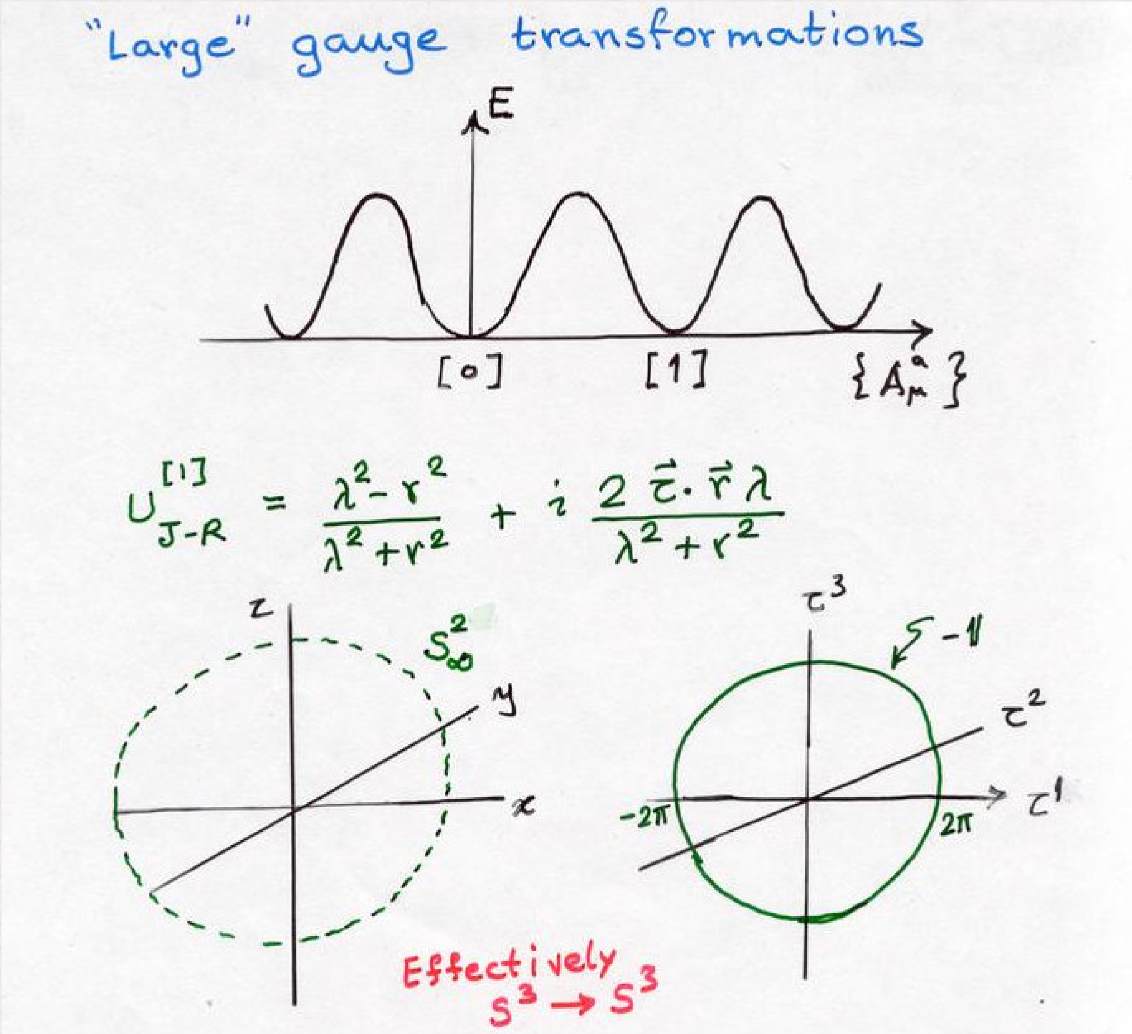
$$S_{\text{sphaleron}}, E_{\text{sphaleron}} \sim \frac{1}{\alpha^2_{\text{EW}}} M_W \sim 5\,\text{TeV}$$

- Anomalous processes unsuppressed for $T \gg M_W$

- Two conclusions : (Kuzmin-Rubakov-Shaposhnikov 1986)
  - 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

2.3 Details of : Anomalous violation of $B + L$

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



(Jackiw-Rebbi 1973; Polyakov 1976; Klimkhammer-Manton; Soni 1984)
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

$$\Delta N_F = \Delta N_g$$

3 Scenarios and constraints

3.1 Leptogenesis – high scale

- *CP* related to low energy neutrino data
- Mass scale related to reheat temprature and gravitino abundance
- flavour effects

m_ν too small : Yukawa couplings too small to bring heavy N into equilibrium
m_ν too large : Erasure processes too efficient
Buchmuller Di Bari Plumacher

$$M_N \gtrsim O(10^9)\mathrm{GeV}\left(\frac{2.5\times10^{-3}}{Y_N}\right)\left(\frac{0.05\mathrm{eV}}{m_\nu}\right)$$

$M_N \gtrsim 10^9$ GeV – does not sit well with hierarchy in non-SUSY case

- Tension with with SUSY unification gravitino overproduction

The mass M determining the decay rate enters the CP violating diagrams; M is connected to light ν mass through see-saw.

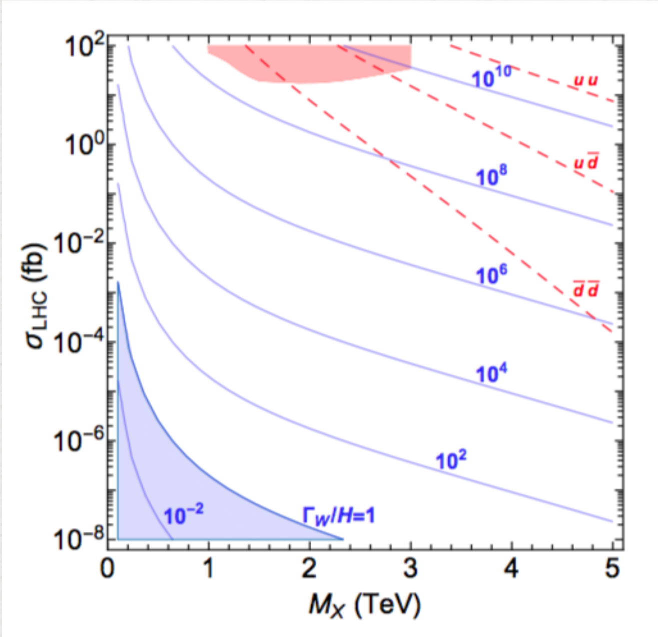
- Analysis of see-saw formula with three generations taken into account show, for thermal leptogenesis, (Davidson and Ibarra 2002)

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

- This can be too small for producing the asymmetry

3.1.1 Lepton number violation (LNV) at colliders

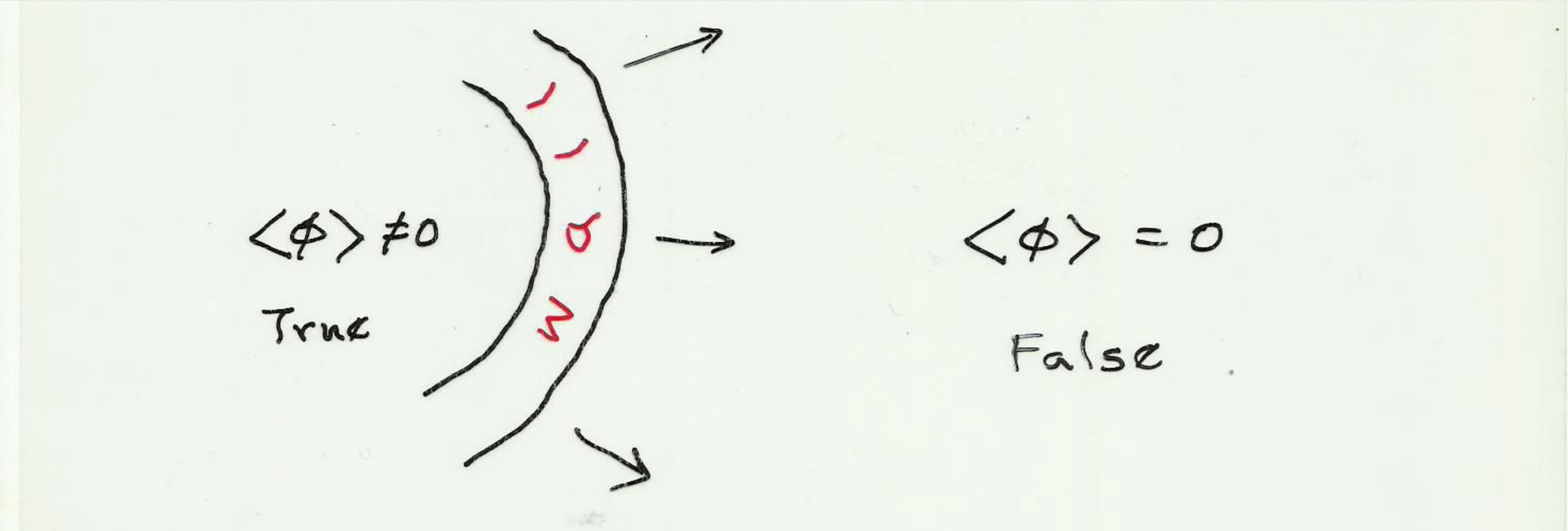
Testing wash out rate against mass of a resonance Lepton Number Violating X occuring in $pp \to l^{\pm} l^{\pm} jj$ (Deppisch Harz Hirsch 2014)



3.2 TeV scale baryogenesis

- 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 $\lesssim$ 90GeV ...

Generic requirements on bubble walls :



Whatever be the order parameter of the transition, e.g., 2 Higgs doublets,

– Thick wall, slow bubbles : scalar condensate with transient CP phase; sphalerons fit in the wall (Turok, Zadrozni 1992)

– Thin wall, fast bubbles : CP phase as before, fermions scatter asymmetrically from the walls (Cohen, Kaplan and Nelson 1993)

In either case we need to go beyond the SM :

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

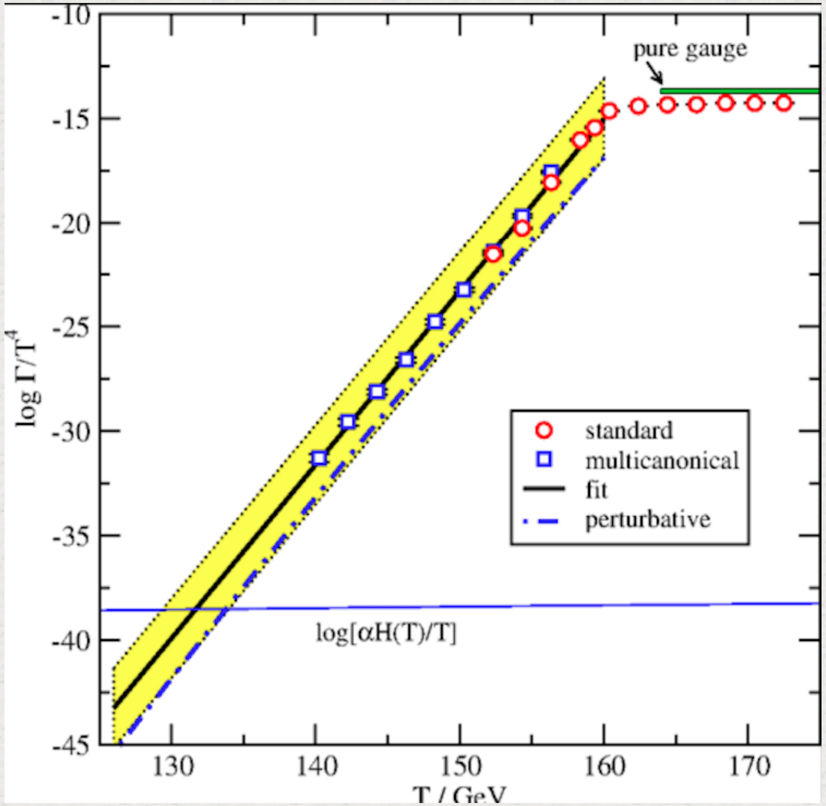
→ At least two scalars as order parameters of the phase transition. Minimal model : 2 Higgs Doublets

→ MSSM realistic and adequate but in tension with 7 TeV data

→ Observational possibility – Gravitational waves from bubble wall decays (Grojean, Servant, Caprini, Durrer 2009)

Recent summary : Cline (Morion 2017) “Is electroweak baryogenesis dead?”

3.3 Sphaleron rate with Higgs boson, D>2012



Rummukainen et al (2014)

But "sphaleron" B+L violation possible at colliders!! (Shaposhnikov 199x)

4 Leptogenesis – low scale

Precursors … relative importance of the diagrams producing *CP*
“Resonant” leptogenesis (Pilaftsis 1997)

$$\mathscr{L}_{\text{Yuk}} = -\sum_{i,j=1}^{3}\left(h^{\nu}_{ij}\bar{L}_i\tilde{\Phi}\frac{(1+\gamma^5)}{2}N_j + \hat{h}^{l}_{ij}\bar{L}_i\Phi\frac{(1+\gamma^5)}{2}l_i + h.c.\right)$$

A. Pilaftsis, T.E.J. Underwood / Nuclear Physics B 692 (2004) 303–345 305

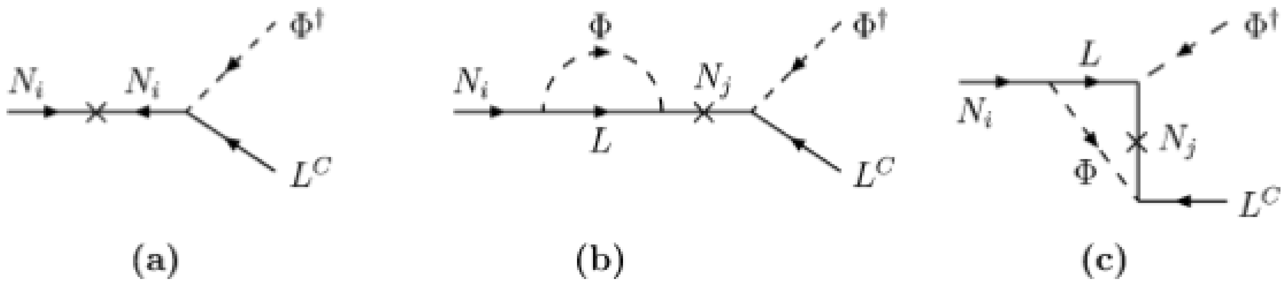


Fig. 1. Feynman diagrams contributing to the L-violating decays of heavy Majorana neutrinos, $N_i \to L^C\Phi^\dagger$, where L and Φ represent lepton and Higgs-boson iso-doublets, respectively: (a) tree-level graph, and one-loop (b) self-energy and (c) vertex graphs.

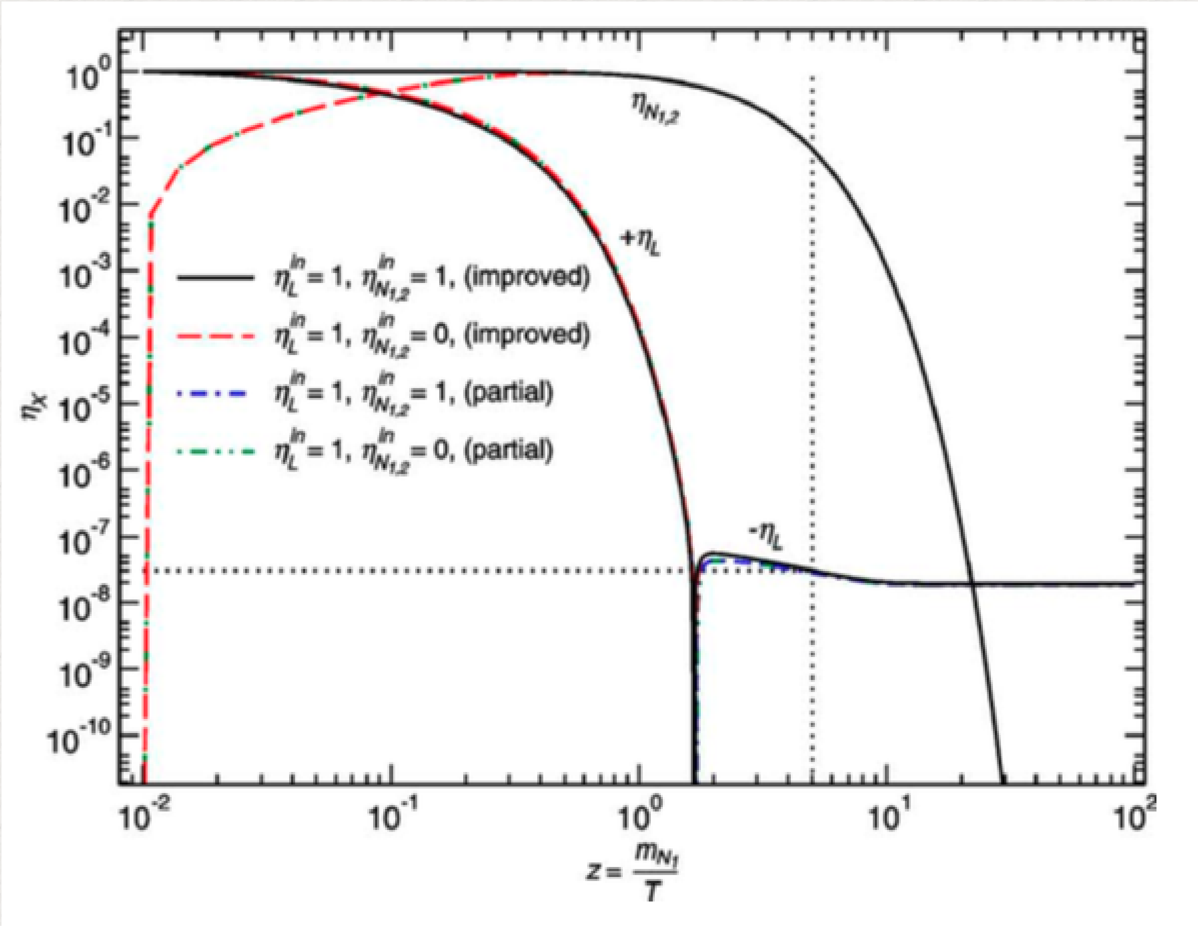
– *CP* violation from interference of tree level and absorptive part of the loop diagrams

→ “ϵ-type” (originating in oscillation) from self energy diagram

→ "ϵ'-type" (also involving decay) from the vertex diagram

– ϵ-type much larger and can be order 1 if the mass difference of the heavy neutrinos of the order of their decay widths.

The last requirement makes the QFT interpretation and calculation difficult. Resummation technique is required.

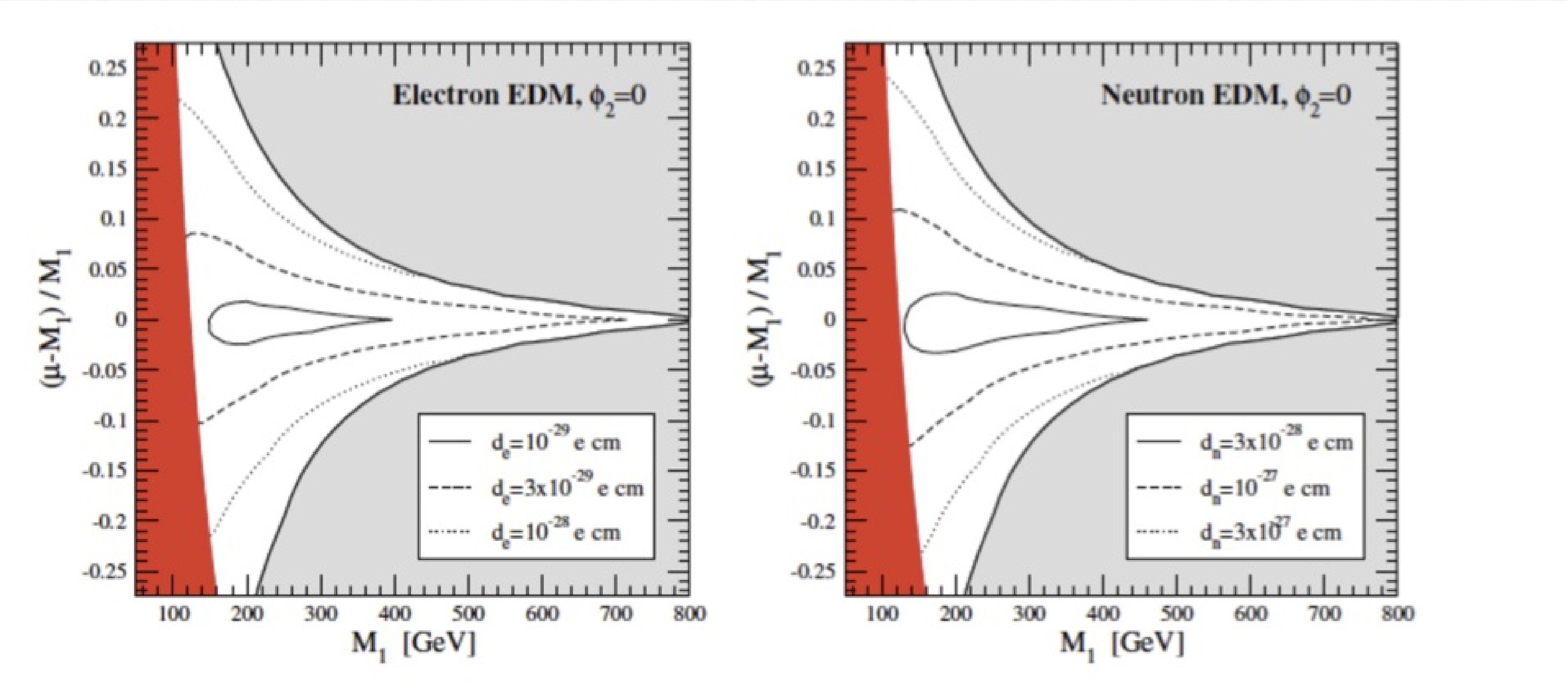


Sample results for $M_N \sim 1\text{TeV}$, $\Delta M_N / M_N \sim 10^{-9}$, $\epsilon \sim 10^{-7}$, $\eta_L \sim 1$.
The dotted line 5×10^{-7} indicates the required Lepton asymmetry so that after sphaleronic processes the required Baryon asymmetry would be produced.

4.1 Soft leptogenesis and Inflation, DM linkages ...

- In sneutrino sector mixing of $\tilde{N}$ and $\tilde{N}^*$ through soft terms after SUSY breaking
- Warm inflation and Baryogenesis (Bastero-Gil Berera Ramos Rosa)
- Resonanat enhancement may help several of these
- A-D mechanism and Type IIB string theory (Allhaverdi Ciccoli Muia)

4.2 Electron EDM and *CP* violation



Morrissey and Ramsey-Musolf (2012)

$$d_f \cong \sin\delta_{CP}\left(\frac{m_f}{\text{MeV}}\right)\left(\frac{1\text{TeV}}{M}\right)^2 \times 10^{-26}\, e\,\text{cm}$$

→ With $M \sim 500\text{GeV}$ for sufficient abundance at 100GeV, $\delta_{CP} \sim 0.01$ and not adequate source of baryon asymmetry from the walls.

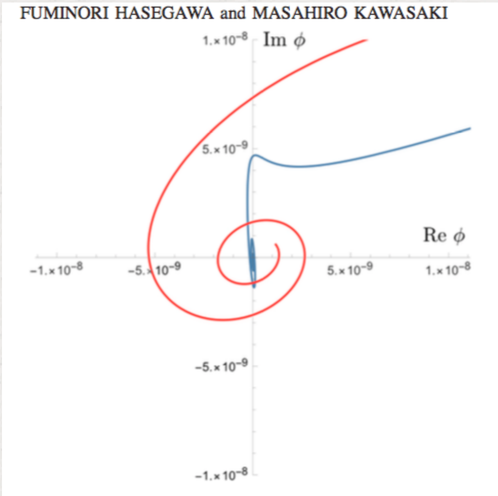
→ SUSY partner becoming heavy (split SUSY) can suppress the one-loop EDM, yet preserve B-genesis –> untestable from EDM.

5 Affleck-Dine baryogenesis

Coherent motion of a scalar moving on otherwise flat direction
Flatness lifted by a high order operator after SUSY breaking

$$\phi = \varphi(t) e^{i\theta(t)}$$

After inflation $\varphi(t)$ converges to some fixed point while $\dot{n}_B \sim \varphi(t)^2 \dot{\theta}(t)$
Parametrically $n_B \sim m_{3/2} \varphi(t_{\mathrm{end}})^2$ after $\phi(t)$ evolves through its potential.



Hasegawa Kawasaki PRD 2017

5.1 Affleck-Dine mechanism and Q ball Dark Matter

– "Q balls" (Coleman 1985) are non-topological solitons; stationary time dependence of the phase of a scalar

– Energy per unit charge less than the mass of lightest elementary particles

$$m_Q \sim Q^{3/4}$$

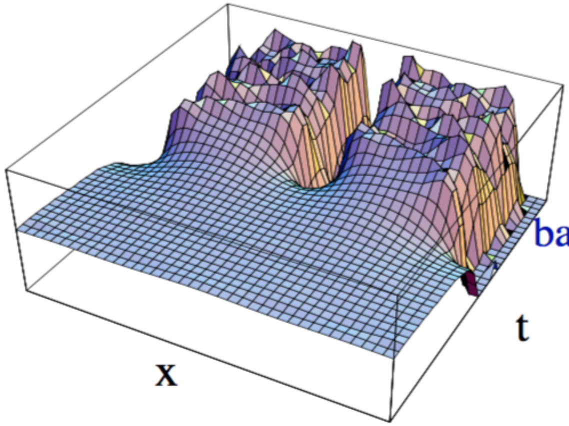
– In SUSY realised as (Kusenko) $\theta \sim \omega t$ for a $\phi(t)$ displaced along a flat direction

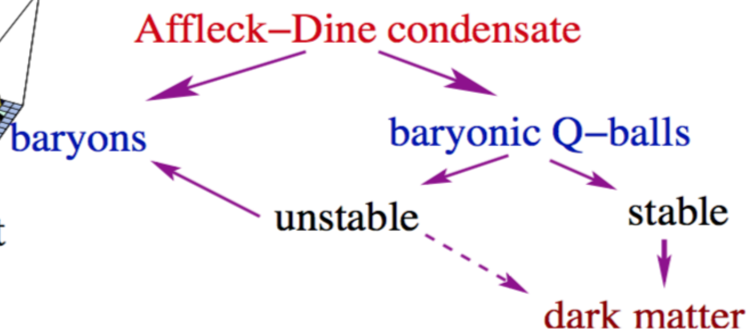
– The Q=B in MSSM –> B balls

– Conditional constraints from observations on B value tied up in the Q balls vs SUSY scale

Fragmentation of AD condensate can produce Q-balls

SUSY Q-balls may be stable or unstable
if stable ⇒ **dark matter**



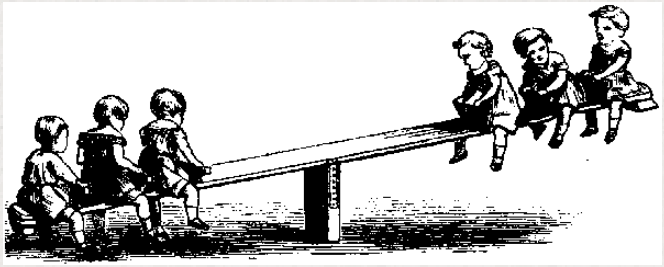


[AK, Shaposhnikov; Enqvist, McDonald]

6 *D*-parity domain walls

- Robust elements of fundamental physics – gauge symmetries, gauged $B-L$, Supersymmetry
- Bubble walls automatic
- CP sources
- compatibility with Wash out
- The scenario can be pitched at a PeV scale
- Gravitational wave signature

A low scale see-saw can still be a lot of fun (Sahu UAY, PRD 2004)



$$M_N \approx \frac{m_D^2}{m_\nu} \sim \quad 10^{14}\text{GeV}\frac{m_D^2}{(100\text{GeV})^2}\frac{0.1\text{eV}}{m_\nu} \quad \sim 10\text{TeV}\frac{m_D^2}{(1\text{MeV})^2}\frac{0.1\text{eV}}{m_\nu}$$

6.1 Minimal SUSY L-R Model – MSLRM

[Aulakh, Bajc, Melfo, Rasin, Senjanovic (1998 ...)]

The minimal set of Higgs superfields required is,

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

Under discrete parity symmetry the fields are prescribed to transform as,

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

The F-flatness and D-flatness conditions lead to the following set of vev's for the Higgs fields as one of the possibilities,

$$<\Omega_c> = \begin{pmatrix} \omega_c & 0 \\ 0 & -\omega_c \end{pmatrix}, \quad <\Delta_c> = \begin{pmatrix} 0 & 0 \\ d_c & 0 \end{pmatrix}, \quad <\Phi_i> = \begin{pmatrix} \kappa_i & 0 \\ 0 & \kappa_i^{'} \end{pmatrix} \tag{2}$$

This ensures spontaneous parity violation Mass scale see-saw

- An R symmetry ensures Ω mass terms in superpotential are vanishing, no new spurious mass scale
- Leads naturally to a see-saw relation

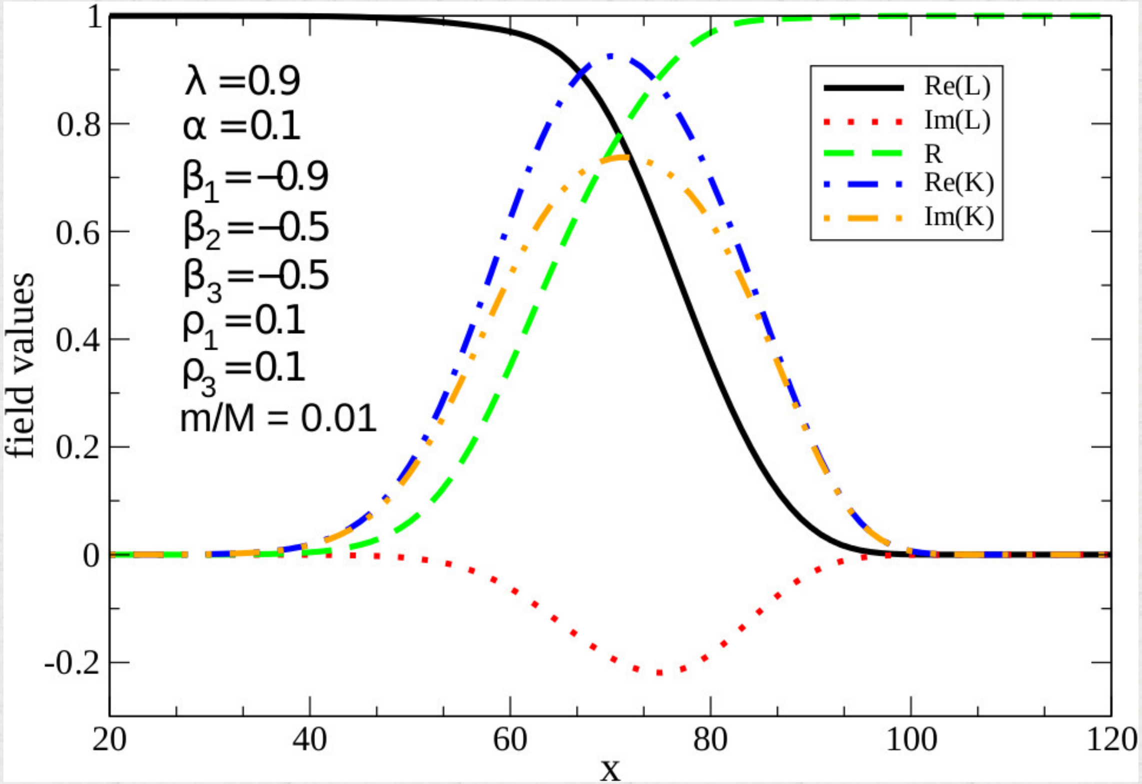
$$\boxed{M_{B-L}^2 = M_{EW} M_R}$$

- Leptogenesis postponed to an energy scale closer to M_{EW} not a high scale like $10^9 - 10^{14}$ GeV

After L-R breaking in the early Universe, due to degeneracy domains of ubroken $SU(2)_R$ or domains of $SU(2)_L$ form spontaneously.
These have to be destroyed through a small selection effect, giving the required time asymmetric evolution to moving domain walls.

6.2 *CP* violation source

Example of simulated domain walls in a Left-Right symmetric model



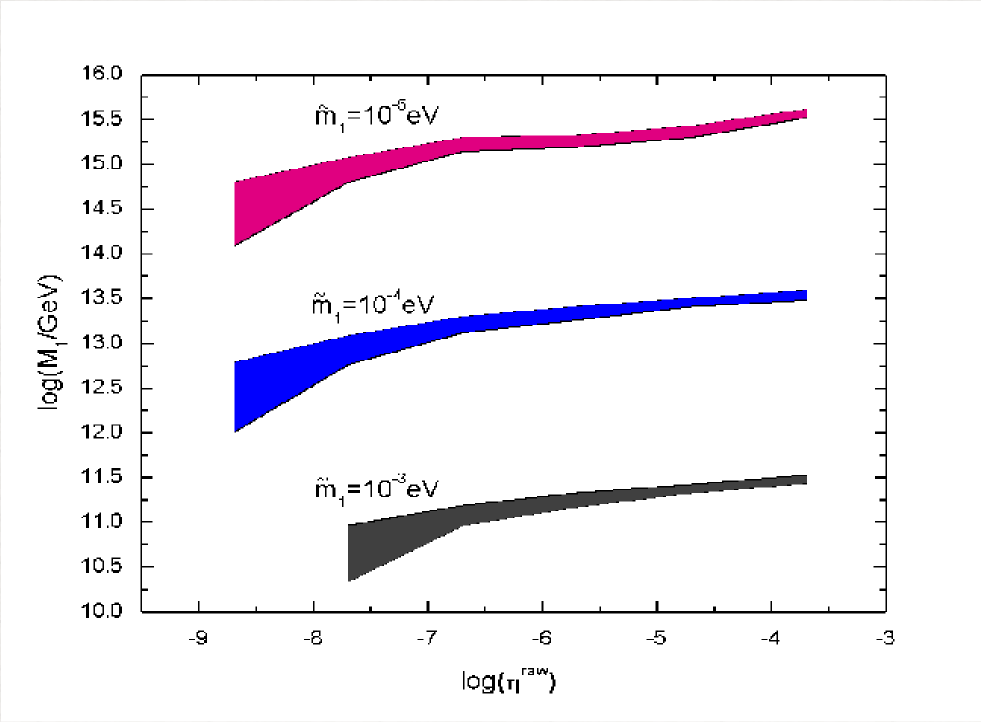
Open questions :

→ Relating the dynamical $O(1)$ CP phase to static phases in EDM etc.

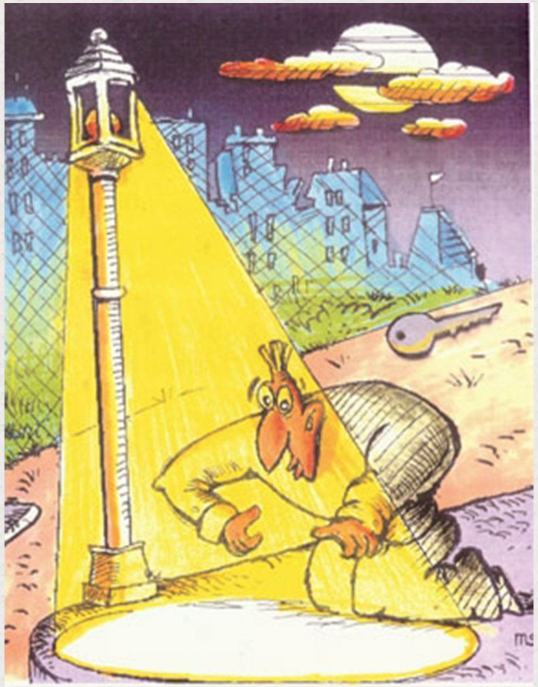
→ Deducing possibel gravitational wave signature from wall collapse

6.3 Wash out constraint

The L-R domain walls can produce large L asymmetry.
Can it be erased jsut sufficiently to recover the observed BAU?
The answer is yes. (Cline, Rabikumar and UAY, PRD 2002; Anjishnu Sarkar, UAY PRD 2003)



The scenario may suffer from the key not being under the lamppost.
Low scale leptogenesis may be more vexatious to verify



der Alte dropped the key well within the house but in a dark corner

7 Observational proposals; Flavour-genesis

– Akhmedov-Rubakov-Smirnov mechanism. Sterile neutrinos.

– SHiP experiment

– See the review volume
"Leptogenesis: Current Challenges for Model Building, Phenomenology and Non-Equilibrium Field Theory" (ArXiv 1711.xxxxx)
Bhupal Dev, Mathias Garny, Juraj Klaric, Peter Millington, Daniele Teresi, C. Hagedorn, R. N. Mohapatra, E. Molinaro, C. C. Nishi, S. T. Petcov et al

8 Conclusions

- The presence of BAU appears to be per se agnostic of SUSY
- SUSY does possess natural mechanisms for large B and L creation, with counterchecks through inflation and DM
- A variety of possibilites now exists in the Lepton sector
- Flavour may play an important role
  - window into flavour and hidden sectors
- Classic spontaneously broken gauge theories posess the requried ingredients naturally
- Compact scenarios like
  (i) intermediate PeV scale L-R symmetry including Pati-Salam
  (ii) SO(10)
  elegant, present natural mechanisms, but verification may pause greater challenges
- Gravitational waves and "new astronomies" may provide clues or confirmations

8.1 Thanks

Bhupal Dev, Debasish Borah, Narendra Sahu, Vikram Rentala for inputs

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