Relating transient *CP* violation and electron EDM

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BASED ON PIYALI BANEJEE AND UAY JHEP (2021)

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1 Motivation

Electroweak baryogenesis models rely on

- a cosmological phase transition
- Movement of bubble walls
- $\mathcal{CP}$ violation within the width of the wall

The $\mathcal{CP}$ phase is transient : both time and space dependent.

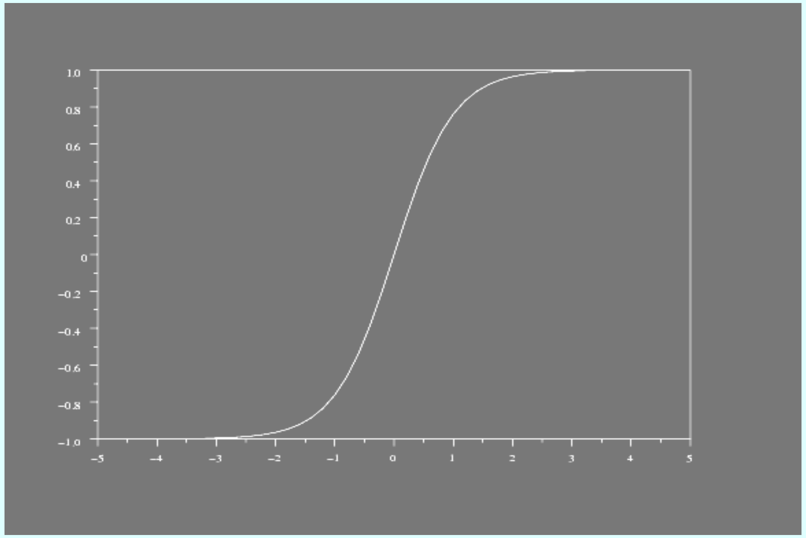
Further,

- Thermal letpgenesis with high scale has difficulties
- The EW Bgenesis scenarios can be adapted for leptogenesis

How to relate transient $\mathcal{CP}$ violation to low energy physics.

Key issues :

- Bubble walls are solitonic solutions
  - Space dependent *CP* phase is also solitonic
  - Machine errors in end values can produce a completely different curve.
  - Difficulty relating values at a finite boundary to interior values.



- Bubble walls occur at finite temprature. Need to relate finite temprature parameter values to observable zero temperature values.

1 Genesis of baryogenesis

Just a little asymmetry

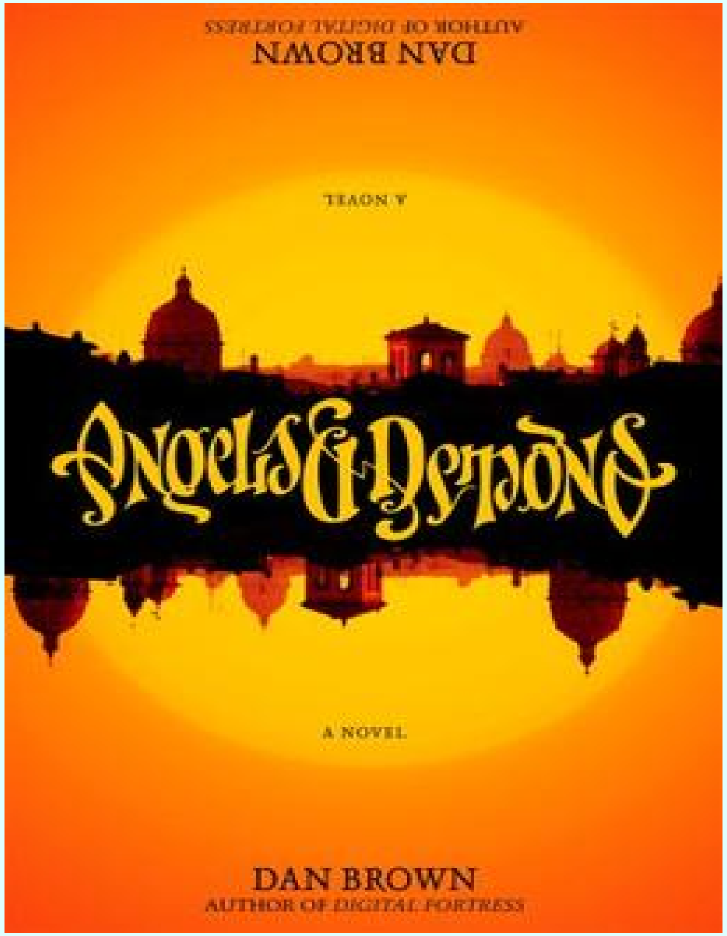
Annus Mirablis of Cosmology
Two discoveries of 1964

→ CP violation in $K^0 - \overline{K^0}$

→ CMB !!!

Weinberg comment in Brandeis Lectures 1964.

Sakharov model elucidating the criteria 1967



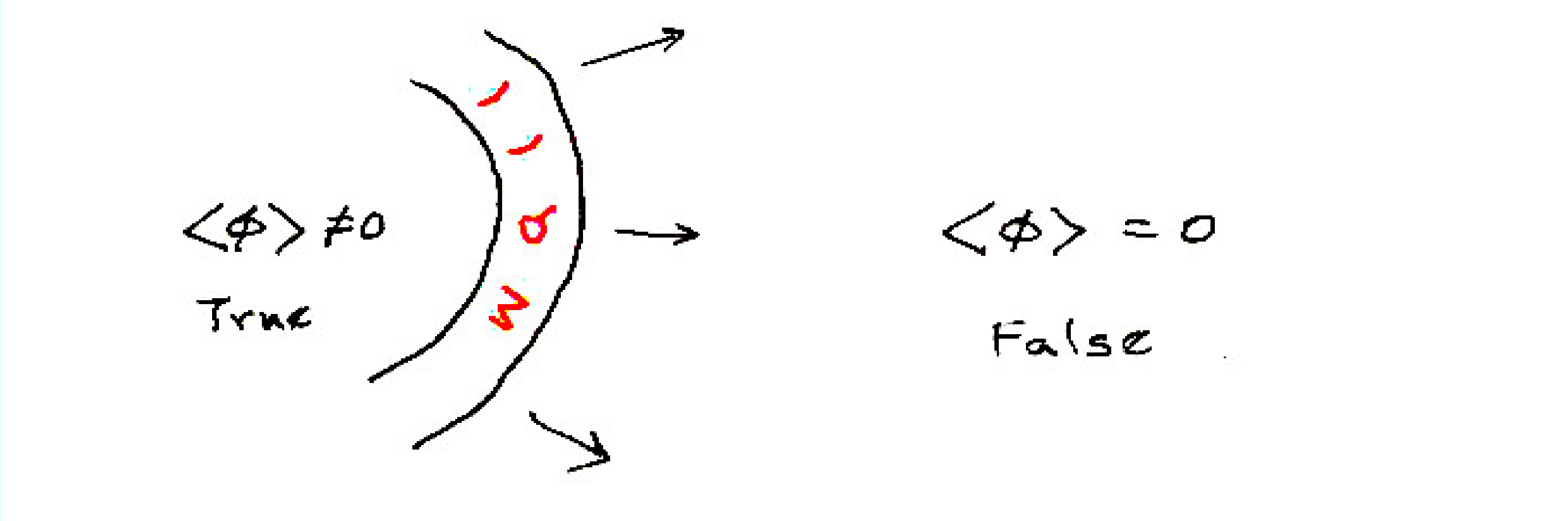
1.1 GUT baryogenesis

- Out of equlibrium decays of GUT scale leptoquarks
- The Particle Physics rates and expansion rate of the Universe compete : out-of-equilibrium decays

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

1.2 Electroweak baryogenesis (Low scale)

- Expansion rate H too slow at electroweak scale
  - need another source of out of equilibrium conditions
  - moving phase boundaries of a First Order Phase Transition (FOPT)



- But FOPT in SM requires Higgs mass to be $\lesssim$90GeV

2 Baryogenesis from leptogenesis

Replay the Baryon asymmetry recipes for Leptons

- Thermal solution : Out of equilibrium decays of Majorana neutrinos – high scale
- Phase transition : Moving phase boundaries of Left-Right symmetric model – can be low scale

2.1 Difficulties of High scale leptogenesis

out-of-equilibrium decays of heavy Majorana neutrinos
[see eg. Buchmuller, Di Bari and Plumacher (2004)]

- Getting Majorana neutrinos to be in equilibrium

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

- Have sufficiently large CP violation – assuming see-saw mechanism and 3 generations

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

- Preventing washout of the produced asymmetry by the same Majorana neutrino mediated processes

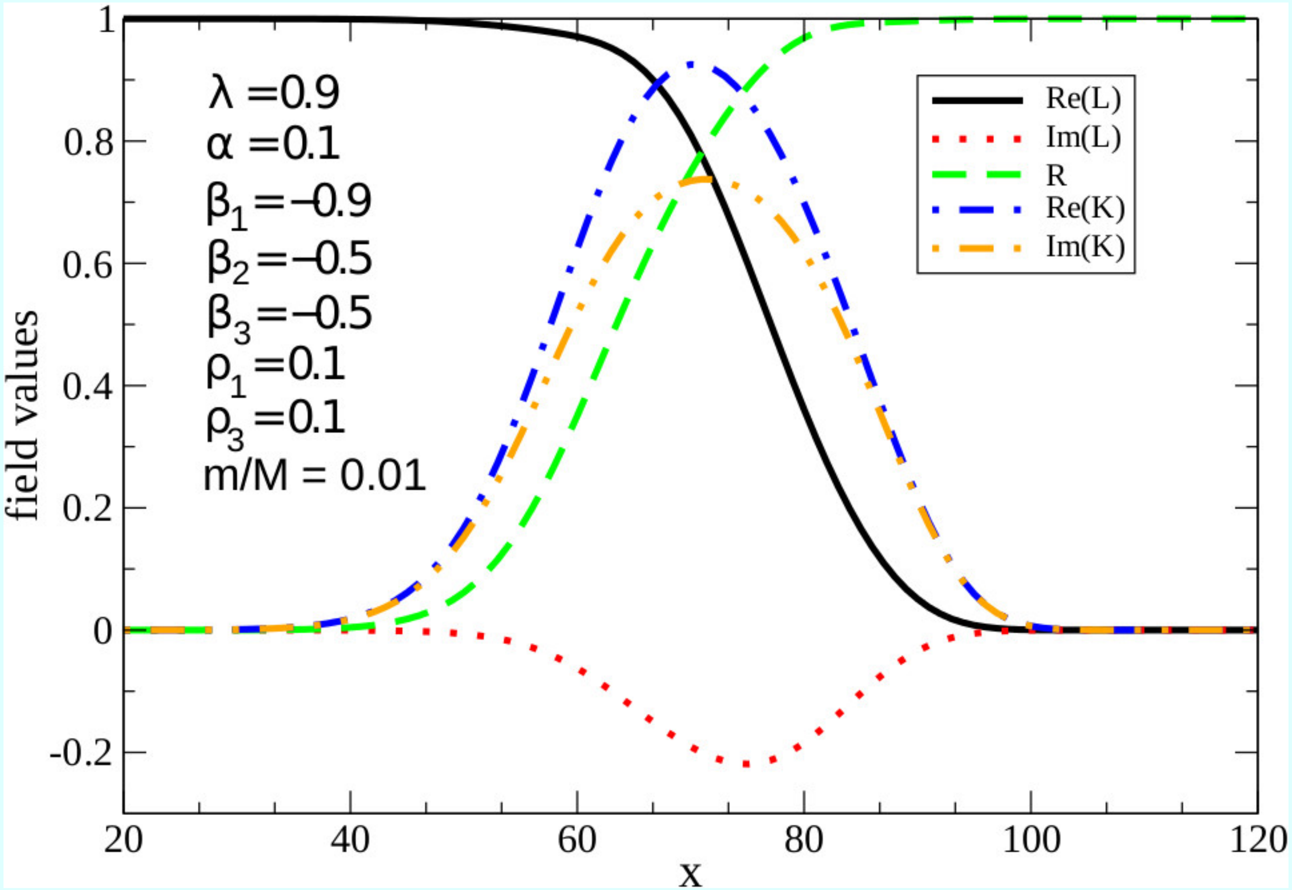
3 L-genesis in left-right symmetric world

- Intorduce ν_R and an $SU(2)_R$
- Assume flip symmetry $SU(2)_L \leftrightarrow SU(2)_R$ (possible in $SO(10)$)
- $B - L$ automatically a local symmetry – ensures we start with a clean slate $B - L = 0$ at the Big Bang.
- Two kinds of vacua - $SU(2)_L$ breaking or $SU(2)_R$ breaking
  - one desirable, the other accidental
- Big Bang universe has horizons
  - patchwork of both kinds of domains
- So we have
  - → L number violation for Majorana neutrinos
  - → Out of equilibrium wall motion (bring us to SM)

→ CP violation – transient values in the core of the DW

Moving phase boundaries at $SU(2)_R$ breaking

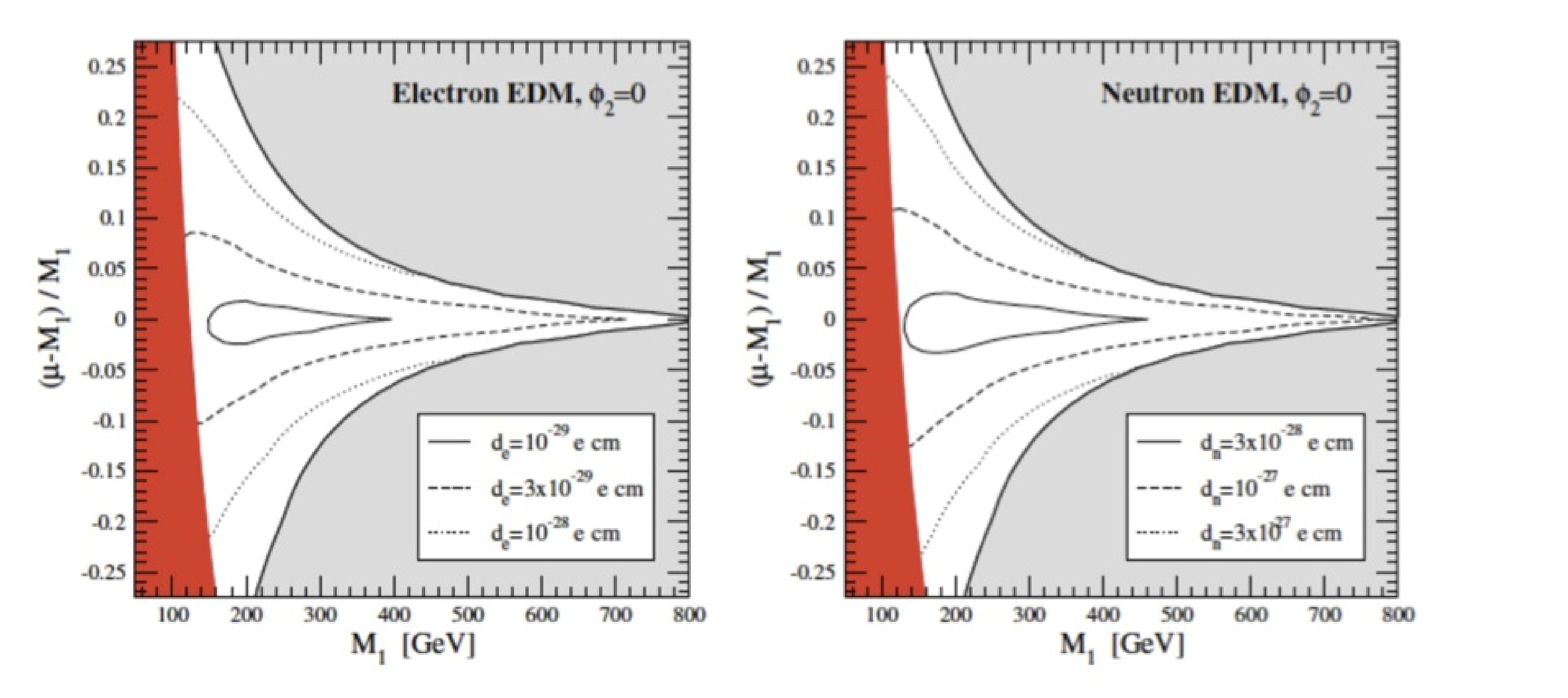
[Sarkar, Abhishek and UAY NPB 2008]



How can we verify this?

3.1 Relating *CP* violation to EDM

In MSSM++ models,



Morrissey and Ramsey-Musolf (2012)

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

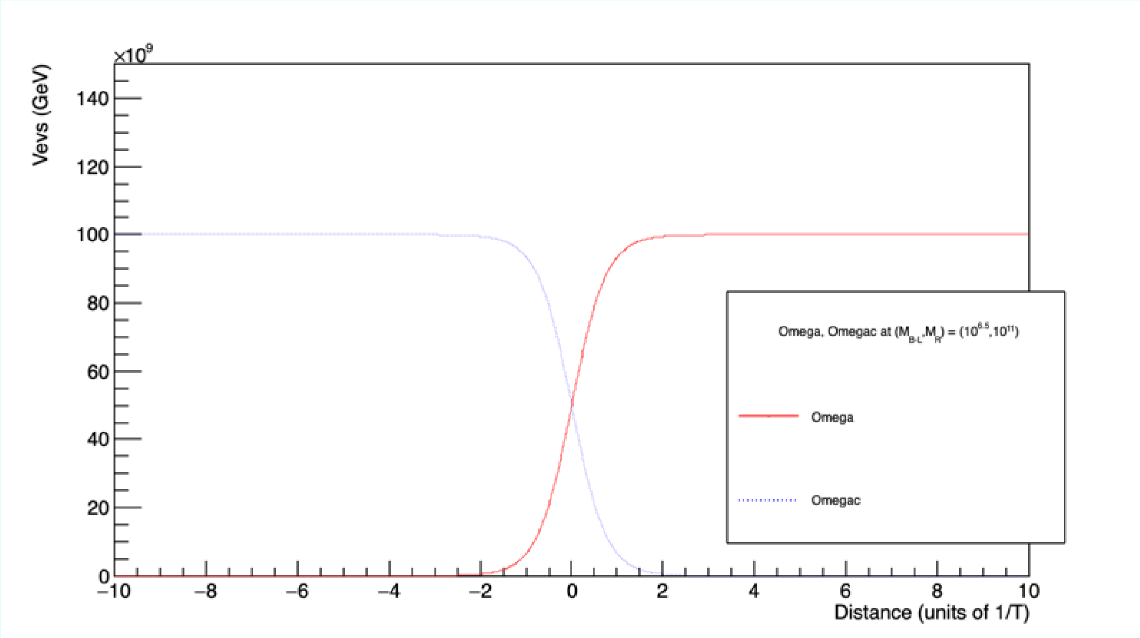
4 A renormalisable SUSY LR model

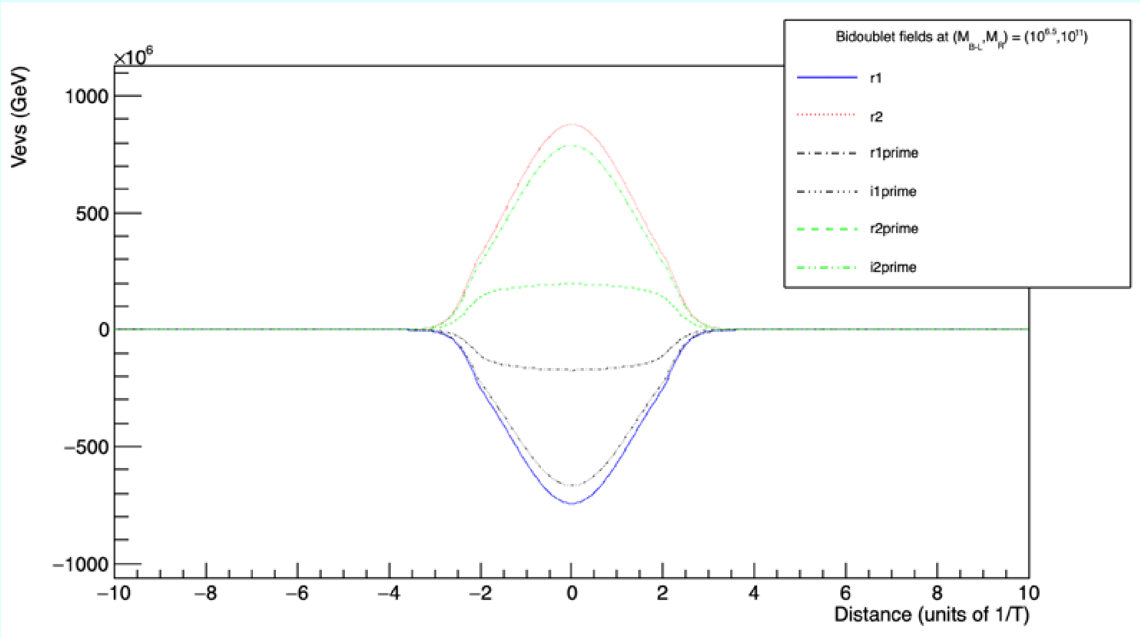
[Benakli, Aulakh, Senjanovic (1997)]

- Higgs content : Bidoublet Φ, Triplets Δ_L, Δ_R with $B-L=2$, Triplets Ω_L, Ω_R with $B-L=2$.
  - Renormalisable model
- Two stage gauge symm breaking : $M_R \sim SU(2)_R \rightarrow U(1)_R$ and $M_{B-L} \sim U(1)_R \otimes U(1)_{B-L} \rightarrow U(1)_Y$

– Avoid new mass scale by imposing an R symmetry $\rightarrow M^2_{B-L} \approx M_{EW} M_R$

$$
\begin{aligned}
W = \; & m_\Delta (\mathrm{Tr}\Delta\,\bar{\Delta} + \mathrm{Tr}\Delta_c\,\bar{\Delta}_c) + \frac{m_\Omega}{2}(\mathrm{Tr}\Omega^2 + \mathrm{Tr}\Omega_c^2) + \mu_{ij}\mathrm{Tr}\tau_2\,\Phi_i^T\,\tau_2\,\Phi_j \\
& + a\,(\mathrm{Tr}\Delta\,\Omega\,\bar{\Delta} + \mathrm{Tr}\Delta_c\,\Omega_c\,\bar{\Delta}_c) \\
& + \alpha_{ij}\,(\mathrm{Tr}\Omega\,\Phi_i\,\tau_2\,\Phi_j^T\,\tau_2 + \mathrm{Tr}\Omega_c\,\Phi_i^T\,\tau_2\,\Phi_j\,\tau_2)
\end{aligned}
$$





Piyali Banejee
and UAY JHEP
(2021)

4.1 Corroborating with EDM

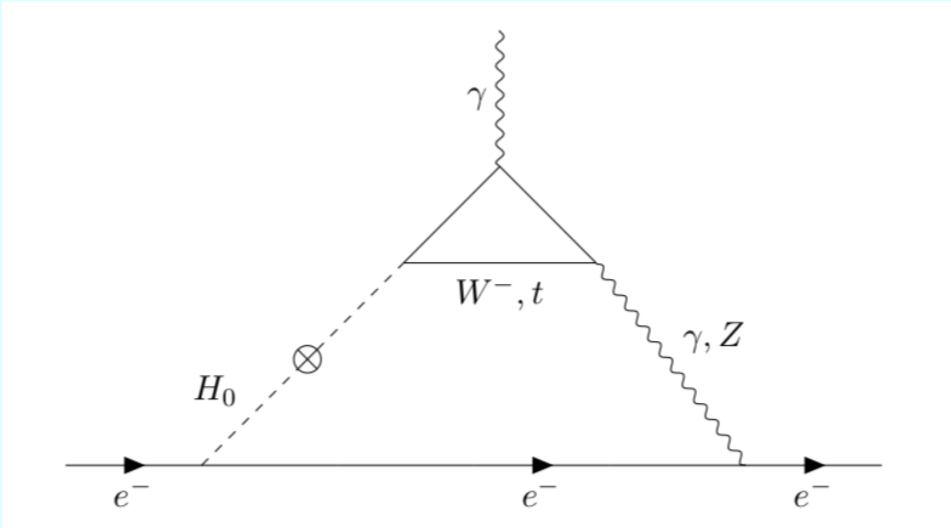
- Assume all scalar vevs entering the DW to be corrected by temperature correction $O(g^2T^2)$

- In a simple bidouble Higgs model, a 1-loop formula is

$$\frac{d_e}{e} \sim \frac{\alpha\, m_e}{4\pi M_h^2} \sin\delta$$

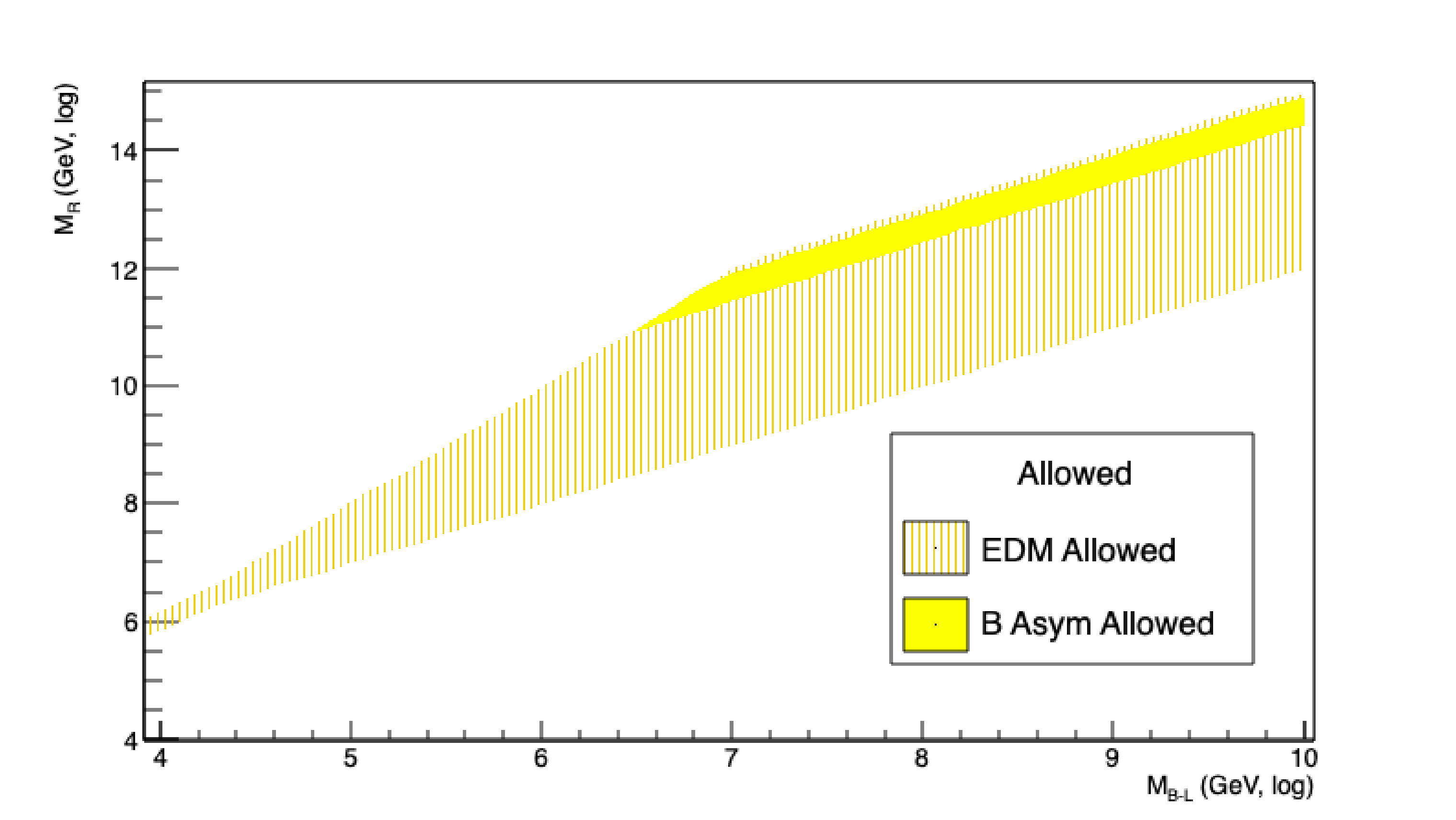
- For large values of M_{B-L} and M_R two loop effects arising from the neutral scalars dominate the one loop

$$(d_e/e)|_{\text{twoloop}} = \frac{G_F\, m_e\, \alpha \sin\delta}{\pi^3\sqrt{2}} \left(f_{W,H\gamma\gamma}(M_W^2/M_h^2) + f_{W,HZ\gamma}(M_W^2/M_h^2) \right.$$
$$\left. + f_{t,H\gamma\gamma}(M_t^2/M_h^2) + f_{t,HZ\gamma}(M_t^2/M_h^2) \right).$$



and four other such diagrams

Thus we obtain constraints on the mass scales M_R and M_{B-L}.



→ Interesting lesson : the R-symmetry compatible formula of Benaqli, Aulakh and Senjanovic is in tension.

→ Can be repaired by including the $m_\Omega \Omega\Omega$ term in superpotential

5 Conclusion

→ GUT Bgenesis and EW Bgenesis are now remote possibilites

→ Thermal leptogenesis requires fine tuning

→ Low (TeV to PeV) scale leptogenesis viable through phase transition Domain Walls

  - But difficulty of independent confirmation
  - $\mathcal{CP}$ violation inside DW is transient . . . no scale residue

→ We have provided a case study where this transient $\mathcal{CP}$ phase can be traced to its zero temperature value

  - and be verified through Electron EDM

Thank You

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