Domain walls and CP violation with left right supersymmetry: implications for leptogenesis and electron EDM

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Outline of the talk

- Motivation
- Left Right Supersymmetry (LRSUSY) and Domain Wall (DW)
- Leptogenesis and Baryogenesis
- Electric Dipole Moment (EDM) of the electron
- Conclusion

Motivation

Problems with SM:

No explanation for small non-zero neutrino masses.

Higgs mass divergence / extreme fine tuning, no dark matter, ...

Possible solutions:

Left Right SM: RH neutrino, seesaw, ...

SUSY: Less divergence / minimal finite tuning, dark matter candidate (with exact R-parity), ...

Left Right supersymmetry (LRSUSY): Best of LRSM + SUSY

Not enough CP violation and no first order EW phase transition for successful explanation of baryon asymmetry of universe in SM ☹

This work: LRSUSY can overcome this too ☺

Left Right SUSY (LRSUSY) Model

- Gauge group $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$, $L \leftrightarrow R$ discrete symmetry.
- $(u_R, d_R), (\nu_R, e_R), \ldots, \rightarrow \mathrm{SU}(2)_R$ doublets.
- $\mathrm{SU}(2)_L$ Higgs doublet H of SM replaced by $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ Higgs bidoublets Φ_1, Φ_2.
- $\mathrm{SU}(2)_L$, $\mathrm{SU}(2)_R$ Higgs triplets Ω, Ω_c for left right parity breaking at a high scale M_R (Imp. step by Aulakh et al.)
- $\mathrm{SU}(2)_L$, $\mathrm{SU}(2)_R$ Higgs triplets Δ, Δ_c for neutrino seesaw at a lower scale M_{B-L}.
- $\mathrm{SU}(2)_L$, $\mathrm{SU}(2)_R$ Higgs triplets $\bar{\Delta}$, $\bar{\Delta}_c$ for anomaly cancellation.
- LRSUSY $\rightarrow$ MSSM, broken parity, exact R-parity $\rightarrow$ SM
- Small non-zero neutrino masses, Higgs mass stabilised, dark matter candidate ✓

LRSUSY Model

Higgs superpotential:

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

where $\alpha_{ii} = 0$, $\alpha_{12} = -\alpha_{21} = \alpha$ and $\mu_{ij} = \mu_{ji}$.

Breaking of $\mathrm{SU}(2)_R$ / $\mathrm{SU}(2)_L$ at scale M_R followed by breaking of $\mathrm{U}(1)_{B-L}$ at lower scale M_{B-L} while keeping SUSY intact gives

$$M_R = \frac{m_\Delta}{-a}, M_{B-L} = \frac{\sqrt{2m_\Delta m_\Omega}}{-a} \implies M_R = \frac{M_{B-L}^2}{-2am_\Omega}.$$

Domain Walls in LRSUSY gauge breaking

Two mass scales: $M_R = $ scale of parity i.e. $\mathrm{SU}(2)_L$ or $\mathrm{SU}(2)_R$ gauge breaking, $M_{B-L} = $ scale of $\mathrm{U}(1)_{B-L}$ gauge breaking, $M_R \gg M_{B-L}$.

Wall

LH Domain	RH Domain
Break: $\mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \to \mathrm{U}(1)_Y$	Break: $\mathrm{SU}(2)_L \times \mathrm{U}(1)_{B-L} \to \mathrm{U}(1)_Y$
Final gauge: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	Final gauge: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_Y$
$\langle(\Omega_c, \Delta_c)\rangle = (M_R, M_{B-L})$	$\langle(\Omega, \Delta)\rangle = (M_R, M_{B-L})$
$\langle(\Omega, \Delta)\rangle = (0, 0)$	$\langle(\Omega_c, \Delta_c)\rangle = (0, 0)$

Breaking of discrete left right symmetry breaking creates an energy barrier between LH and RH domains called domain wall (DW).

Network of domain walls (DW) conflicts with standard cosmology.

Mechanisms proposed to remove DW early enough: slightly breaking LR symmetry via soft terms, non renormalisable terms.

So DW came and went at around 10^{-15} s, before EW symmetry breaking at 10^{-12} s, are there any lasting effects of the domain walls?

This work: Domain Walls and Baryon Asymmetry

M_R = scale of parity i.e. $\mathrm{SU}(2)_L$ or $\mathrm{SU}(2)_R$ gauge breaking, M_{B-L} = scale of $\mathrm{U}(1)_{B-L}$ gauge breaking, $M_R \gg M_{B-L}$.

Wall

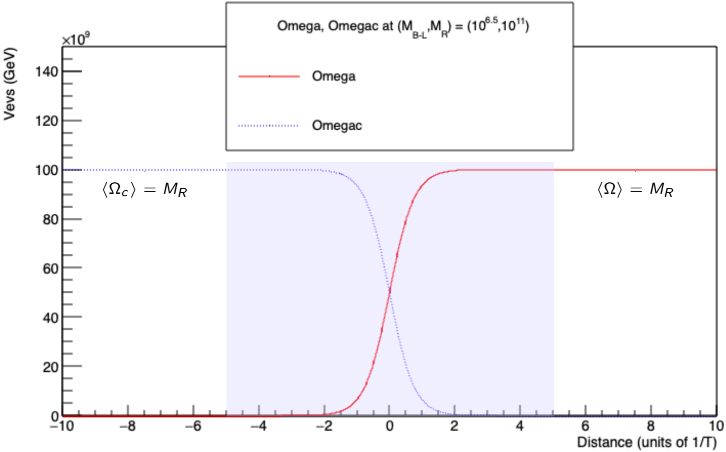
LH Domain	RH Domain
Final gauge: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	Final gauge: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_Y$
$\langle(\Omega_c, \Delta_c)\rangle = (M_R, M_{B-L})$	$\langle(\Omega, \Delta)\rangle = (M_R, M_{B-L})$
$\langle(\Omega, \Delta)\rangle = (0, 0)$	$\langle(\Omega_c, \Delta_c)\rangle = (0, 0)$

Network of domain walls (DW) i.e. energy barriers is a problem for standard cosmology. But can be removed early enough ...

This work: Employ DW fruitfully to show dynamical generation of baryon asymmetry of universe, which SM fails to explain.

Stringent bounds on (M_R, M_{B-L}) parameter space of LRSUSY obtained for the first time.

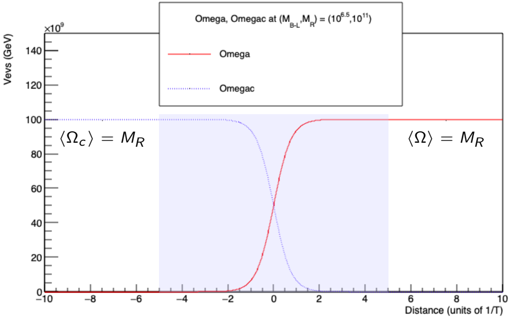
Spatially varying vevs in LRSUSY breaking: I



We know vevs of Ω, Ω_c (the heaviest vevs) outside the wall.

Take a tanh kink ansatz to make them transit smoothly from left to right passing through the wall on the way $\rightarrow$ Spatially varying vevs for Ω, Ω_c.

Spatially varying vevs in LRSUSY breaking: II



Write a functional of remaining Higgs fields expressing energy density per unit area of domain wall.

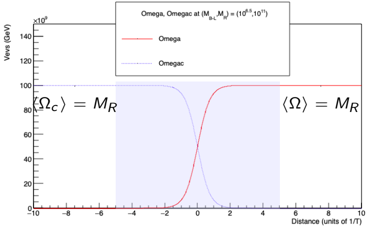
Minimise functional by Euler-Lagrange obtaining spatially varying vevs.

$$H = \int dx \, (\frac{1}{2}(\dot{d}^2 + \dot{\bar{d}}^2 + \dot{d_c}^2 + \dot{\bar{d}}_c^2 + \dot{r_1}^2 + \dot{i_1}^2 + \dot{r_1'}^2 + \dot{i_1'}^2 + \dot{r_2}^2 + \dot{i_2}^2 + \dot{r_2'}^2 + \dot{i_2'}^2) + \langle V_{\mathrm{SUSY}} \rangle + \langle V_{\mathrm{soft}} \rangle).$$

First four: Vevs of triplet Higgs Δ, $\bar{\Delta}$, Δ_c, $\bar{\Delta}_c$.

Remaining: Real and imaginary parts of vevs of bidoublet Higgs Φ_1, Φ_2.

Spatially varying vevs in LRSUSY breaking: III



Energy density per unit wall area per unit volume

$$H = \int dx \, \Big(\frac{1}{2} \big(\dot{d}^2 + \dot{\bar{d}}^2 + \dot{d}_c{}^2 + \dot{\bar{d}}_c^2 + \dot{r}_1{}^2 + \dot{i}_1{}^2 + \dot{r}_1'{}^2 + \dot{i}_1'{}^2 + \dot{r}_2{}^2 + \dot{i}_2{}^2 + \dot{r}_2'{}^2 + \dot{i}_2'{}^2 \big) + \langle V_{\mathrm{SUSY}} \rangle + \langle V_{\mathrm{soft}} \rangle \Big).$$

Minimise by E-L equations.

V_{SUSY} is the SUSY scalar potential. V_{soft} is the soft SUSY breaking potential.

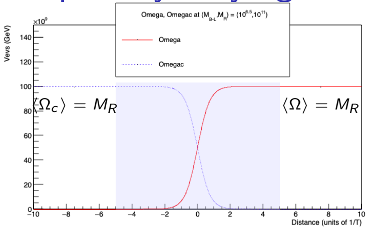
$$\begin{aligned} V_{\mathrm{soft}} = & -\mu_1^2 \mathrm{Tr}\,(\Phi_1^\dagger \Phi_1) - \mu_2^2 \mathrm{Tr}\,(\Phi_2^\dagger \Phi_2) \\ & - e^{i\beta_3} \mu_3^2 \mathrm{Tr}\,(\Phi_1^\dagger \tau_2 \Phi_1^* \tau_2) - e^{i\beta_4} \mu_4^2 \mathrm{Tr}\,(\Phi_2^\dagger \tau_2 \Phi_2^* \tau_2) - e^{i\beta_5} \mu_5^2 \mathrm{Tr}\,(\Phi_1^\dagger \tau_2 \Phi_2^* \tau_2) \\ & + \mathrm{h.c.}, \end{aligned}$$

β_3, β_4, β_5 $\rightarrow$ explicit CP phases.

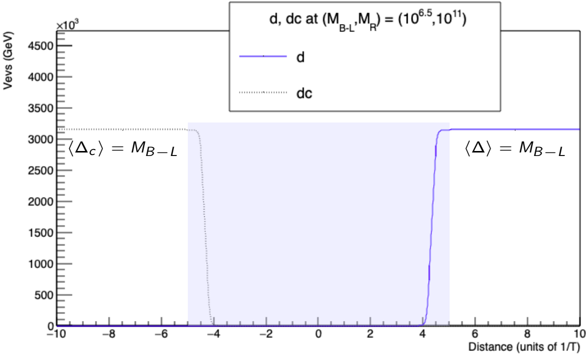
Now solve E-L equations numerically. Get spatially varying vevs.

Vevs of bidoublets Φ_1, Φ_2 spatially varying and complex inside the wall.

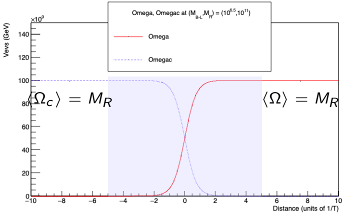
Spatially varying vevs in LRSUSY breaking: IV

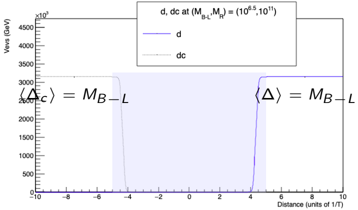


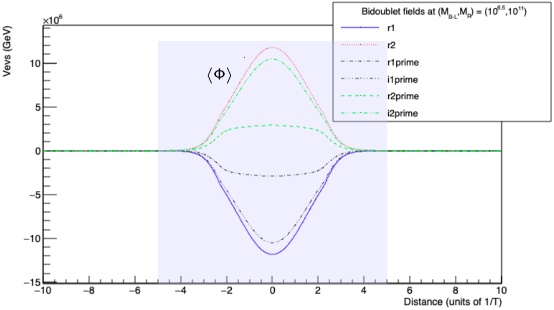
Shape of other Higgs vevs obtained by solving E-L equations.



Spatially varying vevs in LRSUSY breaking: V

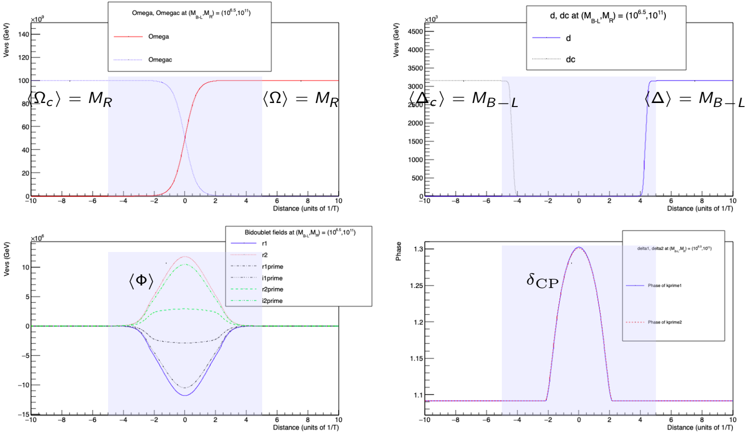






Bidoublet vevs complex and spatially varying inside the wall; almost zero outside.

Spatially varying vevs in LRSUSY breaking: VI

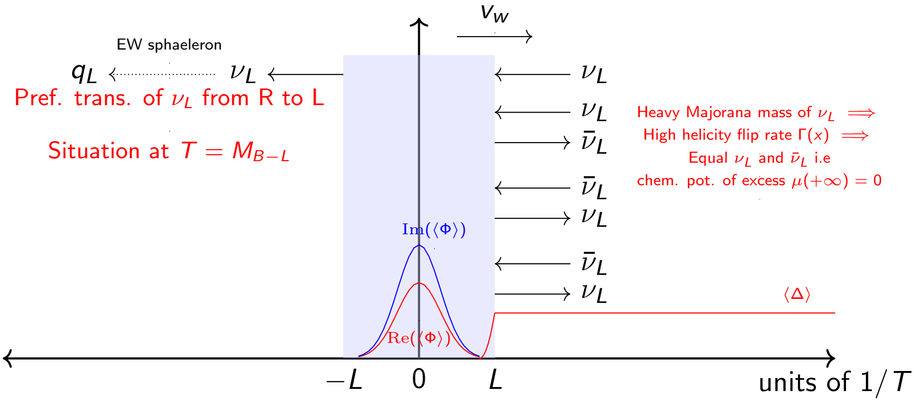


Bidoublet vevs complex and spatially varying inside the wall; almost zero outside. Constant non-zero phase outside.

Wall moves because of slight breaking of LR symmetry via e.g. soft terms, non-renorm. terms, disappearing completely before EW symmetry breaking.

Implications for baryon asymmetry and electron EDM ☺

Baryon asymmetry from moving wall: I



Diffusion Eq: $-D\mu'' + v_w\mu' + \Gamma(x)\mu = S(x), S(x) \sim (m_\nu(x)\delta'(x))''$

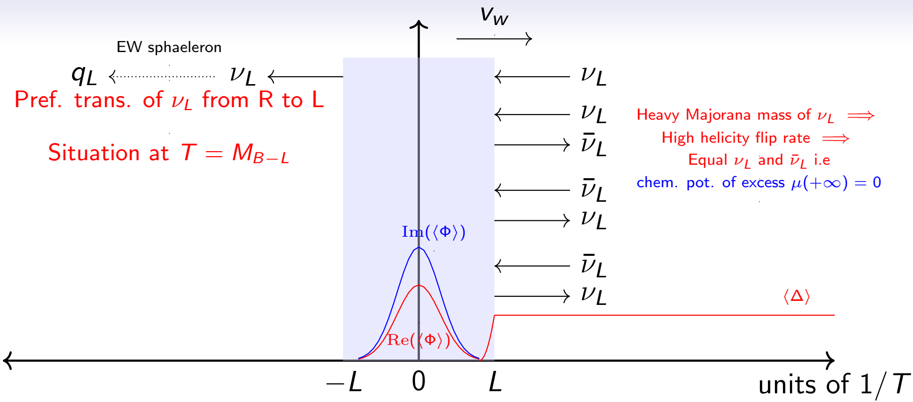
Solve it numerically, raw lepton asymmetry $\sim \frac{\mu(-\infty)T^2}{6}$ in LH domain.

Partial washout inv. decay heavy $\nu_R \rightarrow$ Surviving lepton asym. LH domain.

EW sphaelerons $\rightarrow$ lepton asym. partially converted to final baryon asym.

Compare with 6×10^{-10} experimental value (Canetti et al. 2012).

Baryon asymmetry from moving domain wall: II

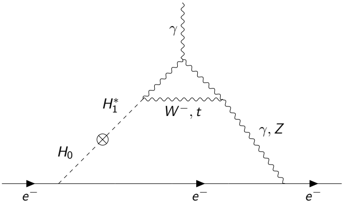


Spatially varying complex mass of ν_L inside wall (C+CP violation: Sakharov 1) + L $\rightarrow$ R movement of wall (Strong loss of equilibrium: Sakharov 2) $\Longrightarrow$ Excess ν_L in LH domain. $\mu(x)$ obtained from diffusion equation.

Part of initial lepton asym. $\mu(-\infty)$ washed out by various processes.

Part of surviving excess ν_L in LH domain $\xrightarrow{\text{Sphaeleron}}$ excess baryons (Baryon number violation: Sakharov 3) Expt. value: 6×10^{-10} (Canetti et al.)

Electron EDM



Smoking gun sign of CP violation in a theory.

SM: $\sim 10^{-37}$ e cm EDM at 3 loop level.

ACME 2: $< 10^{-29}$ e cm at 95% C.L. Consistent with zero EDM.

Additional contribution to EDM in LRSUSY at 1 and 2 loop levels. 2 loop dominant (Barr-Zee).

Note that EDM is measured in the lab which is in LH domain at zero T.

So far calculations of bidoublet mass matrix done at $T = M_{B-L}$. Hence correct for zero temperature by lowering masses by $O(M_{B-L}^2)$.

Maximum contribution by two lowest mass eigenstates H_0 and H_1, $\otimes$ denotes a CP violating contribution of $\sin\delta$, δ being relative phase of H_0 and H_1.

Compute 2 loop contribution now and compare with ACME 2 upper bound.

Gravitational waves from collapsing DW

The domain walls formed during gauge symmetry breaking of LRSUSY eventually collapse at some point. Gravitational waves are produced then.

Suppose domain walls annhilate when temperature $T_{\rm ann} = 200$ GeV, just above EW scale and below SUSY breaking scale. Then number of relativistic degrees of freedom g_*, g_{*s} is around 105.

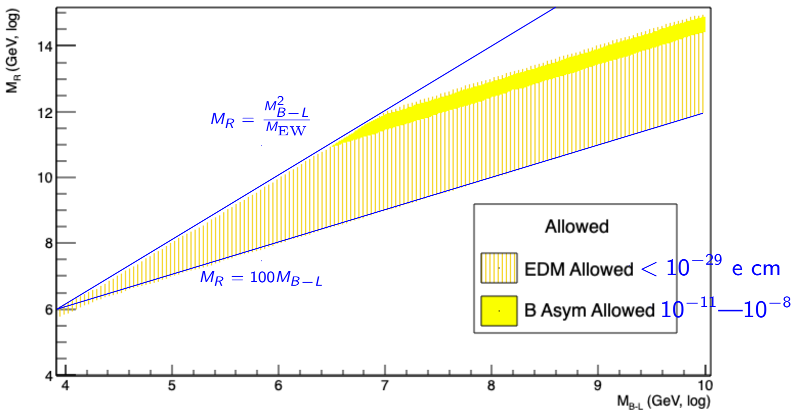
The peak frequency of gravitational waves is then calculated to be

$$f_{\rm peak} = 1.1\times 10^{-7}\,\text{Hz}\,\left(\frac{g_*}{10}\right)^{1/2}\left(\frac{g_{*s}}{10}\right)^{-1/3}\left(\frac{T_{\rm ann}}{\text{GeV}}\right) = 3.256\times 10^{-5}\,\text{Hz}.$$

This frequency is about six orders of magnitude below what LIGO can detect today.

However, proposed space-based gravitational wave detectors like eLISA may be able to detect such frequencies and energy densities, serving as an important test of the model.

Allowed region in (M_R, M_{B-L}) plane



$L = \frac{5}{T}$, $v_w = 0.3$, Trilinear $\Omega\Phi\Phi$ coupling $\alpha = 0.006$, bidoublet mass terms $\sim M_R$, soft mass terms $\sim \alpha^2 M_R$, explicit phases in soft terms ~ 1.

$M_{B-L} > 10^{6.5}$ and M_R lies in a narrow band significantly below $\frac{M_{B-L}^2}{M_{\mathrm{EW}}}$

Conclusion

• After scanning the parameter space, we get $M_{B-L} > 10^{4.5}$ GeV ($\alpha \approx 0.1$) for consistency with both experiments.

• Almost always, M_R lies in a narrow band significantly below $\frac{M_{B-L}^2}{M_{\rm EW}}$; tension with Aulakh et al.'s original suggestion $M_R \approx \frac{M_{B-L}^2}{M_{\rm EW}}$.

• Our bounds are in perfect agreement with PeV scale SUSY of recent works, where gravitino can be much heavier than $M_{\rm EW}$.

• Most stringent bounds on the parameter space of LRSUSY.

George Box: All models are wrong, but some are useful!

Thank you for your attention!