Cosmological implications of unification with D-parity

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Overview

- Seeking a GUT – the inevitability of D-parity
- Parity symmetric world at PeV scale –> SUSY L-R
- Domain wall dynamics
  - Domain wall removal
- Minimal Supersymmetric GUT – contenders with SO(10)
- The D-domain wall ... parametric
- Implications to comsology

Collaborators : Piyali Bannerjee, Ila Garg ...(Sasmita Mishra, Anjishnu Sarkar, Desish Borah)

What choices did der Alte have?

Looking beyond the SM in the light of

$\rightarrow$ Baryon asymmetry

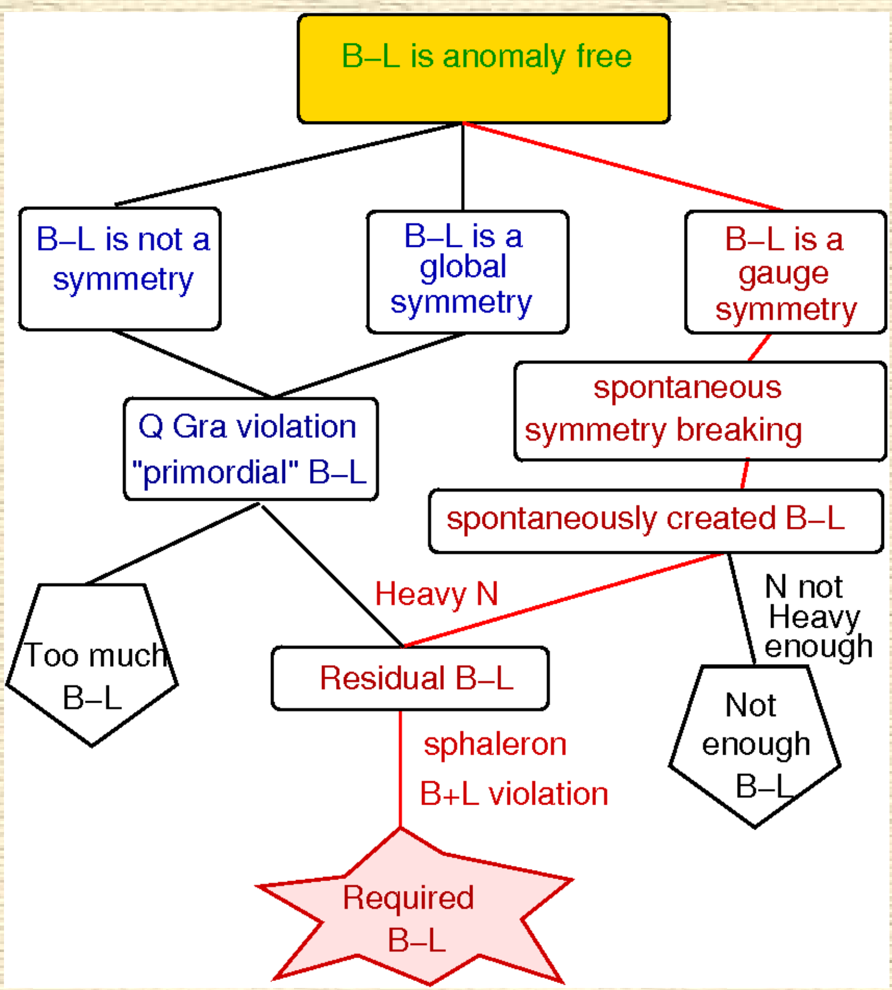
$\rightarrow$ Neutrino masses and mixing

Toolkits

- Gauge principle – massless vector bosons; quantisation of charge
- Chirality – massless fermions
- Scalars – symmetry breaking and universal source of masses
  - $O(1)$ CP volation natural

Other than Dark Matter and Dark Energy, the almost massless neutrino begs inclusion within above principles ...
$B - L$ is one exact anomaly free ungauged charge

What choices did der Alte have?



“Just” Beyond the SM ?

The see-saw and the GUT scale

– Tentalising possibility ... or
– False start about high scale?

GUT naturalness of gauge coupling unification —> see-saw M_N was expected to fit in.
But note that

$$\begin{aligned} m_N &\approx \frac{m_D^2}{m_\nu} \\ &\approx 10^{14}\mathrm{GeV}\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)\left(\frac{m_D}{100\,\mathrm{GeV}}\right)^2 \\ &\approx 10^{4}\mathrm{GeV}\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)\left(\frac{m_D}{1\,\mathrm{MeV}}\right)^2 \end{aligned}$$

So in the absence of any suggestive high scale, may as well explore the PeV scale. (Narendra Sahu and UAY PRD 2005)

Minimal SUSY L-R Model – MSLRM

Just Beyond the Standard Model ... $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

$$Q = \tau_L^3 + \tau_R^3 + \frac{1}{2} X$$

- In praise of $B - L$ ... the only conserved charge of SM which is not gauged! –> Hereby it gains the status of being gauged

The minimal set of Higgs superfields required is,

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

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.

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

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

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

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

This ensures spontaneous parity violation [Aulakh, Bajc, Melfo, Rasin, Senjanovic (1998 ...)] 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

The D-degeneracy of vacua

A $U(1)_D$ path connecting $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_R$ like vacua :

$$W_L = \; m_\Delta \cos^2\frac{\theta}{2}\, d^2 + 2\, m_\Omega \cos^2\frac{\theta}{2}\, w^2 + a\cos^3\frac{\theta}{2}\, d^2\, w$$

$$W_R = \; m_\Delta \sin^2\frac{\theta}{2}\, d^2 + 2\, m_\Omega \sin^2\frac{\theta}{2}\, w^2 + a\sin^3\frac{\theta}{2}\, d^2\, w$$

So when θ=0, we have left like vacuum and for $\theta = \pi$, right like. Now

$$\frac{\partial V}{\partial \theta} = 2\, Re \sum_i \frac{\delta W}{\delta \phi_i} \frac{\partial}{\partial \theta} (\frac{\delta W}{\delta \phi_i})$$

Using $w = \frac{-m_\Delta}{a}$ and $d = (\frac{2\, m_\Delta\, m_\Omega}{a^2})^{\frac{1}{2}}$ whihc gives usual vacua,

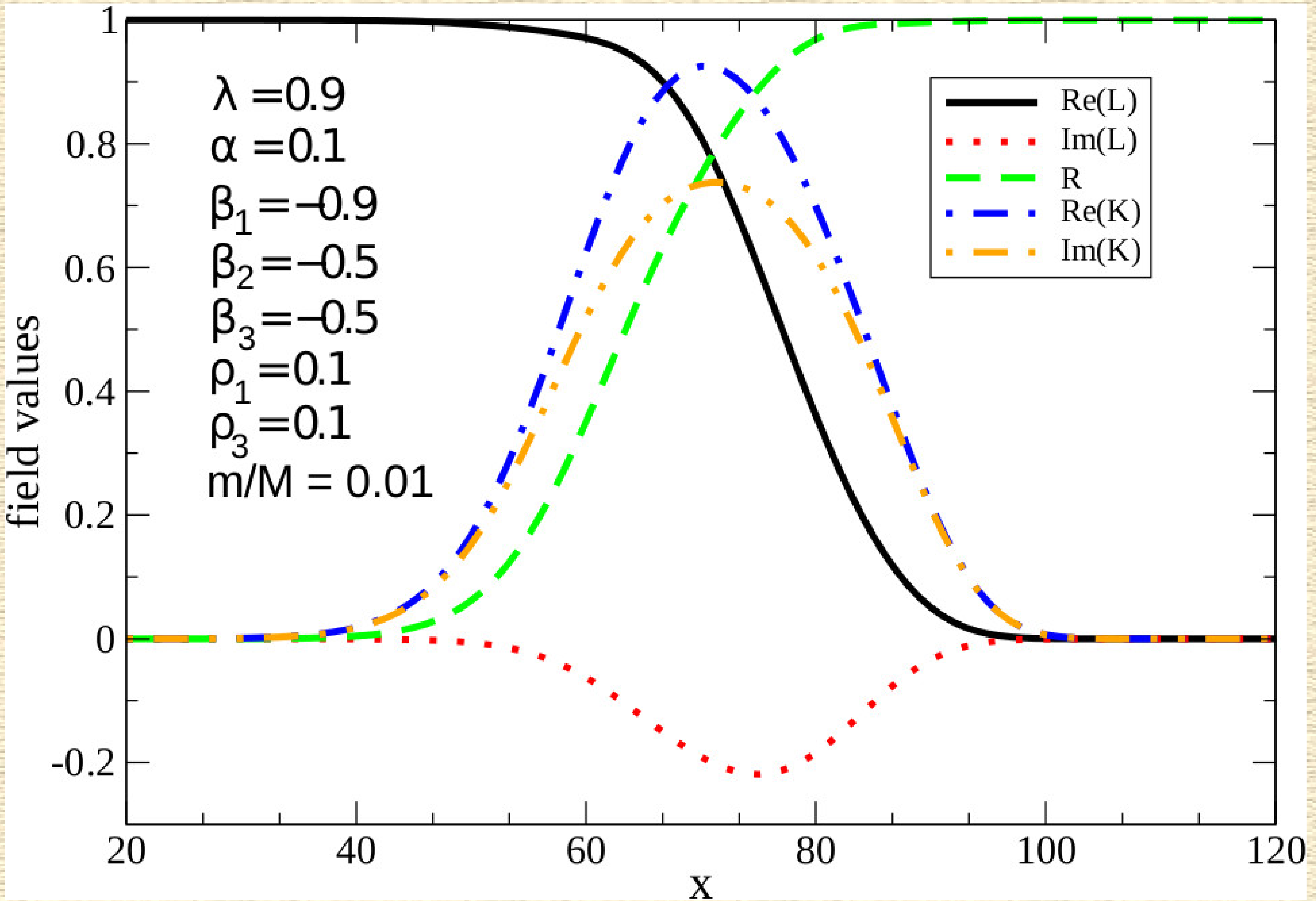
$$\frac{\delta V_{total}}{\delta \theta} = \sin\theta(-d^2\cos\theta\,(w^2 + \frac{a^2}{4}) + a\, d^2\,(\sin\frac{\theta}{2} - \cos\frac{\theta}{2})\,(2\, w^2 - d^2))$$

When $\theta = \frac{\pi}{2}$, we have a another minima and potential energy at that minima is given by,

$$V_{DW} = d^2\, w^2(-a + \frac{1}{\sqrt{2}})^2 + d^2(-a\, d + w)^2$$

D-parity domain wall and CP violation

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



(Cline, Rabikumar and UAY; Anjishnu Sarkar, UAY)

- 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.

- Open question : relating the dynamical $O(1)$ CP phase to static phases in EDM etc.

Domain wall dynamics

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. From this we get required energy density difference

$$\delta\rho \geq G\sigma^2 \approx \frac{M_R^6}{M_{Pl}^2} \sim M_R^4 \frac{M_R^2}{M_{Pl}^2} \tag{3}$$

Domain wall dynamics in a matter dominated phase

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

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

From Eq.(?) we get,

$$T_D^4 \sim \frac{\sigma^{11/6}}{M_{Pl}^{3/2}} \sim \frac{M_R^{11/2}}{M_{Pl}^{3/2}} \sim M_R^4 \left(\frac{M_R}{M_{Pl}}\right)^{3/2} \tag{5}$$

Now requiring $\delta\rho > T_D^4$ we get,

$$\delta\rho > M_R^4 \left(\frac{M_R}{M_{Pl}}\right)^{3/2} \tag{6}$$

This quantifies the extent of effective potential diffference across the walls for them to disappear.

How to rid ourselves of the domain walls

(Preskill, Srednicki, Trivedi and Wilczek)

$$\delta\rho \approx T^4_{\text{Decoupling}} \gtrsim T^4_{BBN}$$

Soft supersymmetric terms in Left-Righ model

$$\begin{aligned}
\mathcal{L}^1_{soft} &= m_1^2 Tr(\Delta\,\Delta^\dagger) + m_2^2 Tr(\bar{\Delta}\,\bar{\Delta}^\dagger) \\
&\quad + m_3^2 Tr(\Delta_c\,\Delta_c^\dagger) + m_4^2 Tr(\bar{\Delta}_c\,\bar{\Delta}_c^\dagger) \qquad (7) \\
\mathcal{L}^2_{soft} &= \alpha_1 Tr(\Delta\,\Omega\,\Delta^\dagger) + \alpha_2 Tr(\bar{\Delta}\,\Omega\,\bar{\Delta}^\dagger) \\
&\quad + \alpha_3 Tr(\Delta_c\Omega_c\,\Delta_c^\dagger) + \alpha_4 Tr(\bar{\Delta}_c\,\Omega_c\,\bar{\Delta}_c^\dagger) \qquad (8) \\
\mathcal{L}^3_{soft} &= \beta_1 Tr(\Omega\,\Omega^\dagger) + \beta_2 Tr(\Omega_c\,\Omega_c^\dagger) \qquad (9)
\end{aligned}$$

$$\mathcal{L}_{soft} = \mathcal{L}^1_{soft} + \mathcal{L}^2_{soft} + \mathcal{L}^3_{soft} \qquad (10)$$

- Demand that the soft parameters differ in the two possible phases $\mathrm{SU}(2)_L \otimes U(1)_Y$ and $\mathrm{SU}(2)_R \otimes U(1)_{\tilde{Y}}$
- Demand that the pressure difference created is enough to get rid of the domain walls well before Big Bang Nucleosynethesis

For PeV scale M_N (RH majorana neutrino mass), we get the constraints :

T_D / GeV	$\sim$	10	10^2	10^3
$(m^2 - m^{2\prime})$ / GeV^2	$\sim$	10^{-4}	1	10^4
$(\beta_1 - \beta_2)$ / GeV^2	$\sim$	10^{-8}	10^{-4}	1

Table 1. Differences in values of soft supersymmetry breaking parameters for a range of domain wall decay temperature values T_D. The differences signify the extent of parity breaking.

Open question : look for a way to generate this difference in V^{eff}
(Sasmita Mishra, UAY PRD 2008; Sasmita Mishra, Anjishnu Sarkar, UAY PRD 2009, Sasmita Mishra, Debasish Borah JHEP 2011)

Minimal Supersymmetric SO(10) GUT

Aulakh, Bajc, Melfo, Senjanovic, Vissani 2004

The Higgs content **210** – Φ_{ijlk}, $\mathbf{126(\overline{126})}$ – Σ_{ijklm} ($\bar{\Sigma}_{ijklm}$), (and additionally H_i)

The $\overline{\mathbf{126}}$ with **210** breaks the SO(10) $\rightarrow$ MSSM .

The renormalizable superpotential

$$W = \frac{m_\Phi}{4!}\Phi^2 + \frac{\lambda}{4!}\Phi^3 + \frac{m_\Sigma}{5!}\Sigma\bar{\Sigma} + \frac{\eta}{4!}\Phi\Sigma\bar{\Sigma} + m_H H^2 + \frac{1}{4!}\Phi H(\gamma\Sigma + \bar{\gamma}\bar{\Sigma}).$$

D-parity is defined as

$$D = \exp(i\pi J_{23})\exp(i\pi J_{67}) \tag{11}$$

In terms of SO(10) vector indices the fields which acquire vev are written as

$$\begin{aligned} P &= [7,8,9,10] \\ A &= [1,2,3,4] + [1,2,5,6] + [3,4,5,6] \\ W_R^0 &= [1,2,7,8] + [3,4,7,8] + [5,6,7,8] + [1,2,9,10] + [3,4,9,10] + [5,6,9,10] \end{aligned}$$

$$
\begin{aligned}
\Sigma_R^- &= -i([1,3,5,7,9]-[2,4,5,7,9]-[2,3,6,7,9]-[1,4,6,7,9] \\
&\quad -i[2,3,5,7,9]-i[1,4,5,7,9]-i[1,3,6,7,9]+i[2,4,6,7,9]) \\
&\quad -(7,9\rightarrow 8,10)+i\,\{7,9\rightarrow 7,10\}+i\,\{7,9\rightarrow 8,9\} \\
\bar{\Sigma}_R^+ &= i([1,3,5,7,9]-[2,4,5,7,9]-[2,3,6,7,9]-[1,4,6,7,9] \\
&\quad +i[2,3,5,7,9]+i[1,4,5,7,9]+i[1,3,6,7,9]-i[2,4,6,7,9]) \\
&\quad -(7,9\rightarrow 8,10)-i\,\{7,9\rightarrow 7,10\}-i\,\{7,9\rightarrow 8,9\} \qquad (12)
\end{aligned}
$$

The sign $+(-)$ in the superscript represents the T_{3R} value. Under the action of D-parity these vevs transform as

$$
\begin{aligned}
&P\rightarrow -P; \quad A\rightarrow A; \quad W_R^0\rightarrow W_L^0 \\
&\Sigma_R^-\rightarrow -\Sigma_L^+; \quad \bar{\Sigma}_R^+\rightarrow -\bar{\Sigma}_L^-
\end{aligned}
$$

Connecting to the D-flipped sector

$$W = m_\Phi\left((1+\sin^2 2\theta)\,p^2 + ((2+\cos 2\theta)^2 - \sin^2 2\theta)\,a^2 + ((-\sin\theta + \cos 2\theta + 2)^2 + (\sin 2\theta + 3\cos\theta)^2)w^2 +\right.$$

$$+2\,\lambda\left(\frac{1}{2}\,(27\cos 2\,\theta - \cos 6\,\theta + 28)\,a^3 + \frac{1}{2}\,(\sin\theta + \sin 3\,\theta + 2)\,(\sin 3\,\theta + 4\cos 2\theta + 5)\,p\,w^2\right.$$

$$+\frac{1}{3}\,(\sin 3\theta + 4\cos 2\theta + 5)\,(\sin\theta + \sin 3\theta + \cos\theta + 2\cos 2\theta + 3)\,a\,w^2$$

$$+\frac{m_\Sigma}{15}\,\sigma\,\bar\sigma\,(4\sin\theta + \sin 3\theta + 30\cos 2\theta + \cos 4\theta + 34)$$

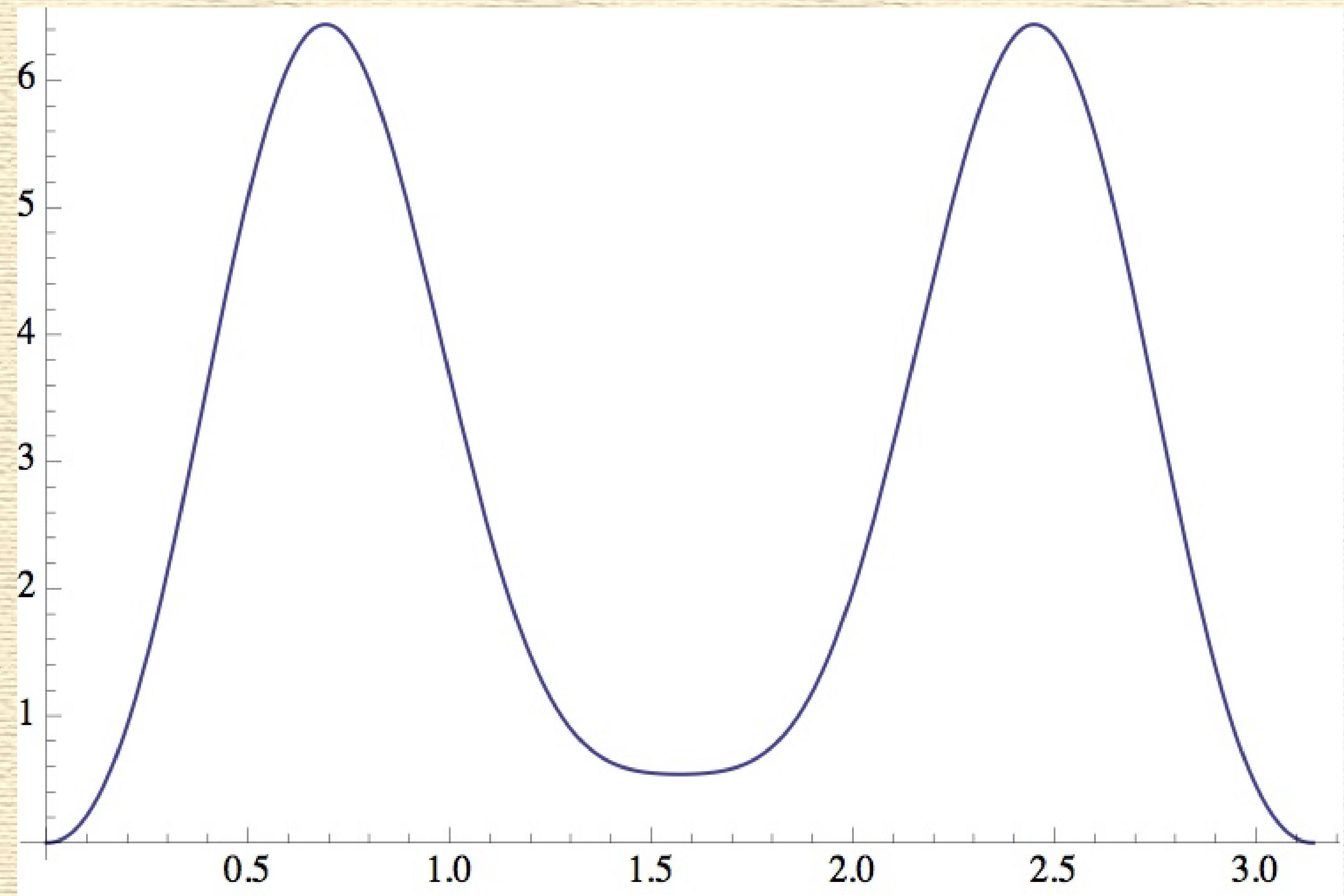
$$+\frac{\eta}{120}\,\sigma\,\bar\sigma(p\,(212\sin\theta + 224\sin 3\theta + 36\sin 5\theta + 240\cos 2\theta - 10\cos 4\theta + 290)$$

$$+a\,(2\,(116\sin\theta + 124\sin 3\,\theta + 20\sin 5\,\theta + 378\cos 2\,\theta + 59\cos 4\,\theta + 2\cos 6\theta + 341))$$

$$+w\,(2\,(67\sin\theta + 93\sin 3\,\theta + 18\sin 5\,\theta + 762\cos 2\,\theta + 115\cos 4\,\theta + 2\cos 6\theta + 657))) \qquad (13)$$

Plot of potential

For representative values of the parameters



As expected we have vacua at 0 and 2π, but we see a double humped feature.
Work in progress ...

Wall removal and cosmology

- Unlike low scale model L-R, available possibilites are different
- Spontaneous formation of a hole in a the wall due to cosmic string formation – dependent on Higgs content
- Planck suppressed non-renormalisable contribution

If the walls are not removed in good time,

- The dynamics may merge with that of the inflaton
- If delayed in removal, could leave CMB signature

Conclusions

- D-parity natural with right handed neutrino
  - Domain wall dominated phase inevitable in generic models
- Non-thermal leptogensis natural through domain walls – so DW not all bad!
- Domain wall disappearance requirement constrains soft terms in low scale JBSM
- For SO(10) D-parity there are implications for inflation and perhaps CMB

–> Thanks page

¡Gracias!

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