Phase Transitions in Complex Triplet Extensions

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Outline

- Motivation
- Model
- Present Constraints
- Preliminary Results

Scalar Triplet Extensions

- Triplet Extensions of the SM scalar sector occur in type II Seesaw
- Minimal extension of the scalar sector with non-trivial SU(2) quantum numbers
- Can embed in GUTs
- Question: What is the phase structure in such a theory? Are multi-step phase transitions possible in such theory as the universe cools?

EW Baryogenesis

Sakharov Conditions:

- B violating interactions
- C and CP violation
- Departure from thermal equilibrium

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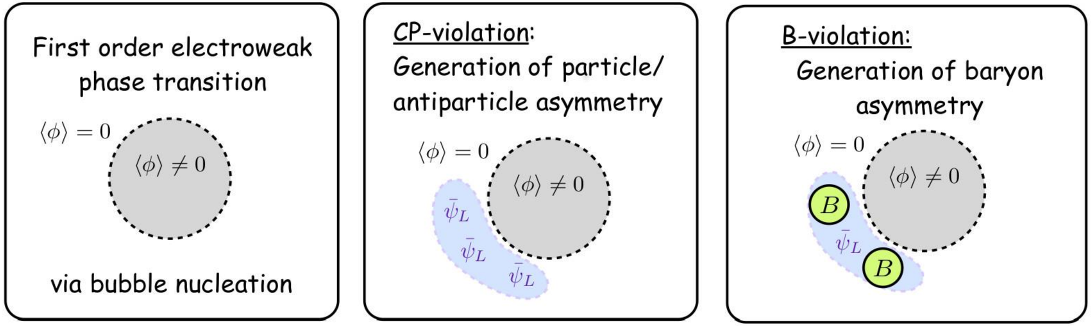


Fig. by H. Patel

EW Baryogenesis

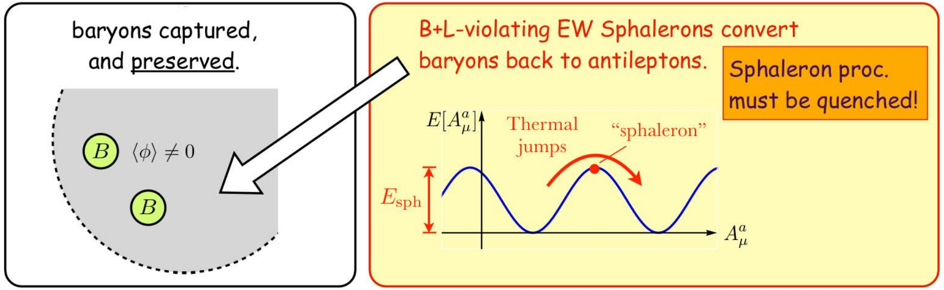
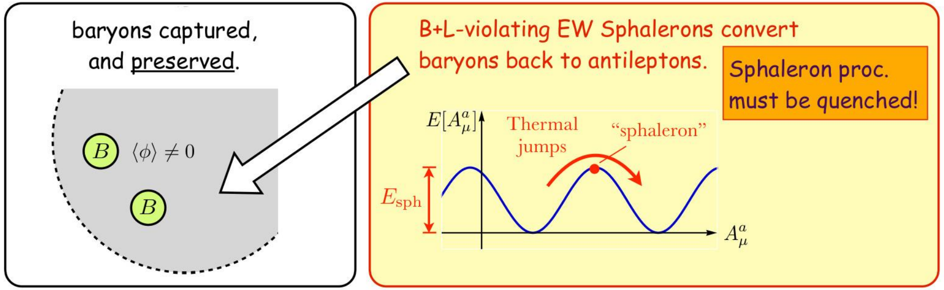


Fig. by H. Patel

- Sphaleron Energy ~ v
- Transition Rate ~ $T^4 e^{-E_{sph}/T}$
- For preserving baryon number we need v/T > 1

EW Baryogenesis



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Strong first order phase transition : necessary condition

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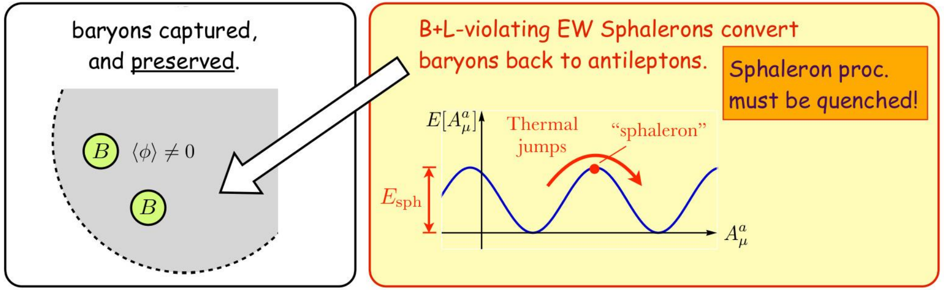

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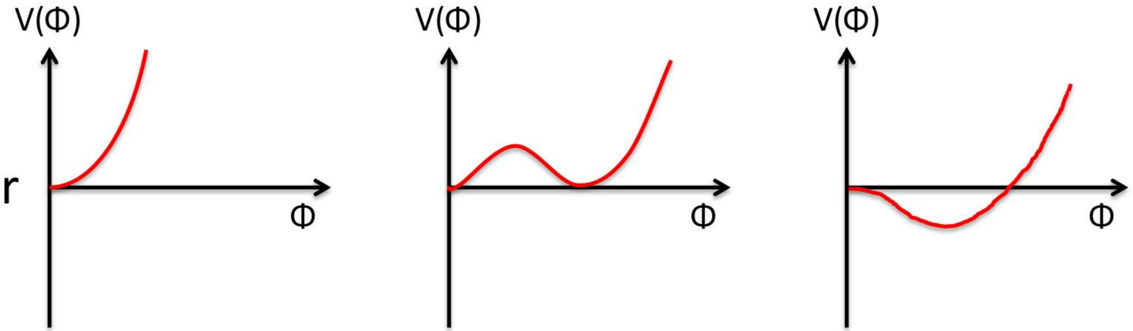
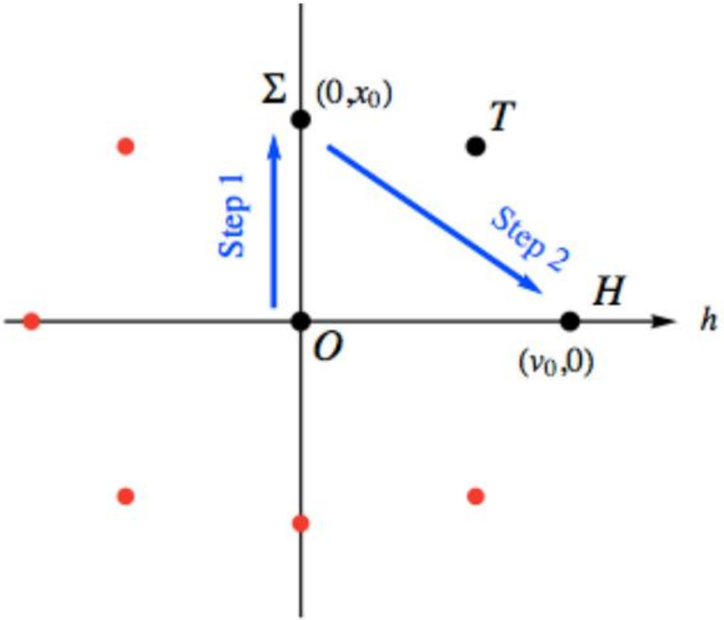
1st order



Multi-step Phase Transition



H. Patel and M. Ramsey-Musolf (arXiv: 1212.5652)

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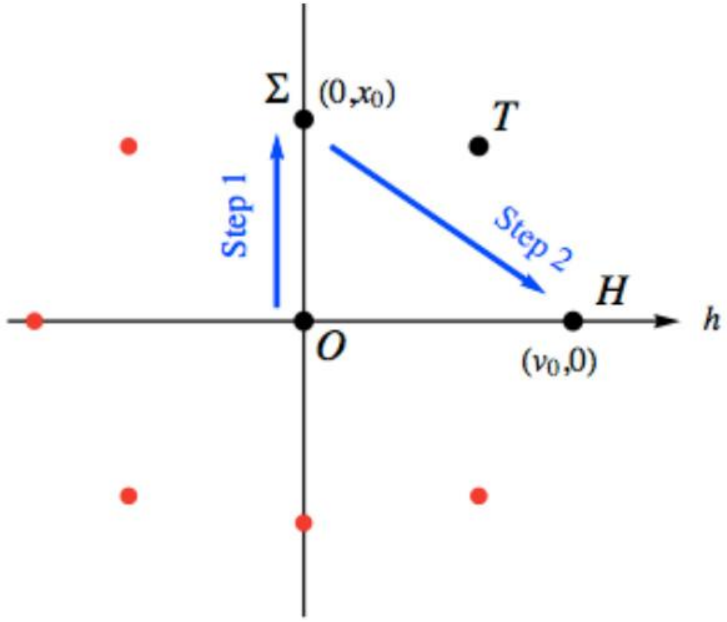

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- First step : Triplet acquires vev
- Baryon asymmetry is generated
- Second step : Triplet vev vanishes while Higgs field acquires vev
- lower critical temperature for step 2

Model

$$H = \begin{bmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(h + v_0 + i\chi^0) \end{bmatrix} \quad \Delta = \begin{bmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \frac{1}{\sqrt{2}}(\delta^0 + i\eta) & -\frac{\delta^+}{\sqrt{2}} \end{bmatrix} \quad S = x_0 + s$$

$$\begin{aligned} V(H, \Delta, S) = & -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 - \frac{b_2}{2} S^2 + \frac{b_4}{4} S^4 \\ & + M^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_2 \left[\mathrm{Tr}(\Delta^\dagger \Delta)\right]^2 + \lambda_3 \mathrm{Tr}[\Delta^\dagger \Delta \Delta^\dagger \Delta] \\ & + \frac{a_2}{2} S^2 H^\dagger H + \frac{c_2}{2} S^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_4 (H^\dagger H) \mathrm{Tr}(\Delta^\dagger \Delta) \\ & + \lambda_5 H^\dagger \Delta \Delta^\dagger H \end{aligned}$$

Model

- Total 11 real scalar fields:

$$h, s, \delta^0, \eta, \chi^0, \chi^+, \chi^-, \delta^+, \delta^-, \delta^{++}, \delta^{--}$$

- Three are goldstone bosons: χ^0, χ^+, χ^-
- η can always be eliminated in favor of δ^0 as they are connected by U(1)
- Five different masses at T=0
- Splitting between δ masses is constrained by T parameter

$$m^2_{\delta^{++}} - m^2_{\delta^+} = m^2_{\delta^+} - m^2_{\delta^0} = -\frac{\lambda_5 v^2}{4}$$

Constraints

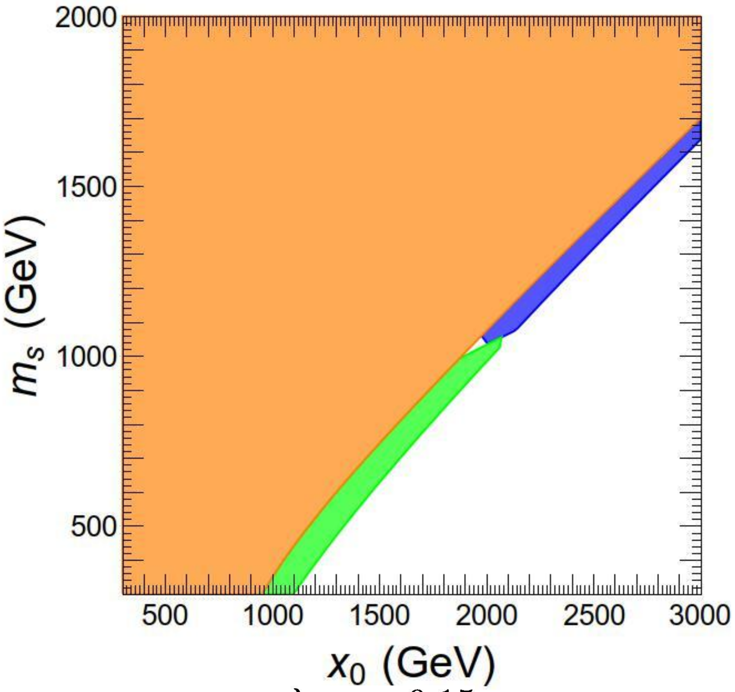
- We trade $a_2, b_2, b_4, \lambda, \lambda_5, M, \mu$ for $m_h, v_0, x, m_s, m_{\delta^+}, m_{\delta^{++}}, \theta$
- Remaining parameters are $c_2, \lambda_2, \lambda_3, \lambda_4$
- These have lower bounds from stability considerations

$$\lambda_2 + \lambda_3 > 0, 2\,\lambda_2 + \lambda_3 > 0$$, etc.

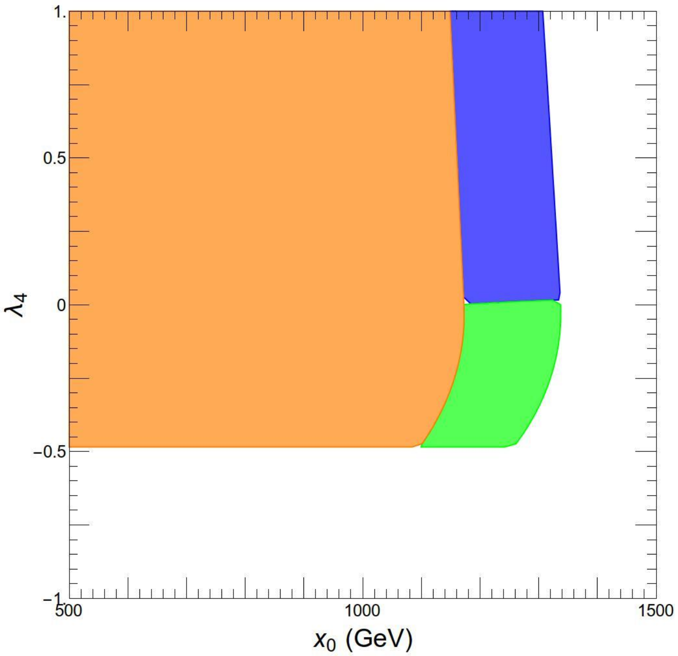
- Upper bounds from perturbativity considerations as quartics appear with positive coefficients in the beta functions of other quartics
- Additional constraints from $h \to \gamma\gamma$ and $h \to Z\gamma$ signal strengths
- Higgs production in gluon fusion at the LHC puts upper bound on $\sin^2\theta < 0.1$
- c_2 sets the overall mass scale of triplet particles

Preliminary Analysis of T=0 Vacua

$$\theta = -0.03, m_{\delta+} = 600\ GeV, m_{\delta++} = 601\ GeV, c_2 = 1.1, \lambda_2 = -0.7, \lambda_3 = 2.45$$



$\lambda_4 = -0.15$



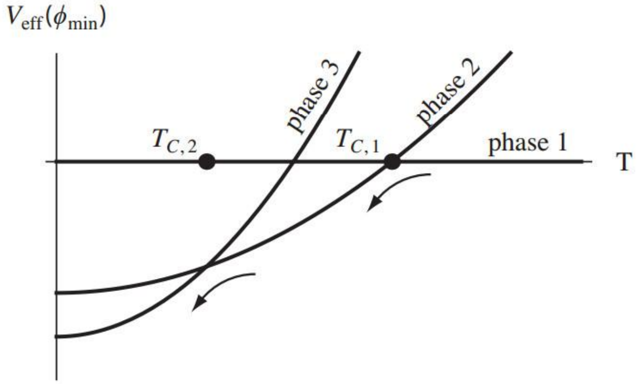
m_s = 500 GeV

Gauge Dependence

- For one loop level, addition of T=0 Coleman-Weinberg terms and finite T corrections make the potential dependent on gauge term
- Problematic of critical temperature calculation
- h-bar expansion is used as resolution
- Expand the potential and the fields at the minimum with loop orders

$$V(\phi, T) = V_0 + \hbar V_1 + \hbar^2 V_2 + \ldots$$
$$\phi_{\min} = \phi_0 + \hbar\phi_1 + \hbar^2\phi_2 + \ldots$$

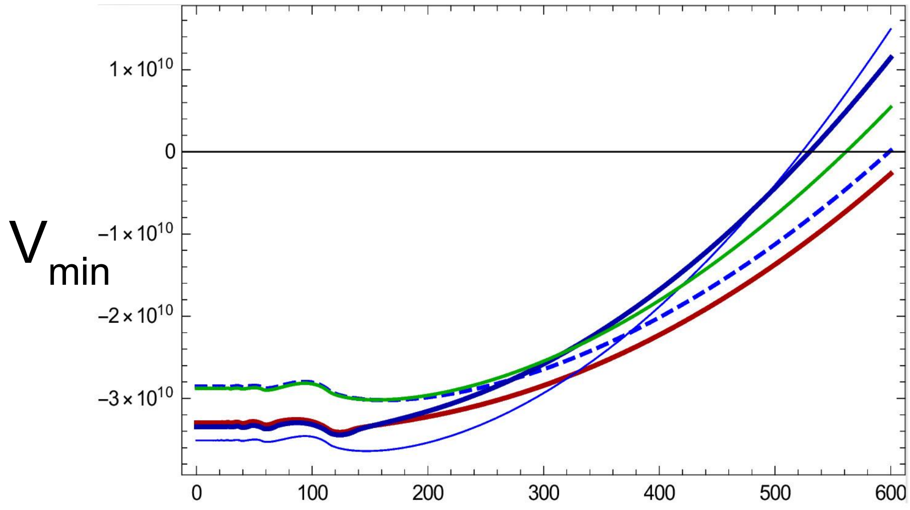
$$\boxed{\begin{aligned} V(\phi_{\min}, T) &= V_0(\phi_0) + \hbar V_1(\phi_0, T) \\ &+\hbar^2\left[V_2(\phi_0, T, \xi) - \frac{1}{2}\phi_1^2(\xi)\frac{\partial^2 V_0}{\partial\phi^2}|_{\phi_0}\right] + \ldots \end{aligned}}$$

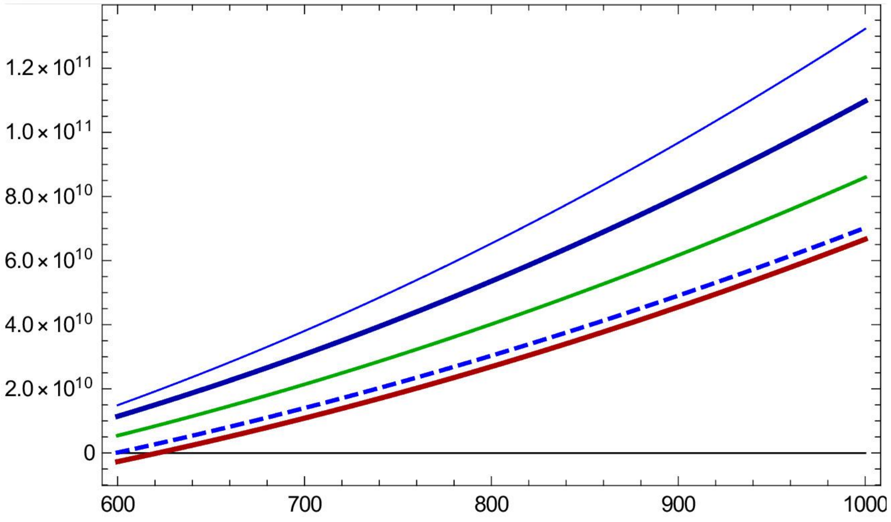


H. Patel and M. Ramsey-Musolf (arXiv: 1101.4665)

Preliminary result

$m_s = 500\ GeV, x_0 = 1300\ GeV, \lambda_4 = -0.15$





T (GeV)

Summary

- Complex triplet extensions of the SM scalar sector are well motivated
- We study the phase transitions in such models
- Preliminary analysis of T=0 vacua reveals different transition patterns
- Critical temperature is evaluated in gauge independent manner
- Presence of singlet mitigates collider constraints but can insert itself as an intermediate phase which could be problem from baryon asymmetry preservation perspective
- Order parameter will also be need to be computed in gauge independent manner