Electroweak Baryogenesis in the μ-from-ν SSM

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Work with D.J.H Chung

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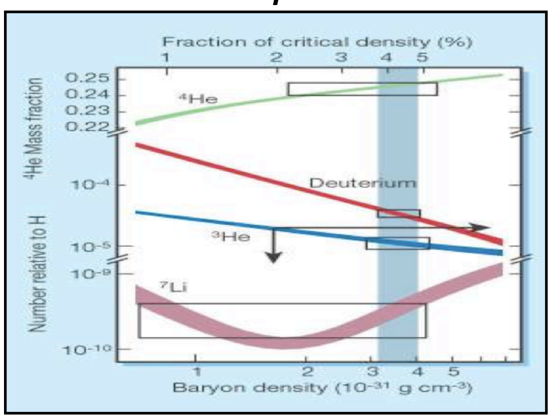
The (Large) Baryon Asymmetry of the Universe

- The BAU can be characterized by the baryon number to photon density

$$\eta = {}^{n_B}\!/\!_{n_\gamma} \qquad\qquad n_B = n_b - n_{\bar{b}}$$

- Measurements of η come from observations of the abundances of light elements and from the anisotropies of the CMB

$$4.7\times10^{-10} < \eta < 6.5\times10^{-10}$$

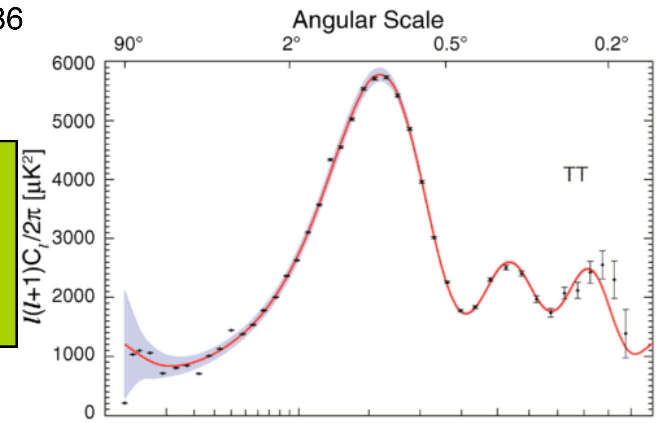


W.M. Yao, *et al*, [Particle Data Group]

WMAP-5, astro-ph/0803.0586

$$\eta_{obs} \approx 6\times10^{-10}$$

$$5.9\times10^{-10} < \eta < 6.4\times10^{-10}$$



- This is a large asymmetry! If the initial conditions were symmetric, $n_B = 0$, and baryons just froze out, we would expect

$$\eta_{fo} \approx 10^{-18} << \eta_{obs}$$

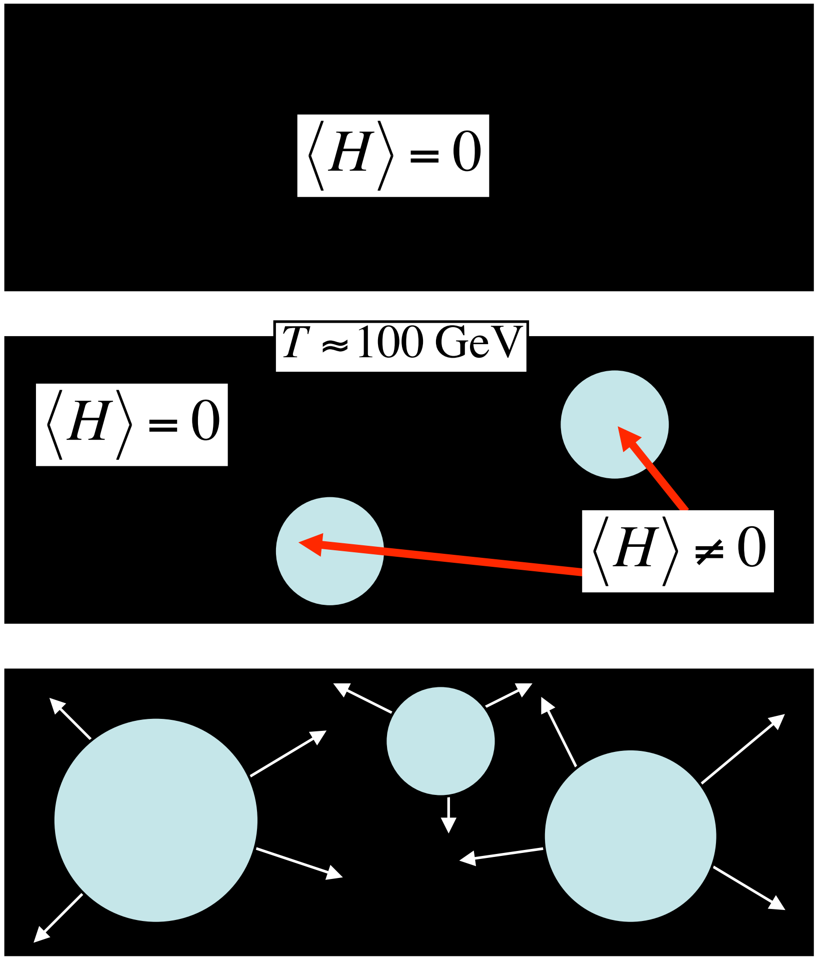
A. Riotto, hep-ph/9807454

There must be a mechanism which generated the baryon asymmetry

Electroweak Baryogenesis (I)

Kuzmin, Rubakov, Shaposhnikov, 1985

1. In the early ($t < 10^{-10}$ sec), hot ($T > 100$ GeV) universe, the electroweak symmetry was restored
2. As the universe cooled to the EW scale, the electroweak phase transition (EWPT) occurred through the nucleation of bubbles ($r \sim 0.01 fm$) of true vacuum
3. The bubbles expanded at nearly the speed of light, merged, and filled all of space, thereby completing the phase transition.

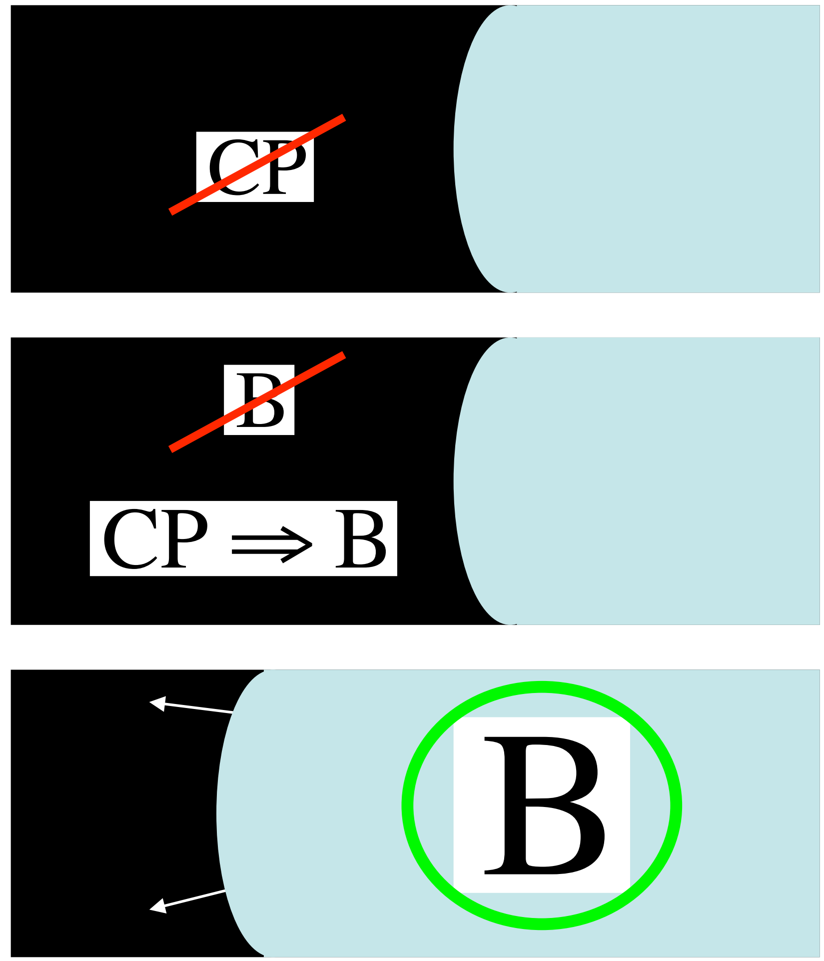


But before that could happen . . .

Electroweak Baryogenesis (II)

4. CP-violating interactions between the Higgs field and the plasma generate a CP-asymmetry in front of the bubble wall.
5. B-violating (BV) processes in the symmetric phase act on the CP-asymmetry and convert it into a baryon asymmetry
6. Baryon number diffuses into the bubble. Inside the bubble, B-violating processes are out of equilibrium, and the baryon asymmetry is not "washed out."

Washout will be prevented if the phase transition is strongly first order (S1PT)



The Problem is "Baryo-Preservation"

B

- The B-asymmetry must survive until today
- The B-violating interactions must be suppressed

$$\Gamma_{BV} \sim (\alpha_W T)^4 e^{-\frac{E_{BV}(T)}{T}}$$

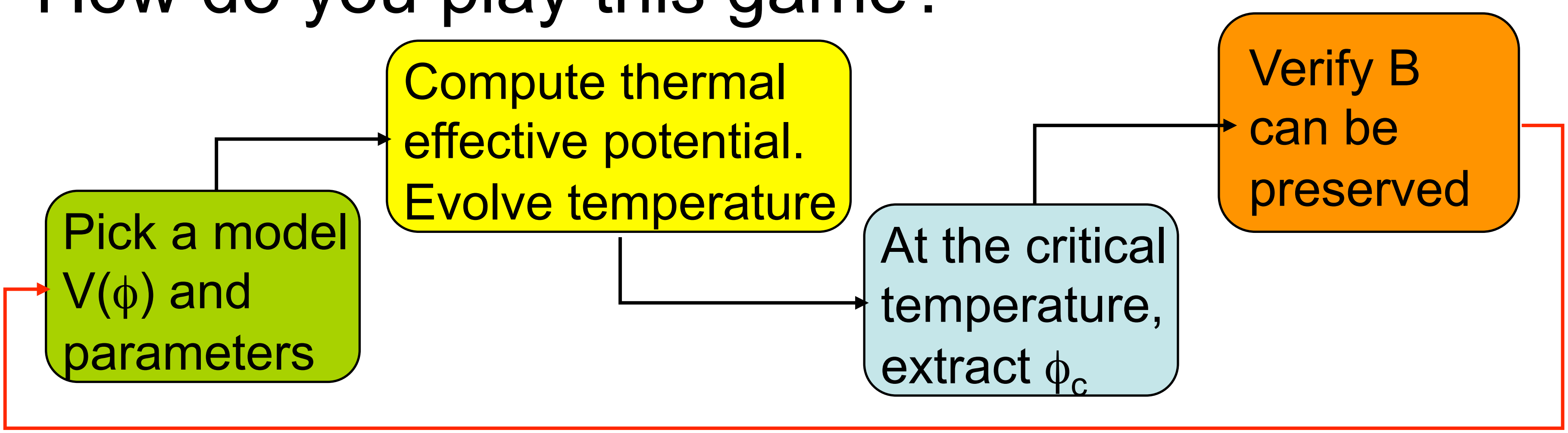
$$E_{BV}(T_c) \propto \langle H \rangle \equiv \phi_c$$

$$\frac{\phi_c}{T_c} > 1.3$$

Low BV Rate ⟶ Large Higgs VEV in Broken Phase

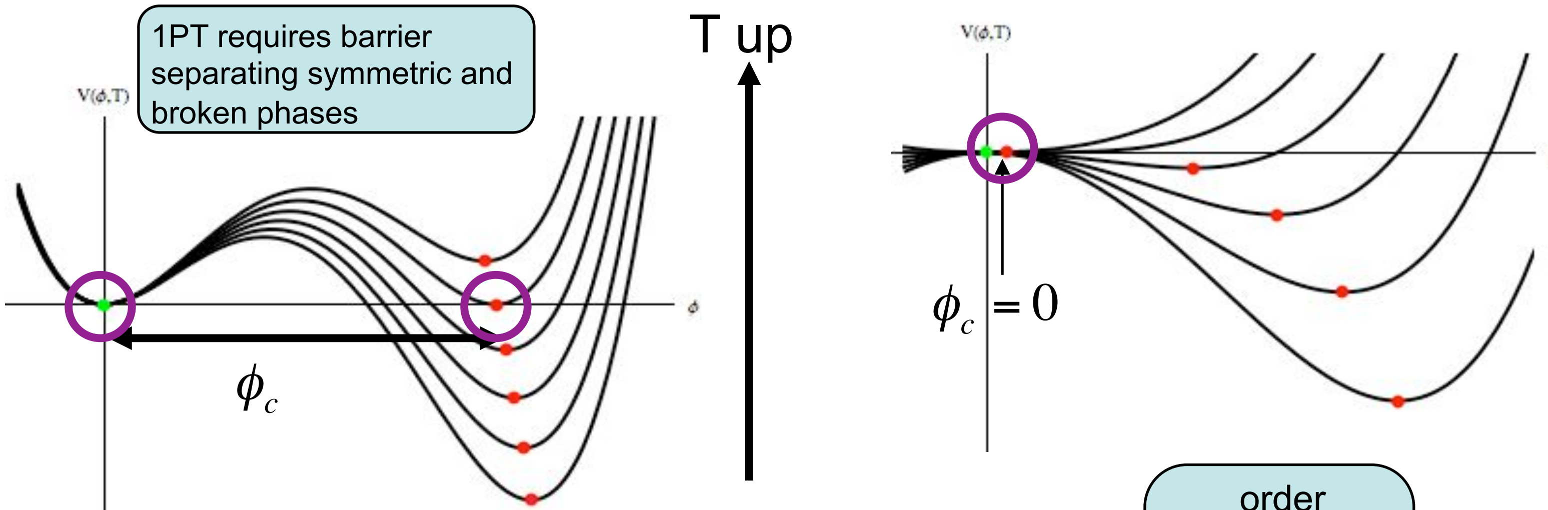
= Strongly First Order Phase Transition (S1PT)

How do you play this game?



A Cubic Term Can Produce a Barrier

- Numerical approach: Evolve the temperature, keeping one eye on the broken phase, and one eye looking for the symmetric phase.



- A barrier can appear if the tree-level potential possesses a cubic term

$$V(\phi,T)=\left[\frac{1}{2}m^2\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4\right] + \frac{1}{2}c_1T^2\phi^2 + \cdots$$

tree-level

leading thermal correction

order parameter

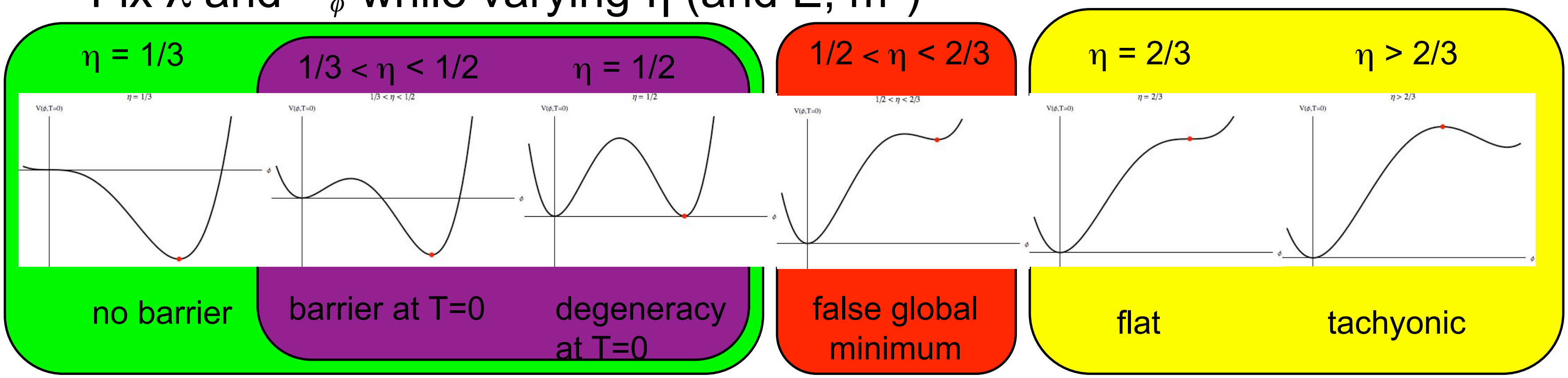
$$\frac{\phi_c(T_c)}{T_c} = \frac{E}{\lambda T_c}$$

Can we just let E be large and λ be small to obtain a S1PT?

→ No

The Cubic Term Must be Finely-Tuned

- It will be useful to reparameterize the potential in terms of
  - v_ϕ , the location of the zero-temperature EWSB vacuum
  - $\eta = E/\lambda v_\phi$, rescaled, dimensionless cubic term
- Fix λ and v_ϕ while varying η (and E, m^2)



- When the cubic term becomes too large, the potential develops a false minimum or tachyonic direction
- We expect the region of parameter space containing strongly first order phase transitions to lie adjacent to these phenomenologically unviable regions

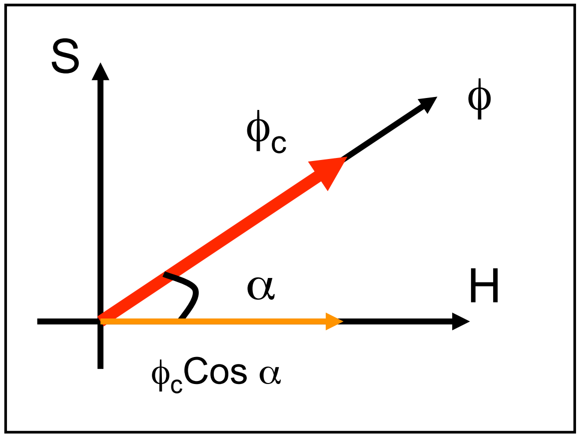
But, where does the cubic term come from . . . ?

Obtain The Cubic Term By Mixing With a Singlet

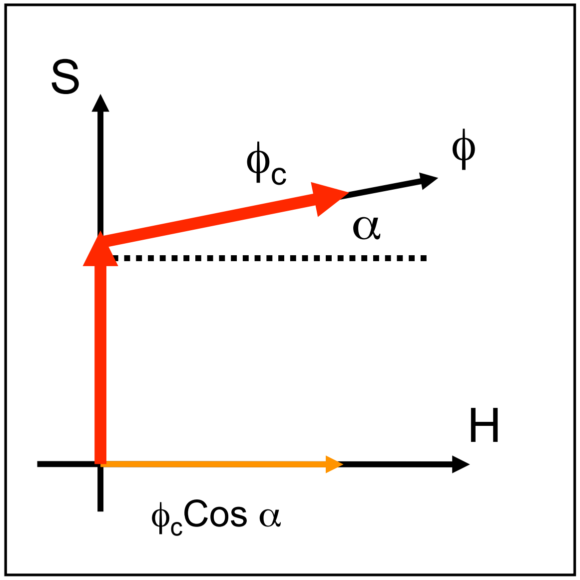
- The order parameter $\frac{\phi_c(T_c)}{T_c} = \frac{E}{\lambda T_c}$ can be enhanced by a negative quartic mixing $V \ni a_2 H^2 S^2$ which suppresses

$$\lambda \sim \lambda_H \cos^4 \alpha + \lambda_S \sin^4 \alpha + a_2 \cos^2 \alpha \sin^2 \alpha$$

M. Ramsey-Musolf, hep-ph/0705.2425



- New structure: the PT can occur in 1 or 2 steps
- The symmetric phase can live anywhere on the <H>=0 *axis*, and it moves as the temperature varies.



Adding a singlet provides a cubic term but complicates the analysis!

The μ-from-νSSM

C. Munoz, hep-ph/0508297

- Extend the MSSM by adding three right-handed neutrino superfields and allow their scalar components to get VEVs: $v_{\nu c}$ = O(100GeV)

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a \hat{L}_i^b \hat{e}_j^c + \boxed{Y_\nu^{ij}\,\hat{H}_2^b \hat{L}_i^a \hat{\nu}_j^c} \right) - \boxed{\epsilon_{ab}\lambda^i \hat{\nu}_i^c \hat{H}_1^a \hat{H}_2^b} + \boxed{\frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c}$$

- As in the NMSSM and nMSSM, the singlet VEV generates an effective μ-term, $\mu_{eff} = \lambda\, v_{\nu c}$, at the electroweak scale.

  P. Fayet, 1975; Pietroni, 1992; Menon, *et al*, hep-ph/0404184

- Neutrino masses are generated by a low-scale seesaw: $M_{maj} = \kappa\, v_{\nu c}$
- Higgs mixing with the right-handed sneutrino provides a cubic term

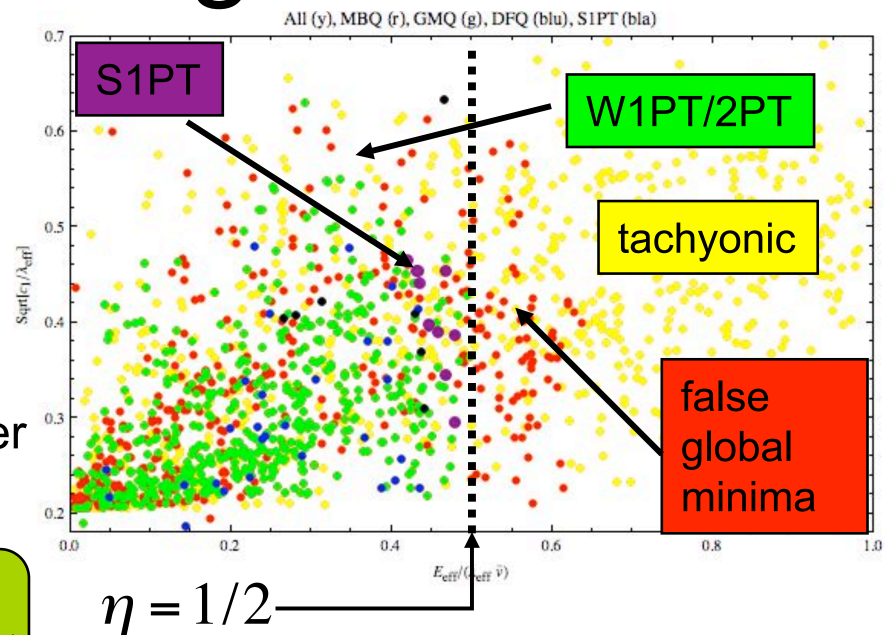
$$V_{soft} \ni \left(A_\lambda \lambda\right)_i \nu_i^c H_1 H_2 + \frac{1}{3}\left(A_\kappa \kappa\right)_{ijk} \nu_i^c \nu_j^c \nu_k^c$$

- The μνSSM has *three* singlets. Now *five* fields participate in the phase transition.

Start with the simplest scenario. . .

Case 1: Only One Singlet Gets VEV

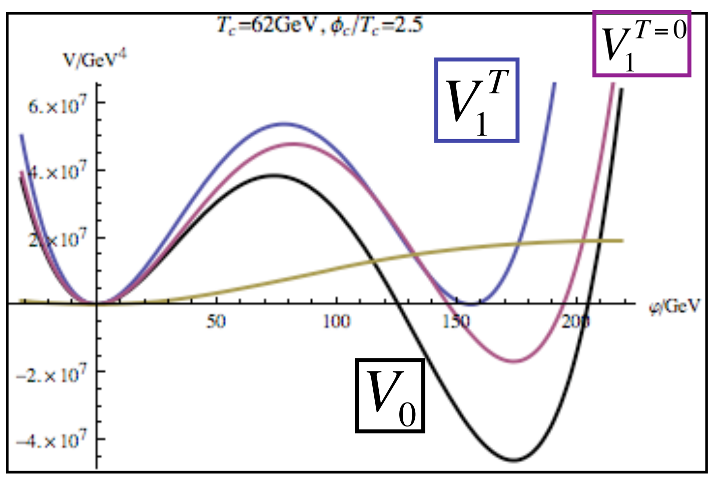
- To simplify the analysis, begin by assuming only the third generation sneutrino get a VEV
- Scan over five free parameters $\{\lambda, \quad \kappa, \quad (A_\lambda \lambda), \quad (A_\kappa \kappa), \quad v_{\nu^c}\}$
- Search for phase transition using full, one-loop, thermal effective potential over the (reduced) three-dimensional field space $\{H_1, \quad H_2, \quad \nu_3^c\}$
- Scan results are consistent with one-dimensional analysis: S1PT are found at η<~1/2

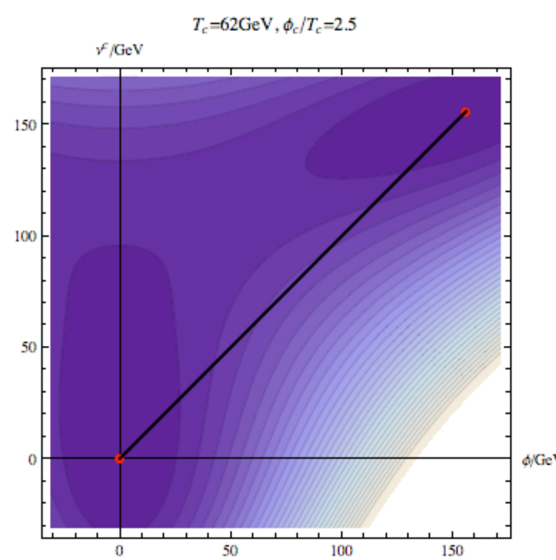


- S1PT favors κ<0 b/c this reduces effective quartic coupling λ

$$a_2 \propto \kappa\lambda$$

- Barrier comes from *tree-level* cubic term





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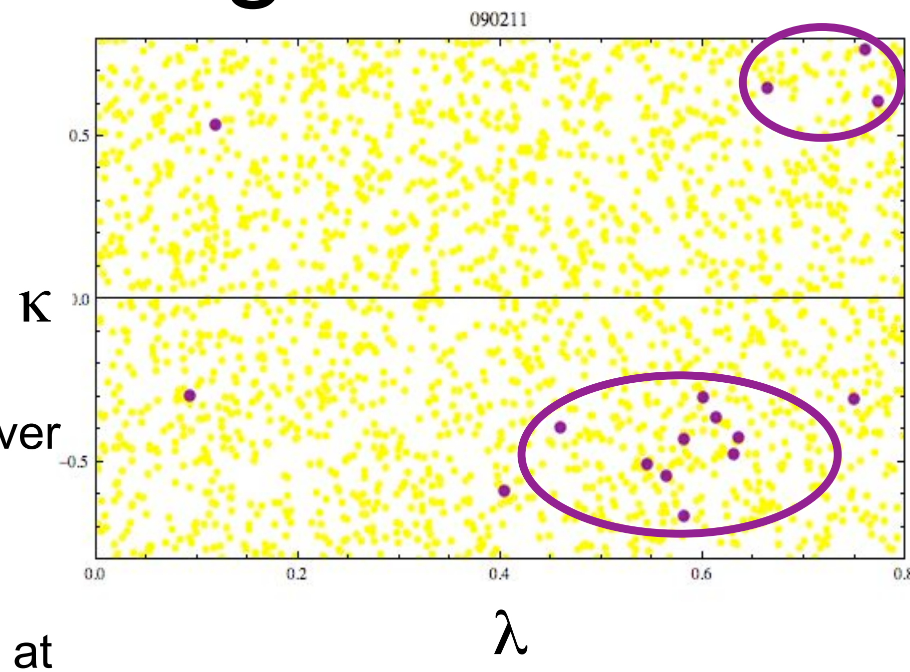

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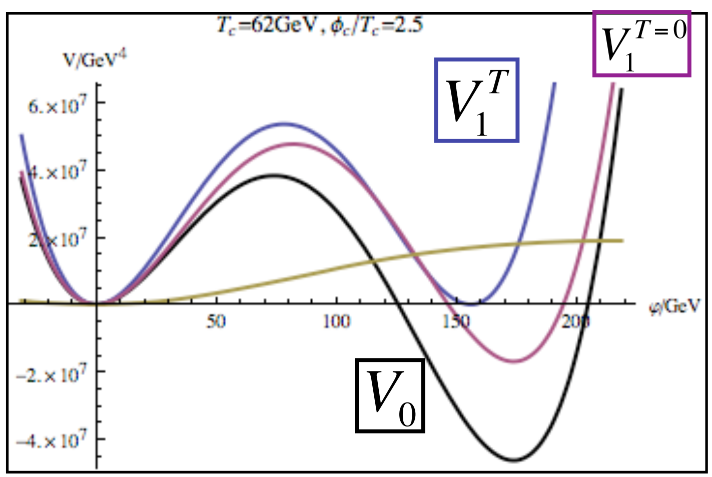
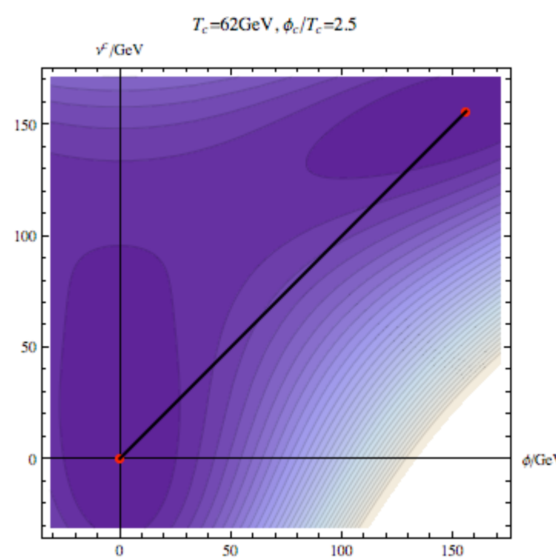
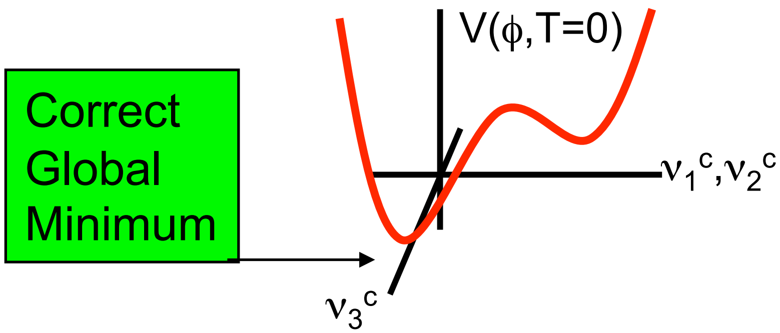
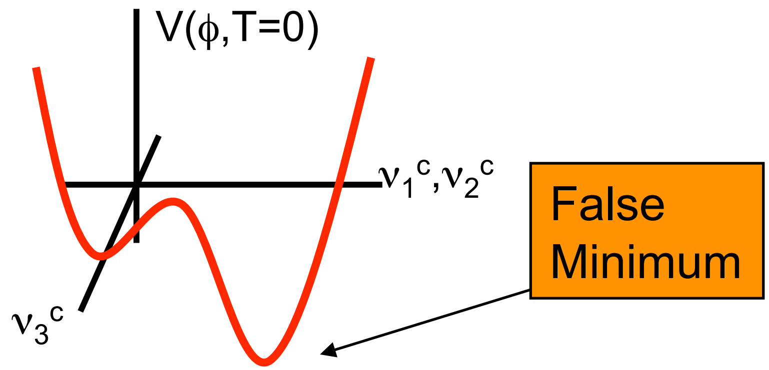




Case 1: Problems with the Other Two Singlets

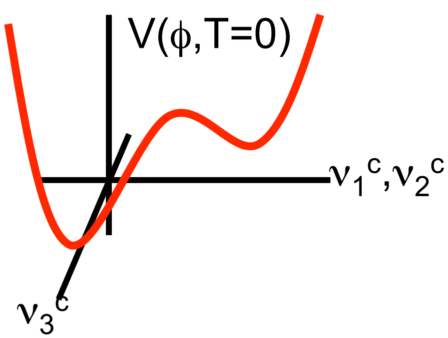
1. The potential possesses false minima deeper than the EWSB vacuum. Cubic terms drive the potential downward in the singlet directions.





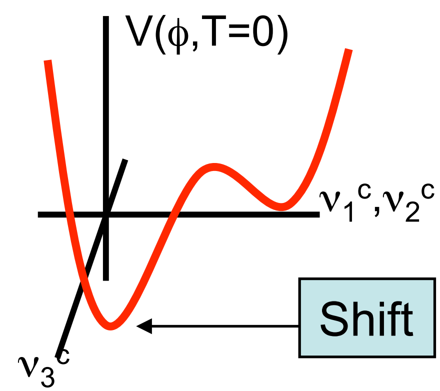
2. As temperature increases, thermal corrections destabilize the $< \nu_i^c >=0$ axes. The minimum of the potential shifts into the $\{\nu_1^c, \nu_2^c\}$!=0 plane, and $< \nu_i^c >=0$ is not restored at high temperature.

–This is a generic problem in models with scalars that possess cubic terms, $E\phi^3$. Due to cubic self-interactions, the field configuration with minimal energy at high temperature is one in which the singlet has a non-zero expectation value



$$V(T) \ni m^2\left(\nu_i^c = \phi\right)T^2 \ni \left(-2E\phi + \lambda\phi^2\right)T^2$$

$$\phi \xrightarrow{\text{high T}} E/\lambda$$

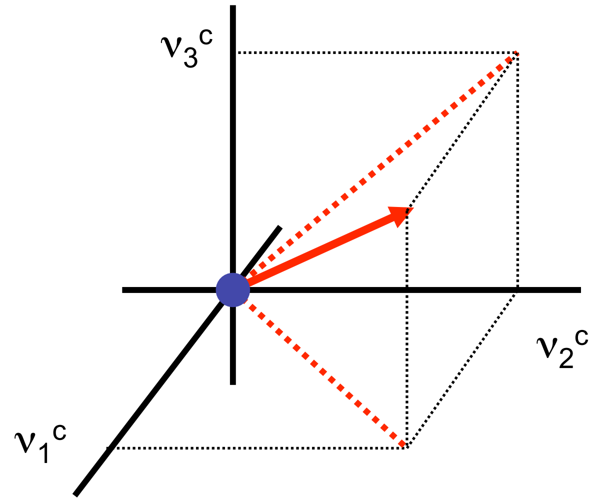


Case 2: Three Singlets Get VEVs

- Simplest parameterization: Allow all three generations of singlets to get equal VEVs,

$$v_{\nu ci} = v_{\nu c}$$

- Since the couplings are also independent of generation, the potential possesses a symmetry under the interchange of any two sneutrinos



- Initial guess: The symmetric phase would lie at the origin $\nu_1^c = \nu_2^c = \nu_3^c = 0$, and the broken phase would remain along the $\nu_1^c = \nu_2^c = \nu_3^c$ axis, thereby reducing relevant field space back to three dimensions.
- New Problem: The symmetric phase can be located anywhere in the three-dimensional singlet field space
  - –Because of the cubic terms and tri-linear mixings, the potential has many minima and saddle points
  - –All three singlets participate in the phase transition.
  - –Interesting but complicated!

Summary

- Unlike other singlet extensions of the MSSM, the $\mu\nu$SSM contains three singlets, which are sneutrinos
- Cubic terms must be finely tuned to avoid tachyons and false minima while remaining large enough to drive a S1PT.
- The parameter space must be constrained to avoid false global minima in the singlet directions
- Analysis of the phase transition is much more complicated due to the presence of three additional singlets
- Preliminary results suggest that the phase transition has a unique structure