Title: Exotic Electroweak Symmetry Breaking

Date: Jul 31, 2015 01:00 PM

URL: http://pirsa.org/15070092

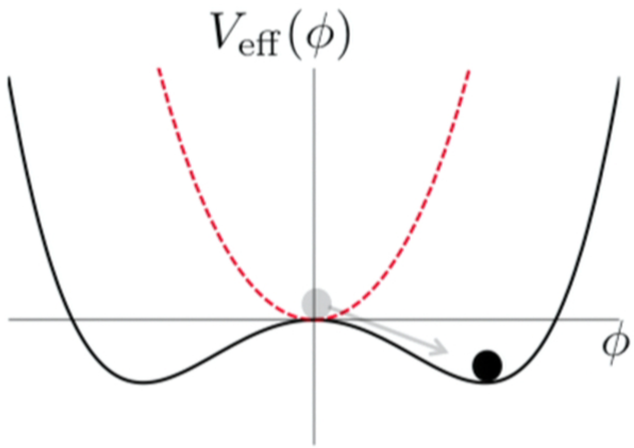
Abstract: <p>Extensions of the Standard Model (SM) Higgs sector often predict the existence of new vacua and can feature novel patterns of symmetry breaking in the early universe. In this talk, I will discuss the implications of such scenarios for electroweak scale cosmology, baryogenesis, and Higgs phenomenology. I will focus on two classes of models, one involving a gauge singlet scalar field and the other an inert SU(2) doublet scalar. The former can give rise to a strong first-order electroweak phase transition, but also to rapidly expanding bubbles which can pose a problem for viable electroweak baryogenesis. In the latter, electroweak symmetry can be spontaneously broken by a first-order phase transition to an exotic vacuum, allowing for successful electroweak baryogenesis decoupled from the Standard Model-like Higgs field. Nevertheless, this class of scenarios generically predicts modifications of the SM-like Higgs couplings within reach of present-day collider experiments.</p>

Overview

The standard picture of electroweak symmetry breaking:

Overview

The standard picture of electroweak symmetry breaking:



At zero temperature, the background field is stabilized away from the origin and EW symmetry is broken

Overview

Was it really that simple?

-Were there only two distinct (metastable) phases?

-Did only one field direction (SM-like Higgs) change its VEV?

-How can we tell and what are the consequences?

Electroweak Baryogenesis

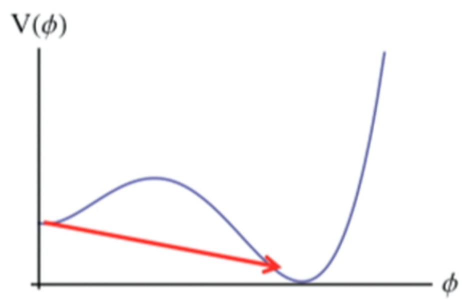
-Standard Model hints at a mechanism for baryogenesis

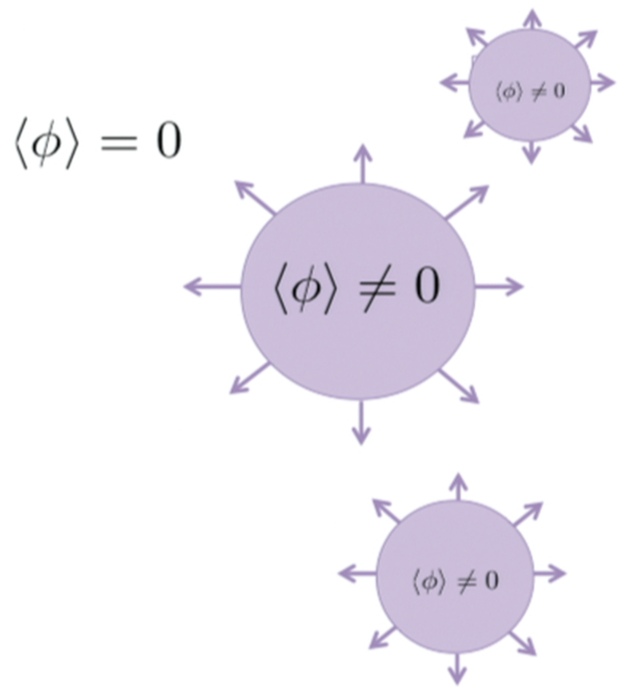
- *B*-violation by *SU(2)* sphalerons
- *C*-violation in the *SU(2)* sector, *CP*-violation in CKM
- Out-of equilibrium at the electroweak phase transition

-Involves electroweak-scale physics, so it's testable!

Electroweak Baryogenesis

The basic picture:

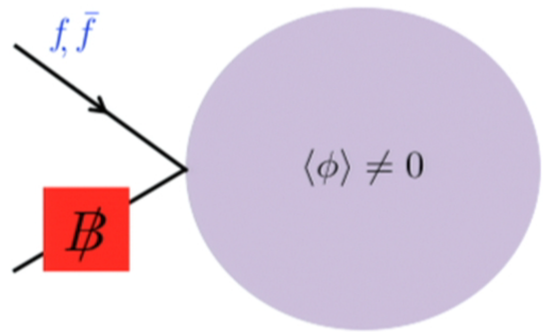




Bubbles nucleate at a first order phase transition

Electroweak Baryogenesis

The basic picture:



B-violation acts on the chiral current diffusing in front of the bubble

Electroweak Baryogenesis

The Standard Model is not enough: no 1st order EWPT

Some generic BSM remedies:

-Thermally generate barrier at T>0

$$\Delta V(h_i, T) = \frac{T^4}{2\pi^2}\left[\sum_B J_B\left(\frac{m_B^2(h_i)}{T^2}\right) - 2\sum_F J_F\left(\frac{m_F^2(h_i)}{T^2}\right)\right]$$

$$\simeq -\frac{\pi^4}{45} + \frac{\pi^2 m^2}{12T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} + \dots$$

Electroweak Baryogenesis

The Standard Model is not enough: no 1st order EWPT

Some generic BSM remedies:

-Thermally generate barrier at T>0

$$\Delta V(h_i,T) = \frac{T^4}{2\pi^2}\left[\sum_B J_B\left(\frac{m_B^2(h_i)}{T^2}\right) - 2\sum_F J_F\left(\frac{m_F^2(h_i)}{T^2}\right)\right]$$

$$\simeq -\frac{\pi^4}{45} + \frac{\pi^2 m^2}{12T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} + \ldots$$

Electroweak Baryogenesis

The Standard Model is not enough: no 1st order EWPT

Some generic BSM remedies:

-Thermally generate barrier at T>0

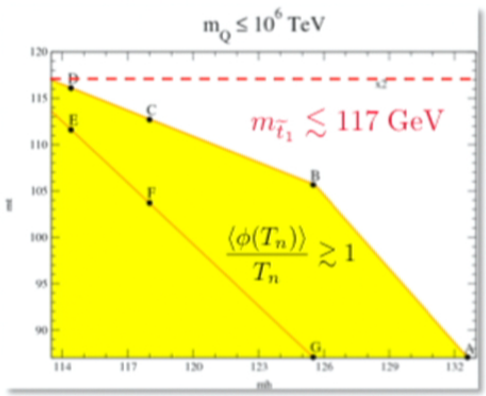
$$\Delta V(h_i,T) = \frac{T^4}{2\pi^2}\left[\sum_B J_B\left(\frac{m_B^2(h_i)}{T^2}\right) - 2\sum_F J_F\left(\frac{m_F^2(h_i)}{T^2}\right)\right]$$

$$\simeq -\frac{\pi^4}{45} + \frac{\pi^2 m^2}{12T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} + \ldots$$

Electroweak Baryogenesis

The LHC tightly constrains many models with thermally-induced barriers

Example: MSSM with light stops



Carena et al, 1207.6330

-Light stops increase gluon-gluon fusion Higgs production cross-section

Menon +Morrissey, 0903.3038; Carena et al, 1207.6330

-Highly constrained by direct searches

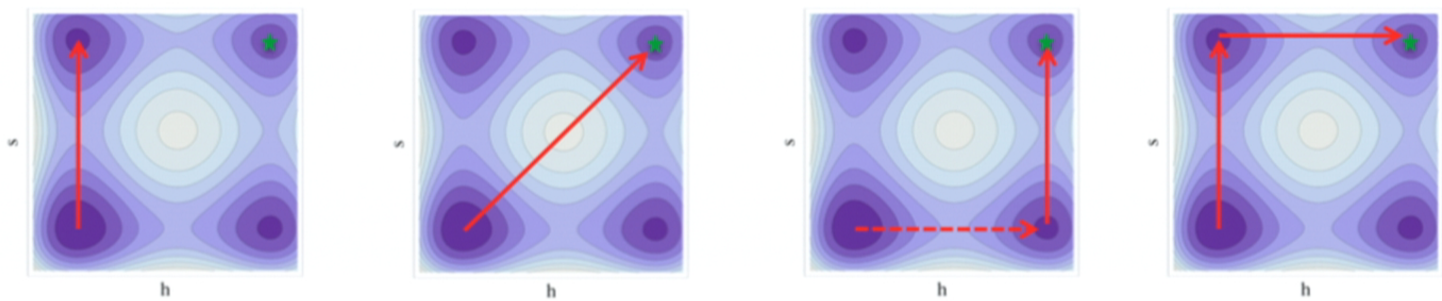
Krizka et al, 1212.4856, Delgado et al, 1212.6847

Scenario 1: Singlet

Supersymmetric example: the **NMSSM**

$$W = W_{\rm MSSM}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

A variety of exotic phase transition histories possible



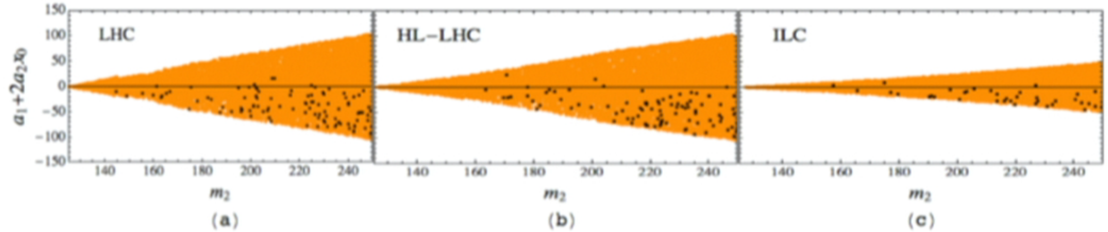
JK et al, 1407.4134
See also *Huang et al, 1405.1152*

Scenario 1: Singlet

Can be difficult to test at colliders

xSM:

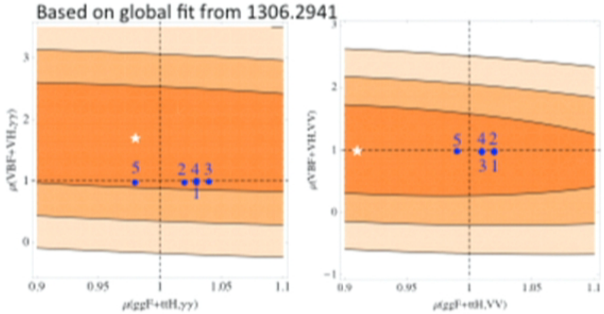
Profumo et al, 1407.5342



NMSSM:

JK et al, 1407.4134

Based on global fit from 1306.2941

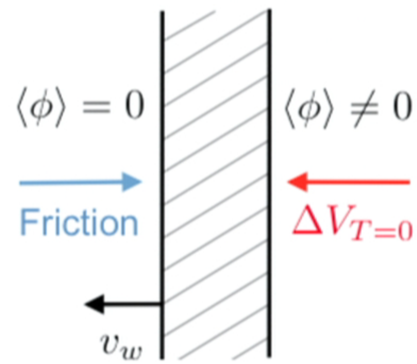


See also *Curtin et al*, 1409.0005
Craig et al, 1412.0258

Scenario 1: Singlet

Generic consequence of additional singlet field directions: **fast bubble walls** *Bodeker + Moore, 0903.4099; JK, 1506.04741*

$$\Box\phi_i + \frac{\partial V(\phi_i)}{\partial \phi_i} + \sum_j \frac{\partial m_j^2(\phi_i)}{\partial \phi_i} \int \frac{d^3p}{(2\pi)^3 2E_j} f_j(p,z) = 0$$



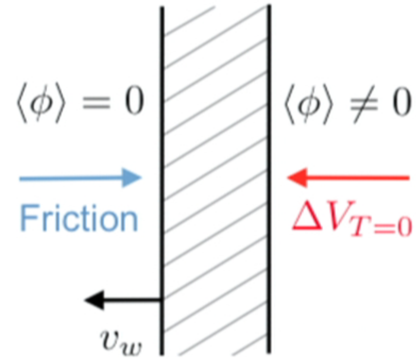
-Terminal velocity reached when friction from plasma balances the vacuum energy difference

-Additional field with changing VEV contributes to ΔV, but not necessarily to the friction

Scenario 1: Singlet

Generic consequence of additional singlet field directions: **fast bubble walls** *Bodeker + Moore, 0903.4099; JK, 1506.04741*

$$\Box\phi_i + \frac{\partial V(\phi_i)}{\partial \phi_i} + \sum_j \frac{\partial m_j^2(\phi_i)}{\partial \phi_i} \int \frac{d^3p}{(2\pi)^3 2E_j} f_j(p,z) = 0$$



-Terminal velocity reached when friction from plasma balances the vacuum energy difference

-Additional field with changing VEV contributes to ΔV, but not necessarily to the friction

Scenario 1: Singlet

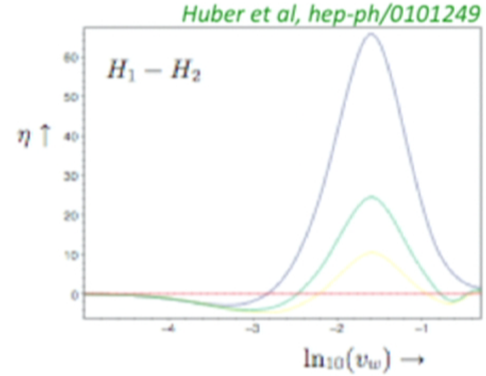
Generic consequence of additional singlet field directions: **fast bubble walls** *Bodeker + Moore, 0903.4099; JK, 1506.04741*

-But EWB requires slowly moving, subsonic bubble walls (for an exception, see *Caprini + No, 1111.1726*)

$$\tau_{\text{capture}} > \tau_{\text{conversion}}$$

$$\Rightarrow v_w < \frac{1}{N}\frac{D}{L_w} \sim \frac{1}{N} \times (0.1 - 0.3) \quad [\text{SM}]$$

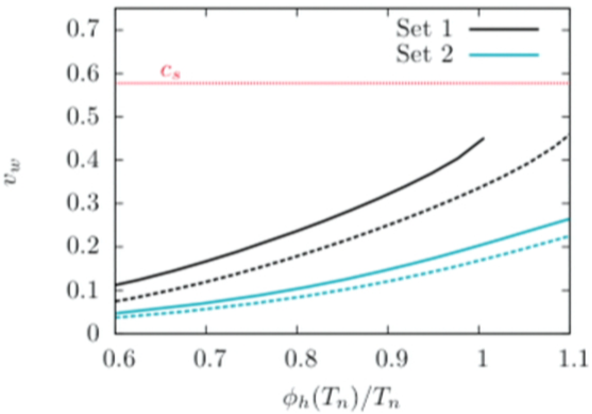
Huber et al, hep-ph/0101249



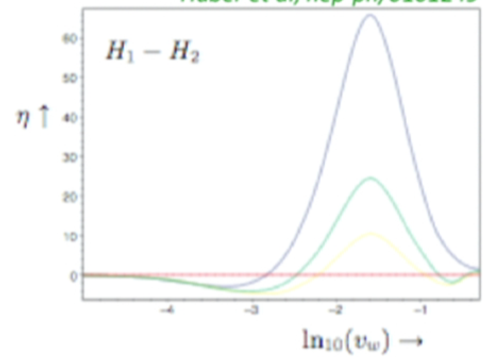
Scenario 1: Singlet

Generic consequence of additional singlet field directions: **fast bubble walls**

Bodeker + Moore, 0903.4099;
JK, 1506.04741



Huber et al, hep-ph/0101249



Can be challenging for electroweak baryogenesis

Potentially interesting for gravitational wave production (see e.g. Huber + Konstandin, 0806.1828)

Scenario 1: Singlet

-Singlet-extended Higgs sectors can accommodate a strong first order electroweak phase transition without large deviations in SM-like Higgs properties

-Singlet can result in phase transitions to exotic (EW-symmetrey conserving) vacua in the early universe

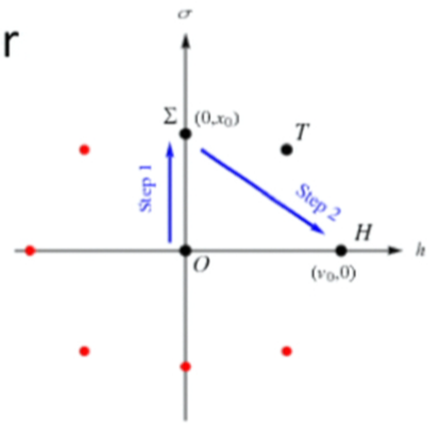
-Bubbles tend to expand quickly. Can potentially test with gravity waves

Is it possible to have an exotic stage of electroweak symmetry breaking in the early Universe during which electroweak baryogenesis can occur?

Scenario 2: Inert Multiplet

The idea: *break EW symmetry by a first order PT to an exotic vacuum in the early Universe, then transition to the standard vacuum*

-Requires additional (inert) field charged under $SU(2)_L$



-First studied in a triplet extension by Patel and Ramsey-Musolf in 1212.5652

Scenario 2: Inert Multiplet

General features can be understood via a simple toy model

$$-\mathscr{L} = -\mathscr{L}_{\text{kinetic}} - \mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \left(y_T\Phi_1\overline{T}_L T_R + \text{h.c.}\right) \, ,$$

Defining $\Delta\lambda_1 \equiv \lambda_1 - \frac{\mu_1^2}{\mu_2^2}\lambda_3$, $\Delta\lambda_2 \equiv \lambda_2 - \frac{\mu_2^2}{\mu_1^2}\lambda_3$, there are 3 distinct vacuum configurations at T=0

$\Delta\lambda_1 < 0, \Delta\lambda_2 > 0 :$ $(v_1, 0)$ is a stable minimum with $(0, v_2)$ unstable

$\Delta\lambda_1 < 0, \Delta\lambda_2 < 0 :$ $(v_1, 0)$ and $(0, v_2)$ are both stable minima

$\Delta\lambda_1 > 0, \Delta\lambda_2 > 0 :$ $(v_1, 0)$ and $(0, v_2)$ are both saddle points

Scenario 2: Inert Multiplet

General features can be understood via a simple toy model

$$
\begin{aligned}
-\mathscr{L} &= -\mathscr{L}_{\text{kinetic}} \\
&\quad -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 \\
&\quad + \left(y_T \Phi_1 \overline{T}_L T_R + \text{h.c.}\right) \ ,
\end{aligned}
$$

Defining $\Delta\lambda_1 \equiv \lambda_1 - \frac{\mu_1^2}{\mu_2^2}\lambda_3$, $\Delta\lambda_2 \equiv \lambda_2 - \frac{\mu_2^2}{\mu_1^2}\lambda_3$, there are 3 distinct vacuum configurations at T=0

$\Delta\lambda_1 < 0, \Delta\lambda_2 > 0 :$ $(v_1, 0)$ is a stable minimum with $(0, v_2)$ unstable

$\Delta\lambda_1 < 0, \Delta\lambda_2 < 0 :$ $(v_1, 0)$ and $(0, v_2)$ are both stable minima

$\Delta\lambda_1 > 0, \Delta\lambda_2 > 0 :$ $(v_1, 0)$ and $(0, v_2)$ are both saddle points

Scenario 2: Inert Multiplet

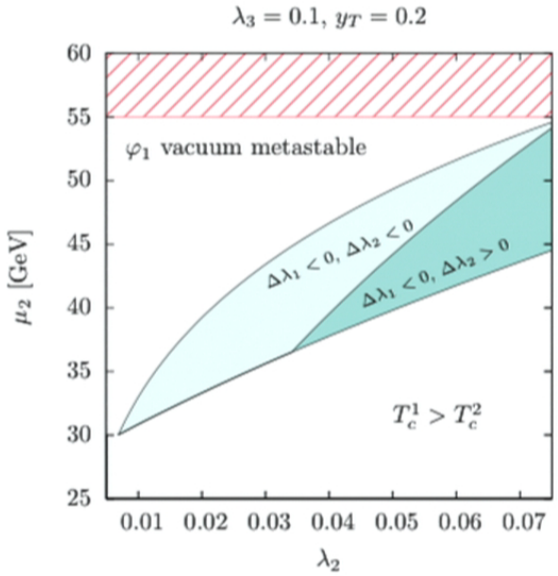
Simple but general requirements for viable exotic symmetry breaking with inert multiplets:

$$\mu_2^2 < \left(\frac{\lambda_3}{\lambda_1}\right)\mu_1^2 \qquad (\Delta\lambda_1 < 0)$$

$$\mu_2^2 < \sqrt{\frac{\lambda_2}{\lambda_1}}\mu_1^2 \qquad (V(v_1) < V(v_2))$$

$$\mu_2^2 > \left(\frac{a_2}{a_1}\right)\mu_1^2 \qquad (T_c^2 > T_c^1)$$

$$\mu_2^2 < \left(\frac{\lambda_2}{\lambda_3}\right)\mu_1^2 \qquad (\Delta\lambda_2 > 0)\ .$$



Scenario 2: Inert Multiplet

We can apply these results to a realistic inert doublet model

$$
\begin{aligned}
V(H,\Phi) \;=\; & -m_H^2 H^\dagger H - m_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 \\
& + \lambda_{\Phi H}(H^\dagger H)(\Phi^\dagger\Phi) + \tilde{\lambda}_{\Phi H}(\Phi^\dagger H)(H^\dagger\Phi) \\
& + \frac{\lambda_5}{2}\left[(\Phi^\dagger H)^2 + \text{h.c.}\right] \; .
\end{aligned}
$$

Assumptions:

$\tilde{\lambda}_{\Phi H} < 0$ with $|\tilde{\lambda}_{\Phi H}| \ll \lambda_{\Phi H}$ — Small neutral – charged state mass splitting realizes approximate custodial symmetry. Reduced λ_3.

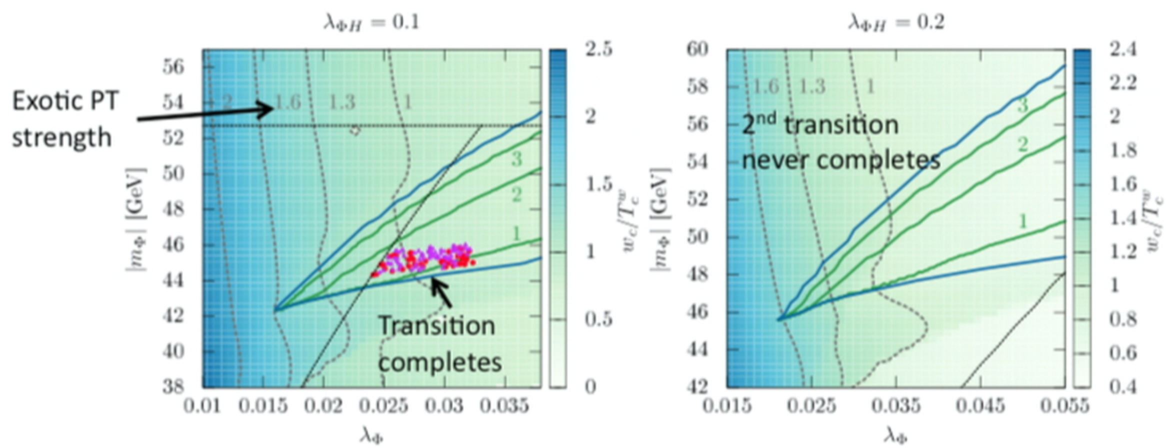
$\lambda_5 \to 0$ — Small CP-even/CP-odd mass splitting evades LEP constraints since $\Delta m < 8$ GeV

Combined, this corresponds to an approximate global *SU(2)* symmetry of the potential. If only the latter, global *U(1)*. If neither, global Z_2

Scenario 2: Inert Multiplet

We can apply these results to a realistic inert doublet model

$$V(H,\Phi) = -m_H^2 H^\dagger H - m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 + \lambda_{\Phi H}(H^\dagger H)(\Phi^\dagger \Phi) + \tilde{\lambda}_{\Phi H}(\Phi^\dagger H)(H^\dagger \Phi) + \frac{\lambda_5}{2}\left[(\Phi^\dagger H)^2 + \text{h.c.}\right] .$$



Small cross-quartic required for second transition to complete

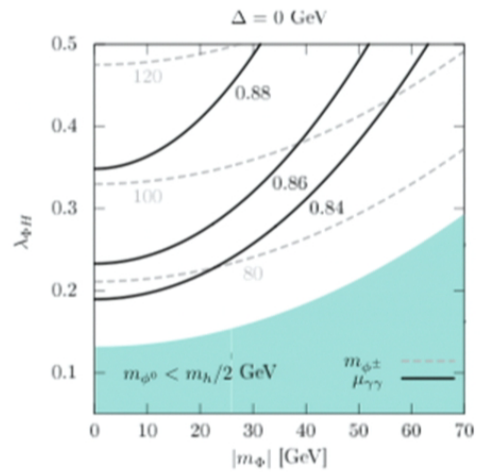
Scenario 2: Inert Multiplet

Spectrum?

$$m_{\phi^0}^2 = \frac{1}{2}\left(\lambda_{\Phi H} + \widetilde{\lambda}_{\Phi H}\right) v^2 - m_\Phi^2$$

$$m_{\phi^\pm}^2 = \frac{1}{2}\lambda_{\Phi H} v^2 - m_\Phi^2$$

Electroweak baryogenesis from exotic EWSB generically predicts light charged states!



-Strongest constraints from invisible *Z, h* decays

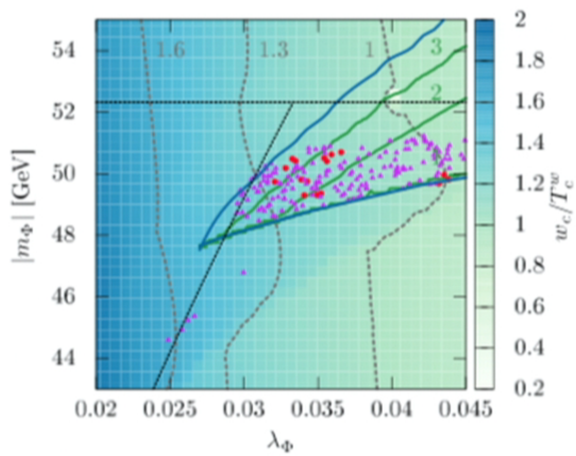
-Forces $m_{\phi^0} \gtrsim 63$ GeV, which is incompatible with exotic electroweak baryogenesis in minimal models

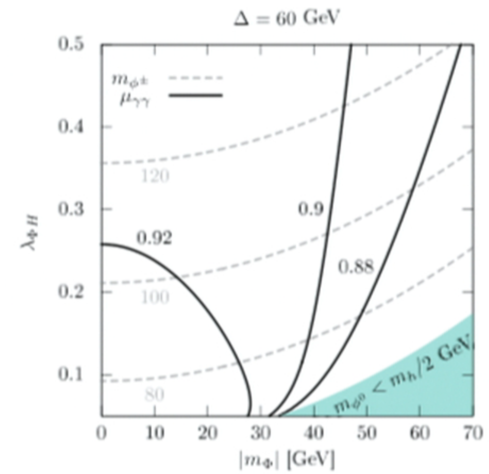
-Require additional mass contribution Δ

Scenario 2: Inert Multiplet

One solution: additional singlet with a VEV

Mass squared contribution $\Delta^2 = \frac{\lambda_{S\Phi}}{2} v_S^2$





EWB from exotic electroweak symmetry breaking is possible and manifestly testable

Takeaways

Electroweak symmetry breaking in the early Universe may have involved multiple scalar fields and vacua

Singlet extensions:

-Can lead to multi-step phase transitions (observable cosmologically?)

-Electroweak phase transition can be strongly first order for very SM-like Higgs

-Substantial change in singlet VEV can pose a challenge for electroweak baryogenesis

Inert multiplet extensions:

-Can allow for electroweak baryogenesis during a transition to an exotic vacuum

-Generically predict light inert states accessible in Higgs coupling measurements and possibly direct searches

Stay tuned...