# Baryogenesis via the electroweak phase transition: the options remaining

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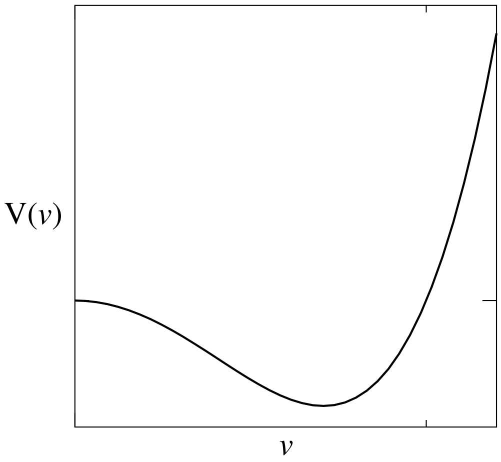
The ground state of the electroweak theory is in a state of a "broken symmetry":




This is not a global symmetry, but a gauge symmetry $\Rightarrow$ there is no gauge-invariant local order parameter, and no strict qualitative difference between the Higgs and confinement phases.

Nevertheless, one may ask: in analogy with condensed matter systems (ferromagnetism, superconductors, etc), is there some sort of a phase transition at high temperatures?

**Yes!** $T_c \sim$ EW scale $\sim 100$ GeV.

Kirzhnits, Linde 1972
Weinberg 1974
Dolan, Jackiw 1974

**Such temperatures can exist in the Early Universe!**

**So what?**

## Motivation

The existence of a matter-antimatter (baryon) asymmetry is an experimental fact.

⋆ no antinuclei are observed in cosmic radiation.

⋆ there is no observation of significant 150 MeV gamma-radiation, originating from $p\bar{p}$ annihilation.

⋆ nucleosynthesis (the production of $^4$He, D, Li) $\Rightarrow$

$$\frac{n_B}{n_\gamma} = (1...9) \times 10^{-10}.$$

Nevertheless, we expect that after inflation $B = 0$.

The electroweak phase transition is in a sense the most conservative ($\equiv$ lowest energy, latest) scenario for baryon asymmetry generation, and at the same time the only one testable at LEP and the Tevatron.

Kuzmin, Rubakov, Shaposhnikov 1985

How to generate a baryon number $B = \sum_{i=\text{ quarks}} \int d^3x \bar{\psi}_i \gamma_0 \psi_i$?

0. $B$ is violated by the anomaly. The rate is fast at high temperatures, exponentially suppressed at low temperatures.

1. In addition, need non-equilibrium. Otherwise,

$$\langle B(t) \rangle_T \propto \mathrm{Tr}\, e^{-H/T} e^{iHt/\hbar} B e^{-iHt/\hbar} = \langle B(0) \rangle_T = 0.$$

2. In addition, need CP-violation: $B$ is $P+, C-$.

In CMBR, say, the remnant is already there, $\langle E_\gamma(0) \rangle_T \neq 0$, and one simply needs to switch the system out of equilibrium, by cooling to low temperatures.

Here, if one passes continuously from one regime to the other, essentially nothing is generated. One needs to have some sort of a singularity. A singularity is provided by a 1st order phase transition. After it, immediately non-equilibrium.

[Another popular scenario, based on Majorana neutrino masses and $L$ violation, operates more like CMBR generation.]

To determine the thermodynamics, we need to compute

$$Z = \mathrm{Tr}\exp(-\beta H) = \int_{\text{b.c.}} \mathcal{D}\Phi \exp[-\frac{1}{\hbar}\int_0^{\beta\hbar} d\tau \int d^3x \mathcal{L}_E(\Phi)].$$

**Method? The problem is non-perturbative!**
(even though the theory is weakly coupled and perturbation theory works perfectly at $T = 0$)

This is due to the IR-problem at finite $T$: Linde 1980
there is a new scale $T$, and there are new expansion parameters!
This comes from:

$$T = 0 \quad \Rightarrow \quad g^2$$

$$T > 0 \quad \Rightarrow \quad g^2 n_b(E) = \frac{g^2}{e^{E/T} - 1} \overset{E \ll T}{\sim} \frac{g^2 T}{E},$$

$$g^2 n_f(E) = \frac{g^2}{e^{E/T} + 1} \lesssim g^2.$$

In perturbation theory the transition is between $v = 0$, $v \sim T$, and $m_W \sim gv \Rightarrow$ the expansion breaks down!

At the same time, it is a multi-scale problem!

- non-zero Matsubara modes, e.g. **all fermions**: $m \sim \pi T$
  (no IR-problems; $\frac{h^2 v^2}{2} \ll (\pi T)^2$; expansion in $\frac{g^2}{(4\pi)^2}$)

- radiatively generated scale $m \sim gT$ for $A_0$ (Debye screening)
  (no IR-problems; expansion in $\frac{g}{4\pi}$)

- the non-perturbative scale $m \sim g^2 T$, for purely bosonic Matsubara zero-modes
  (no perturbative expansion)

**The solution**:

Combine the best parts of perturbation theory and simulations: integrate out massive modes $(\pi T, gT)$ perturbatively, study light modes $(g^2 T)$ non-perturbatively on the lattice!

$\Rightarrow$ **Dimensional reduction into 3d & integrate out $A_0$**

Ginsparg; Appelquist, Pisarski; Nadkarni; Reisz; Kajantie, Rummukainen, Shaposhnikov; Jakovác, Patkós; Braaten, Nieto;. . .

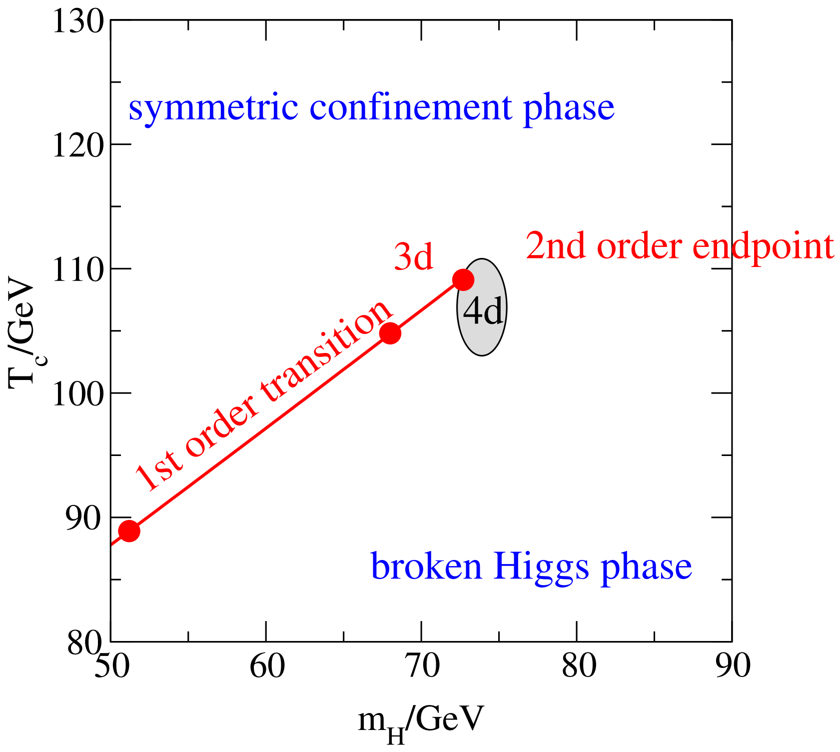
The effective theory left: bosonic zero modes.

$$\begin{aligned}\mathcal{L}_{3\mathrm{d}} &= \frac{1}{2}\mathrm{Tr}\,F_{ij}^2 + \frac{1}{4}B_{ij}^2 + (D_i\phi)^\dagger D_i\phi + m_3^2\phi^\dagger\phi + \lambda_3(\phi^\dagger\phi)^2,\\ Z &= \int \mathcal{D}\Phi\exp[-\beta\int d^3x\mathcal{L}_{3\mathrm{d}}^{(\beta)}(\Phi)].\end{aligned}$$

The couplings, of course, do get modified by the other modes. Formally, the relative error made by throwing out higher-order operators is $\frac{\delta G}{G} \sim \mathcal{O}(g^3)$. In practice, at the percent level.

The effective theory is CP-invariant at this order.

## The result of lattice simulations:




3d lattice results:
[SU(2)×U(1)+Higgs+fermions]
Kajantie et al 1997;
Rummukainen et al 1998

4d lattice results:
[SU(2)+Higgs; relative
endpoint position conserved]
Csikor et al 1998

**No transition at physical $m_H \Rightarrow$ no cosmological remnant!**

For baryogenesis, the same conclusions could be reached also with weaker results:

In order to switch sufficiently out of equilibrium, need a strong transition, $v/T \gtrsim 1$, which is not obtained at any $m_H > m_{H,CW} \sim 10$ GeV. But this depends on the expansion rate.

Furthermore, CP-violation is quite weak in the SM. But here there is a discrepancy of $\gtrsim 13$ orders of magnitude.

**The cosmological motivation for magnetic fields $H_Y$:**

- The galactic magnetic fields observed today may imply the existence of primordial seed fields.

- What is the original **length scale**?

  Normal scaling: $l(T) \sim l(T_{\text{EW}})(\frac{T_{\text{EW}}}{T}) \Rightarrow l_H^{\text{EW}} \cong 1$ AU today.
  MHD scaling: $l(T) \sim l(T_{\text{EW}})(\frac{T_{\text{EW}}}{T})^{1\ldots\frac{5}{3}}$.

  Son; Field and Carroll

  Even after the enhancement, $l(T_{\text{EW}}) > l_H^{\text{EW}}$ seems likely.

- Such large scale magnetic fields can be generated in the Early Universe? (Inflation, string cosmology,. . . )

  Turner and Widrow; Ratra;
  Dolgov and Silk; Gasperini et al;...

- **Magnitude**: equipartition tells that only a small fraction of the total free energy can be in magnetic fields $\Rightarrow$

$$\frac{H_Y}{T^2} \lesssim 2.$$

**Why could a homogeneous magnetic field help?**

**1. The phase transition can be stronger!**

As soon as $H_Y \neq 0$, $m_H \approx m_Z$ is in a special position. The case $m_H < m_Z$ corresponds to **type I superconductors**.

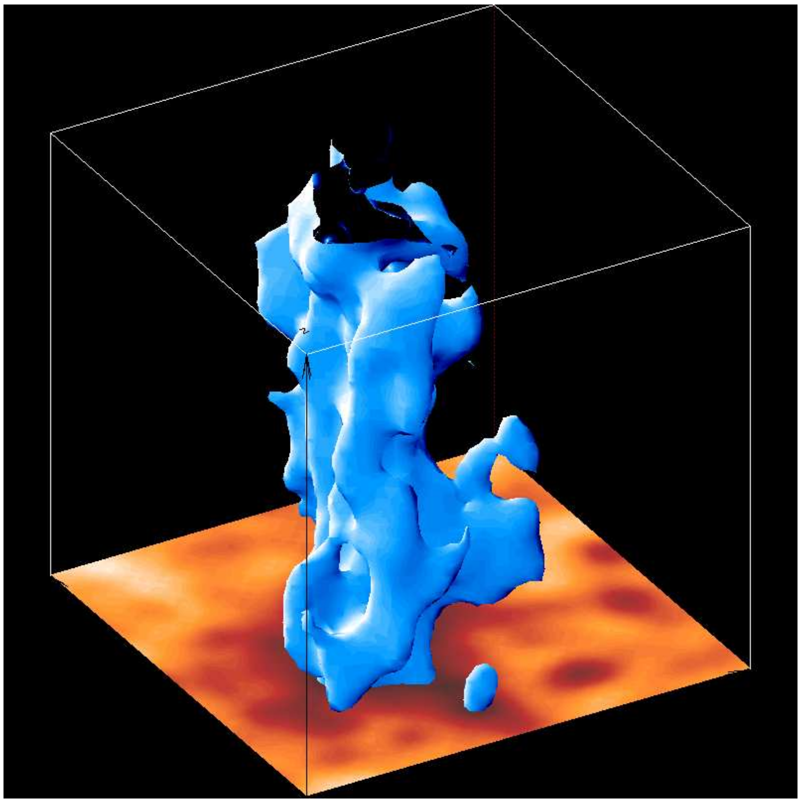
There superconductivity is destroyed by $H_Y$. But a flux cannot go into the SC phase $\Rightarrow$ the normal and SC phase coexist at $H_{Y,c}$ $\Rightarrow$ a strong 1st order transition!

In the electroweak theory, SC phase $\leftrightarrow$ Higgs phase, and the flux can go through, although weakened. But the qualitative effect is the same: the transition gets stronger.

**2. $\vec{H}_Y$ is also CP-odd, so that there is locally a new source of CP-violation!**

The system can be studied non-perturbatively with the same effective theory as before, for modest $H_Y/(\pi T)^2 \ll 1$.

For $m_H < m_Z$, a strong 1st order transition with coexisting regions is indeed observed:

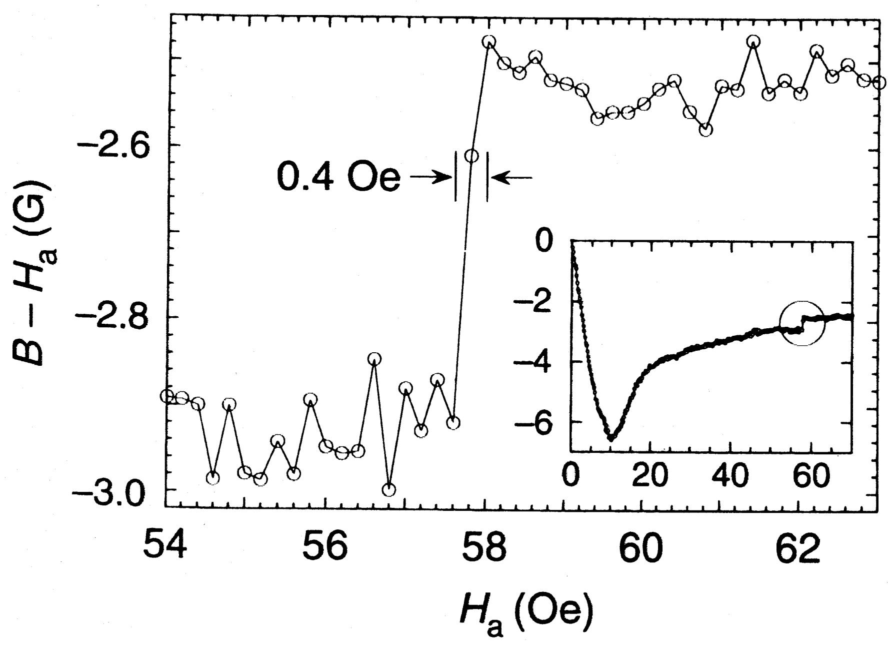


However, as far as baryogenesis is concerned, what seems to be won by a stronger transition is in fact compensated for by a smaller sphaleron energy in a magnetic field, due to its dipole moment. This means that the B violating processes are not sufficiently out of equilibrium.

Comelli et al 1999

And in any case, Higgs masses $m_H < m_Z$ are not physical.

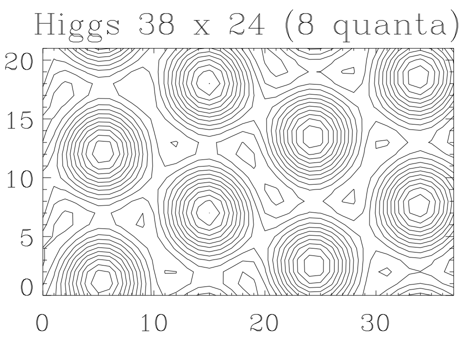
**The physical case** $m_H > m_Z$: the superconductor analogy is now a **type II** (high-$T_c$) material: the flux can penetrate the system via an Abrikosov vortex lattice. But even then, there could be a 1st order transition due to vortex interactions:




E. Zeldov et al, Nature 375 (1995) 373: High-$T_c$ 'BSCCO'

Meissner phase vortex lattice normal (Coulomb) phase

In EW case: an analogous "vortex" phase is found at tree-level!




AO-phase: Ambjørn, Olesen 1989

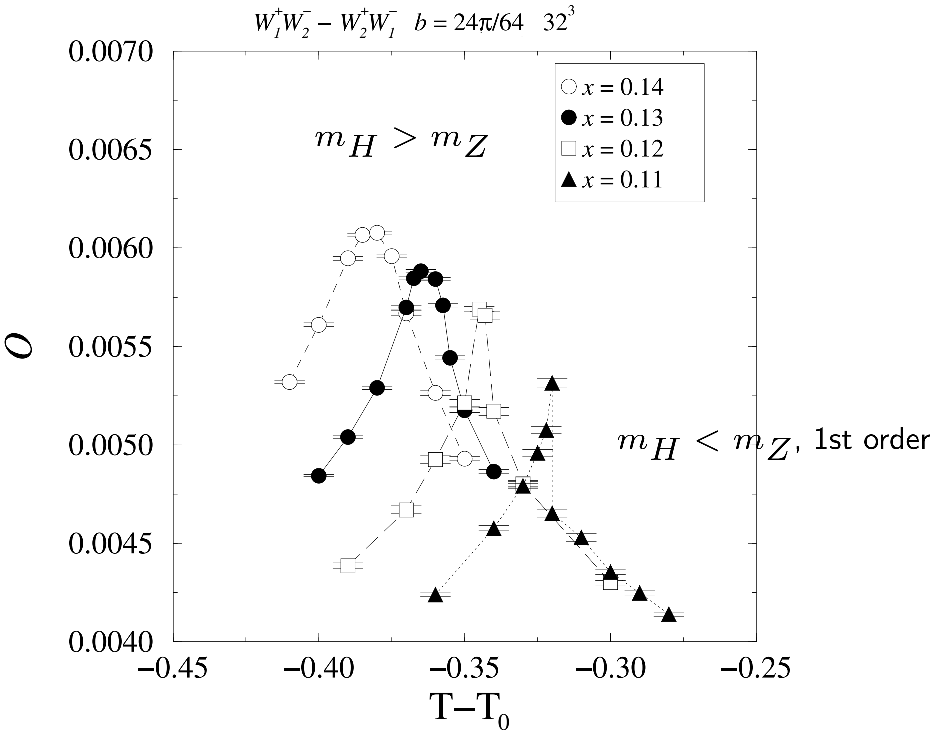
$\Rightarrow$ could interactions generate a 1st order transition?

A way to understand the "instability" is via Landau levels: some excitations become tachyonic, e.g. in the broken phase

$$m^2_{W,\,\text{eff}} = m^2_W - eH_{\text{EM}} < 0$$

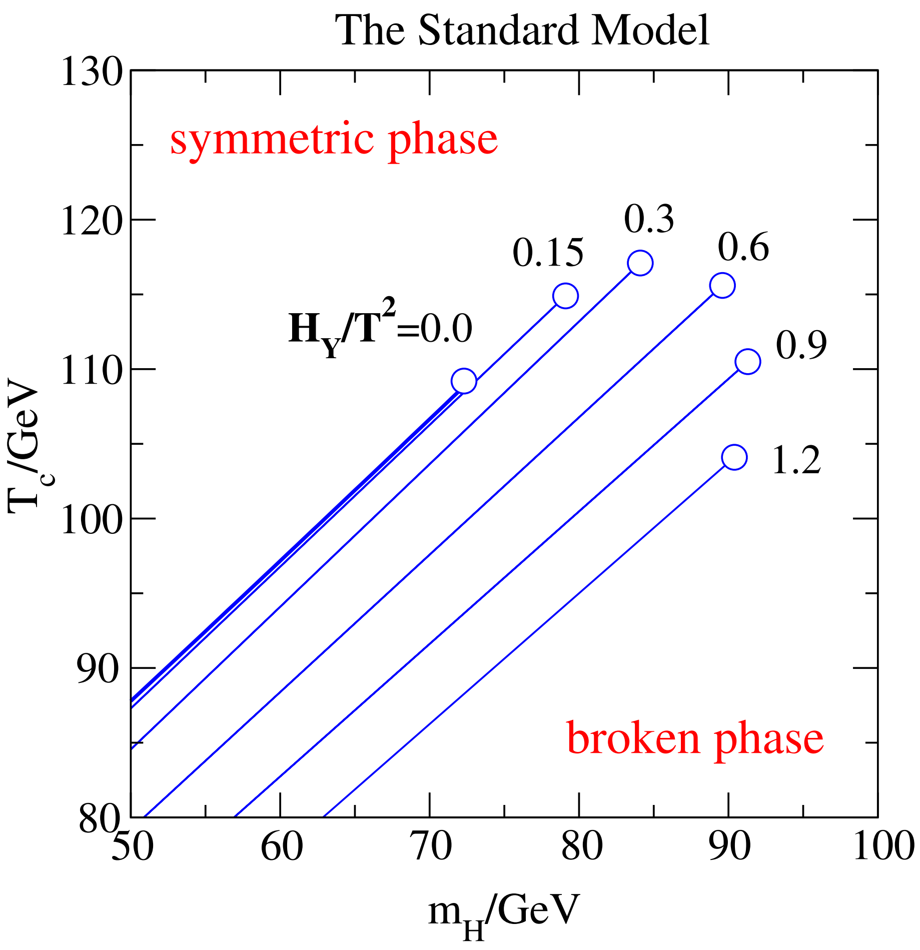
for large enough $H_Y$, or small enough $v$.

Thus, look at the $W^+W^-$ condensate:




$\Rightarrow$ No AO-phase or a related transition is observed in the fluctuating system. $W$ is always heavy due to SU(2) confinement.

The result for cosmologically relevant magnitudes of $H_Y/T^2$:



## Why would MSSM help?

1. There can be a stronger transition!
(More light bosonic d.o.f.'s: the squarks.)

de Carlos and Espinosa; Bödeker et al; Carena at al; Cline and Moore; Losada

Need stops, in order to have a strong coupling to the Higgs. The stops come left- and right-handed, $\tilde{t}_L, \tilde{t}_R$.

However, in order for $\Delta\rho$ to be small, and $m_H$ large, the weakly interacting $\tilde{t}_L$ should be heavy:

$$\Delta\rho \propto \frac{m^2_{\text{top}}}{m^2_{\tilde{t}_L}}, \quad m^2_H \sim m^2_Z \cos^2 2\beta + \frac{3\alpha_W}{2\pi}\frac{m^4_{\text{top}}}{m^2_W} \ln \frac{m_{\tilde{t}_R} m_{\tilde{t}_L}}{m^2_{\text{top}}}.$$

On the contrary, $\tilde{t}_R$ can be light.

2. There can be more CP-violation!
(Complex phases in the new parameters.)

Carena et al; Cline et al; Rius and Sanz; ...

## Lattice simulations in the MSSM

The light degrees of freedom:
two SU(2) Higgs doublets $H_1, H_2$ and an SU(3) triplet $U$.

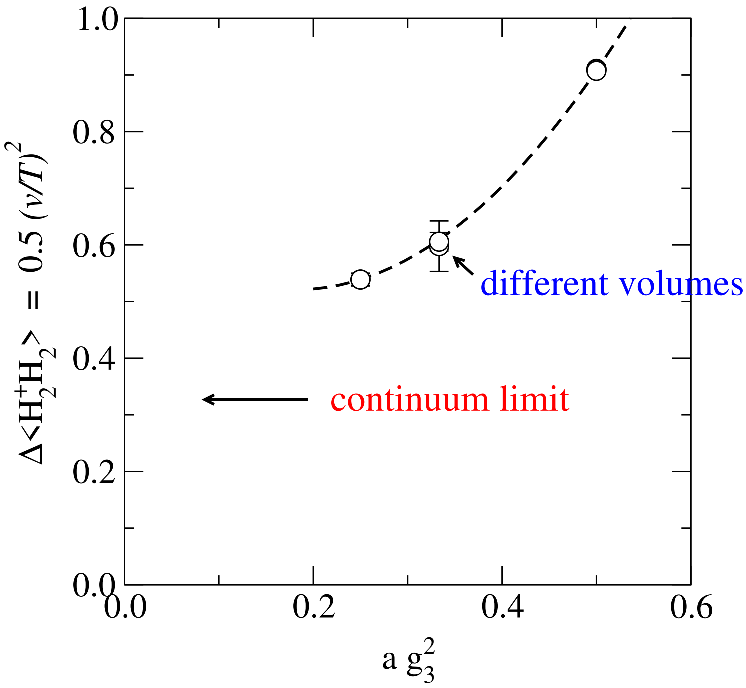
$$
\begin{aligned}
\mathcal{L}_{\text{3d}} &= \frac{1}{2}\mathrm{Tr}\,G_{ij}^2 + (D_i^s U)^\dagger (D_i^s U) + m_U^2 U^\dagger U + \lambda_U (U^\dagger U)^2 \\
&+ \gamma_1 U^\dagger U H_1^\dagger H_1 + \gamma_2 U^\dagger U H_2^\dagger H_2 + [\gamma_{12} U^\dagger U H_1^\dagger \tilde{H}_2 + \mathrm{H.c.}] \\
&+ \frac{1}{2}\mathrm{Tr}\,F_{ij}^2 + (D_i^w H_1)^\dagger (D_i^w H_1) + (D_i^w H_2)^\dagger (D_i^w H_2) \\
&+ m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + [m_{12}^2 H_1^\dagger \tilde{H}_2 + \mathrm{H.c.}] \\
&+ \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger \tilde{H}_2 \tilde{H}_2^\dagger H_1 \\
&+ [\lambda_5 (H_1^\dagger \tilde{H}_2)^2 + \lambda_6 H_1^\dagger H_1 H_1^\dagger \tilde{H}_2 + \lambda_7 H_2^\dagger H_2 H_1^\dagger \tilde{H}_2 + \mathrm{H.c.}].
\end{aligned}
$$

CP-violation already within the super-renormalizable effective theory [$\gamma_{12}$, $m_{12}^2$, $\lambda_5, \lambda_6, \lambda_7 \in \mathbb{C}$], unlike in the SM!

**An example of simulation results with this action:**

Take the parameter values

$$m_A = 120 \text{ GeV}, \quad \tan\beta = 12,$$
$$m_H \approx 105 \text{ GeV}, \quad m_{\tilde{t}_R} \approx 155 \text{ GeV}, \quad m_{\tilde{t}_L} \approx 1 \text{ TeV},$$
$$A_t = |\mu| = M_2 = 200 \text{ GeV}, \mu = i|\mu|.$$




$\Rightarrow$ the transition remains of 1st order in the continuum limit, with $\frac{v}{T} \sim 1$. Increasing $m_A$ would increase $\frac{v}{T}$ slightly.

In an MSSM like theory but without fermions, 4d simulations have also been carried out with similar conclusions.

Csikor et al 2000

## Conclusions

Electroweak baryogenesis is an intriguing possibility, even if Majorana $\nu$'s would be responsible for part of the result.

Nevertheless, it does not work in the SM, even if there were external magnetic fields present.

Could work in the MSSM if $m_H \lesssim 110$ GeV is discovered.

A first principles computation of the baryon number produced around a CP-violating phase boundary in such a case is a formidable theoretical challenge.