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Baryogenesis and the Two-Higgs Doublet Model

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Overview

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Unsolved mysteries

Baryogenesis

Conditions for baryogenesis
Phase transition in the universe
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Dimensional reduction

Why do you exist?

We observe a matter dominated universe [1].

Unsolved mysteries

- Why does the universe contain more matter than antimatter?
- Why does the asymmetry have the specific amount that it does ($\eta \approx 10^{-9}$)?

Conditions for baryogenesis

Sakharov conditions [2]

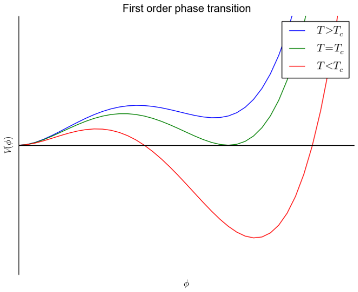
1. Baryon number is violated
2. Deviation from thermal equilibrium
3. CP violation

Phase transition in the universe

First or second order phase transition?

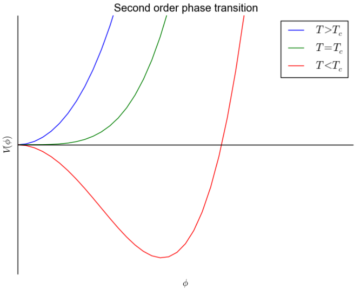
First order phase transition have a barrier:

— Deviation from thermal equilibrium



Second order phase transition does not have a barrier:

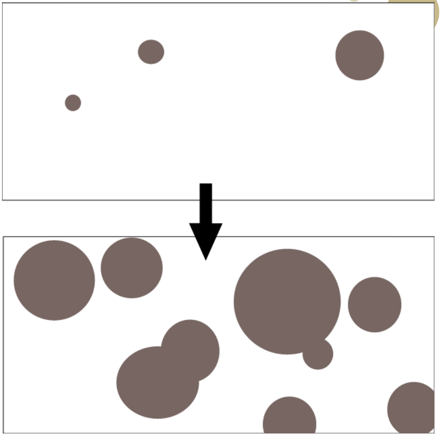
— Can happen continuously



Bubble nucleation

Bubbles with a different vacuum nucleates.
Bubbles of a certain size will:

1. Expand
2. Collide
3. Coalece and fill the whole universe.

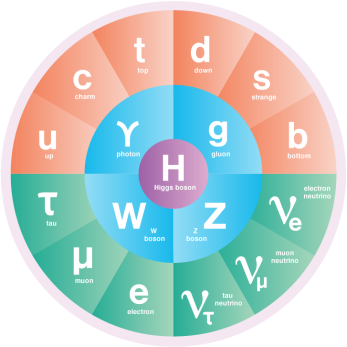


The Standard Model

$$
\begin{aligned}
\mathcal{L}_{SM} = \quad & - \quad \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + \quad i\overline{\psi} \not{D} \psi + \mathrm{h.c.} \\
& + \quad \psi_i Y_{ij} \psi_j \phi + \mathrm{h.c.} \\
& + \quad |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

where

$$V(\phi) = -\frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4$$



Is the Standard Model sufficient to explain baryogenesis?

1. Ok
2. Not quite
3. Not quite

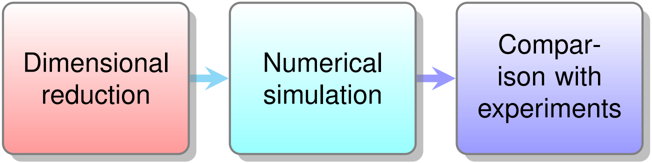
We need an extended model.

Examples: SM + singlet [3], Minimal Supersymmetric SM [4].

Two-Higgs Doublet Model

We add an extra Higgs doublet.

$$
\begin{aligned}
V(\phi_1, \phi_2) = & -\frac{1}{2} m_{11}^2 \phi_1^\dagger \phi_1 - \frac{1}{2} m_{22}^2 \phi_2^\dagger \phi_2 \\
& + \lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 + \lambda_2 \left(\phi_2^\dagger \phi_2\right)^2 \\
& + \lambda_3 \left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4 \left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right) \\
& + \frac{\lambda_5}{2} \left[\left(\phi_1^\dagger \phi_2\right)^2 + \left(\phi_2^\dagger \phi_1\right)^2\right]
\end{aligned}
$$



Thermal field theory

We replace the integral over 4-momentum with a sum-integral.

$$\int \frac{d^4k}{(2\pi)^4} \rightarrow T \sum_{n=-\infty}^{\infty} \int \frac{d^3k}{(2\pi)^3} \equiv \sum\!\!\!\!\!\!\int_K$$

where $K = (\omega_n, \boldsymbol{k})$ is the 4-momentum.

Lorentz symmetry is broken by the heat bath!

Particles acquire a thermal (Debye) mass.

Bosons

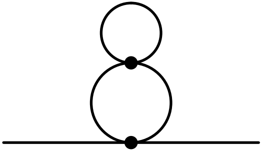
$$\omega_n = 2n\pi T, \quad n \in \mathbb{Z}$$

Fermions

$$\omega_n = (2n+1)\pi T, \quad n \in \mathbb{Z}$$

Infrared divergenses

A quantum correction to the scalar self-energy of order $\mathcal{O}(\lambda^2)$ is



$$= -\frac{\lambda^2}{4} \sum\!\!\!\!\!\!\!\int_P \frac{1}{P^2} T \sum_n \int \frac{d^d k}{(2\pi)^d} \frac{1}{\left[\omega_n^2 + k^2 + m^2\right]^2}$$

where $d = 3 - 2\epsilon$.

For $m^2 = 0$ og $n = 0$ the diagram diverges when $k^2 \to 0$.

We must sum all diagrams of this form (daisy-diagrams), and they yield a finite result.

β-functions for Two-Higgs Doublet Model

The β-functions can be extracted from the counter terms.

$$\beta_{g'} = \frac{g'^3}{6(4\pi)^2}\left[2 + \sum_f Y_f^2\right], \qquad \beta_g = -\frac{g^3}{3(4\pi)^2}\left[21 - \sum_{\text{left}}\right]$$

$$\beta_{\lambda_1} = \frac{1}{(4\pi)^2}\Big[\frac{9}{4}g^4 + \frac{3}{4}g'^4 + \frac{3}{2}g^2g'^2 - \lambda_1(9g^2 + 3g'^2) + 12\lambda_1^2 + 4\lambda_3^2$$
$$+2\lambda_4^2 + 2\lambda_5^2 + 4\lambda_3\lambda_4 + 4\lambda_1\sum_i h_i^2\Big]$$

$$\beta_{\lambda_2} = \frac{1}{(4\pi)^2}\Big[\frac{9}{4}g^4 + \frac{3}{4}g'^4 + \frac{3}{2}g^2g'^2 - \lambda_2(9g^2 + 3g'^2) + 12\lambda_2^2 + 4\lambda_3^2 + 2\lambda_4^2$$
$$+2\lambda_5^2 + 4\lambda_3\lambda_4 + 4\lambda_2\sum_i h_i^2 - 4\sum_i h_i^4\Big]$$

$$\beta_{\lambda_3} = \frac{1}{(4\pi)^2}\Big[\frac{9}{4}g^4 + \frac{3}{4}g'^4 + \frac{3}{2}g^2g'^2 - \lambda_3(9g^2 + 3g'^2) + 2(\lambda_1 + \lambda_2)(3\lambda_3 + \lambda_4)$$
$$+4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + 4\lambda_3\sum_i h_i^2\Big]$$

$$\beta_{\lambda_4} = \frac{1}{(4\pi)^2}\Big[\lambda_4(2\lambda_1 + 2\lambda_2 + 4\lambda_4 + 8\lambda_3 - 9g^2 - 3g'^2) + 8\lambda_5^2 + 4\lambda_4\sum_i h_i^2\Big]$$

$$\beta_{\lambda_5} = \frac{1}{(4\pi)^2}\Big[\lambda_5(2\lambda_1 + 2\lambda_2 + 4\lambda_3 + 6\lambda_4 - 9g^2 - 3g'^2) + 4\lambda_5\sum_i h_i^2\Big]$$

Dimensional reduction

At high temperatures all fermions and almost all bosons (except the $n = 0$ mode) are (super)heavy [5]. We can integrate out the (super)heavy particles, and are left with an *effective teory*:

$$\mathcal{L}(A, \phi, \psi) \to \mathcal{L}_{\text{eff}}(A_0, \boldsymbol{A}, \phi) \to \mathcal{L}'_{\text{eff}}(\boldsymbol{A}, \phi).$$

We find parameters of the three-dimensional theory by matching, i.e. requiring the long distance (zero external momentum) behaviour of corrolators to be the same as in the four-dimensional theory.

Numerical simulations are more tractable [6]: reduced number of dimensions, purely bosonic theory etc.

We can find static (time independent) observables, as the theory is purely spatial.

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