The Electroweak Phase Transition in Two-time Physics

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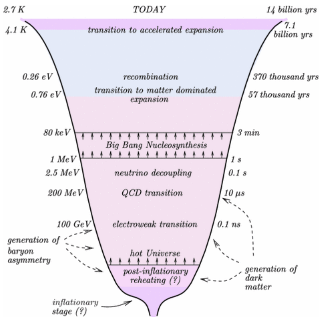
Baryon Asymmetry of the Universe (BAU)



Three conditions of Sakharov

- B-number violation.
- sufficiently effective CP violation.
- deviation from thermail equilibrium.

Beyond Standard Model (BSM)

For the third condition, we need a strong first-order electroweak phase transition (EWPT).
$\Rightarrow$ extend the theory beyond the SM.

Two-time Physics?

- interesting theory BSM with extra dimensions.
- gauge symmetry: $\mathrm{Sp}(2, R)$.
- an extra scalar field: Dilaton Φ.
- has resolved the strong CP problem without a need for the Peccei-Quinn symmetry.

Effective potential

To investigate the EWPT, one usually use *effective potential*.

$$V_{eff}(\phi_c) = -\sum_{n=0}^{\infty} \frac{1}{n!}\phi_c^n \Gamma^{(n)}(p_i = 0), \tag{1}$$

where $\Gamma^{(n)}$ is the one-particle irreducible (1PI) Green function.
We need an sensible approximation method: loop expansion.

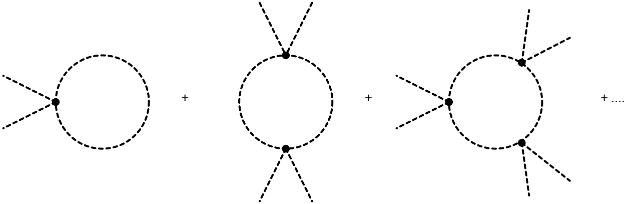
Loop expansion

Calculate the effective potential according to the increasing number of independent loops in the connected Feynman diagrams. Each stage with a number of loop, we have to sum over the diagrams corresponding to all possible external lines.

One-loop approximation

For the scalar field, e.g. in ϕ^4 theory,

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{\lambda}{4!}\phi^4. \qquad (2)$$



$$V_{eff}(\phi_c) = V_0(\phi_c)$$
$$+ i \sum_{n=1}^{\infty} \frac{1}{(2n)!}\phi^{2n}\frac{(2n)!}{2^n 2n}\int \frac{d^4p}{(2\pi)^4}\left[(-i\lambda)\frac{i}{p^2 - m^2 + i\epsilon}\right]^n$$
$$\Rightarrow \; V_1(\phi_c) = \frac{1}{2}\int \frac{d^4p}{(2\pi)^4} \ln\left[p^2 + m^2(\phi_c)\right]. \qquad (3)$$

Effective potential at finite temperature

The particles interaction in place such as the accelerators can be investigated by conventional quantum field theory (empty spacetime). But the temperature and matter density in the early stages of the universe standard cosmology are extremely high.
$\Rightarrow$ field theory at finite temperature.

Effective potential at finite temperature

For scalar field in ϕ^4 theory,

$$V_1^{\beta}(\phi_c) = \frac{1}{2}\int \frac{d^4p}{(2\pi)^4} \ln\left[p^2 + m^2(\phi_c)\right] + \frac{1}{2\pi^2\beta^4} J_B[m^2(\phi_c)\beta^2]. \tag{4}$$

where the thermal bosonic function J_B is defined as

$$J_B(m^2\beta^2) = \int_0^{\infty} dx\, x^2 \ln\left[1 - e^{-\sqrt{x^2+\beta^2 m^2(\phi_c)}}\right]. \tag{5}$$

$$= -\frac{\pi^4}{45} + \frac{\pi^2}{12}\frac{m^2}{T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} - \frac{1}{32}\frac{m^4}{T^4}\ln\frac{m^2}{a_b T^2}$$
$$- 2\pi^{7/2}\sum_{n=1}^{\infty}(-1)^n \frac{\zeta(2n+1)}{(n+1)!}\Gamma\left(n+\frac{1}{2}\right)\left(\frac{m^2}{4\pi^2 T^2}\right)^{n+2}. \tag{6}$$

Effective potential for SM

Only heavy enough particles have significant contribution to the effective potential. After collecting the contribution of these particles, and using dimenstional renormalization, one-loop effective potential at finite temperature for SM

$$V_{\text{eff}}(\phi_c, T) = \frac{\lambda_R}{4}\phi_c^4 - \frac{m_R^2}{2}\phi_c^2 + \Lambda_R + \frac{1}{64\pi^2}\sum_{i=h,W,Z,t} n_i m_i^4(\phi_c)\ln\frac{m_i^2(\phi_c)}{v^2} + \frac{T^4}{2\pi^2}\left\{\sum_{i=h,W,Z} n_i J_B[m_i^2(\phi_c)/T^2] + n_t J_F[m_t^2(\phi_c)/T^2]\right\}. \tag{7}$$

Expand the thermal function J_B, J_F and collect the terms in order of ϕ_c

$$V_{\text{eff}}(\phi_c, T) = \frac{\lambda(T)}{4}\phi_c^4 - ET\phi_c^3 + D(T^2 - T_0^2)\phi_c^2 + \Lambda(T), \tag{8}$$

where

$$\lambda(T) = \frac{m_h^2}{2v^2} - \frac{1}{16\pi^2 v^4}\sum_{i=h,W,Z,t} n_i m_i^4 \ln\frac{m_i^2}{A_i T^2}, \tag{9}$$

$$E = \frac{m_h^3 + 6m_W^3 + 3m_Z^3}{12\pi v^3}, \tag{10}$$

$$D = \frac{m_h^2 + 6m_W^2 + 3m_Z^2 + 6m_t^2}{24v^2}, \tag{11}$$

$$T_0^2 = \frac{1}{D}\left[\frac{m_h^2}{4} - \frac{1}{32\pi^2 v^2}\sum_{i=h,W,Z,t} n_i m_i^4\right], \tag{12}$$

$$\Lambda(T) = \frac{m_h^2 v^2}{8} - \frac{1}{128\pi^2}\sum_{i=h,W,Z,t} n_i m_i^4 - \frac{13\pi^2 T^4}{60}. \tag{13}$$

EWPT in SM

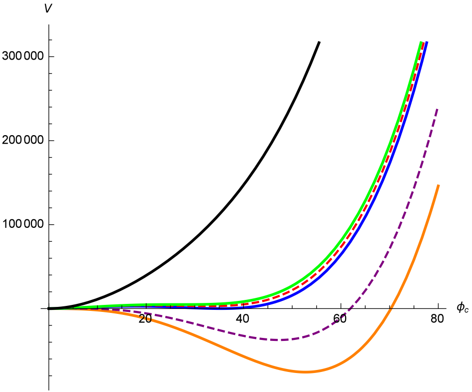


Figure: The effective potential in the Standard Model with different temperature. Black line 160 GeV, green line $T_1 = 158.457$ GeV, red line 158.42 GeV, blue line $T_c = 158.375$ GeV, purple line 158 GeV and orange line $T_o = 157.726$ GeV.

Lagrangian

$$L(A,\Psi^{L,R},H,\Phi)=L(A)+L(A,\Psi^{L,R})+L(\Psi^{L,R},H)+L(A,H,\Phi), \quad (14)$$

Using the gauge fixing, we can reduce the 2T Lagrangian into 1T Lagrangian. We focus on the Higgs-Dilaton Lagrangian

$$\begin{aligned} L(A,H,\Phi) \longrightarrow \frac{1}{\kappa^4}\chi\partial^2\chi - \frac{g_1^2+g_2^2}{4}\chi^2 Z_\mu Z^\mu - \frac{g_2^2}{2}\chi^2 W_\mu^- W^{\mu,+} \quad (15) \\ - \frac{\lambda}{\kappa^4}\left(\chi^2-\alpha^2\phi^2\right)^2 - V(\phi). \end{aligned}$$

Effective potential in 2T physics

$$
\begin{aligned}
V_{\text{eff}}(\phi_c, T) = \\
&\frac{1}{4}\left[\frac{m_h^2}{2v^2} + \frac{1}{16\pi^2 v^4}\left(\sum_{i=h,d,W,Z} n_i m_i^4 \ln\frac{A_b T^2}{m_i^2} + n_t m_t^4 \ln\frac{A_f T^2}{m_t^2}\right)\right]\phi_c^4 \\
&- \frac{T}{12\pi v^3}(m_h^3 + m_d^3 + 6m_W^3 + 3m_Z^3)\phi_c^3 \\
&+ \left[-\frac{m_h^2}{4} + \frac{1}{32\pi^2 v^2}\sum_{i=h,d,W,Z,t} n_i m_i^4 \right. \\
&\qquad \left. + \frac{T^2}{24v^2}(m_h^2 + m_d^2 + 6m_W^2 + 3m_Z^2 + 6m_t^2)\right]\phi_c^2. \\
&= \frac{\lambda(T)}{4}\phi_c^4 - ET\phi_c^3 + D(T^2 - T_0^2)\phi_c^2, \qquad (16)
\end{aligned}
$$

where

$$\lambda(T) = \frac{m_h^2}{2v^2} + \frac{1}{16\pi^2 v^4}\left(\sum_{i=h,d,W,Z} n_i m_i^4 \ln\frac{A_b T^2}{m_i^2} + n_t m_t^4 \ln\frac{A_f T^2}{m_t^2}\right), \tag{17}$$

$$E = \frac{m_h^3 + m_d^3 + 6m_W^3 + 3m_Z^3}{12\pi v^3}, \tag{18}$$

$$D = \frac{m_h^2 + m_d^2 + 6m_W^2 + 3m_Z^2 + 6m_t^2}{24v^2}, \tag{19}$$

$$T_0^2 = -\frac{m_h^2}{4} + \frac{1}{32\pi^2 v^2}\sum_{i=h,d,W,Z,t} n_i m_i^4. \tag{20}$$

m_h	m_d	m_W	m_Z	m_t	v
125.09	400	80.385	91.1876	173.1	246

Table: The masses of particles and the VEV of the Higgs field in units of GeV.

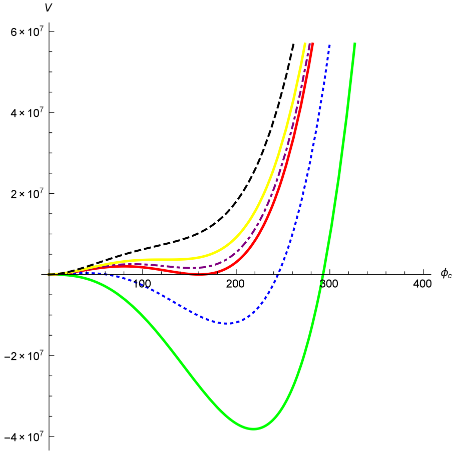


Figure: The effective potential in the Standard Model which reduces from 2T-physics to 1T-physics with different temperature. Black line 130 GeV, yellow line $T_1 = 125.811$ GeV, purple line 124 GeV, red line $T_c = 122.79$ GeV, blue line 115 GeV and green line $T_o = 103.632$ GeV.

- The EWPT in the Standard Model cannot be a strong first order phase transition. Therefore, we need extend BSM.
- The effective potential was contructed from this reduced Lagrangian and had a similar form to the one we had in usual Standard Model but now there was an extra contribution of the dilaton. And as we have shown, this contribution strengthened the first order EWPT by lifting the potential barrier of the effective potential.
- We can calculate the rate of the transition to examine the sphalerons or instaton. Further discussions of the dilaton mass are necessary to learn more about the contribution of the two-time physics.

Thank you for your attention!!