Inert Model and the evolution of the Universe

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Abstract

We consider evolution of the Universe after EWSB leading to the **present Inert phase, containing a SM-like Higgs boson and scalar dark particles among them a Dark Matter candidate**. We address the question, if there is a possibility to have a sequence of the phase transitions instead of a single one leading directly from EW symmeric phase to the Inert one.

Model

2HDM potential for scalar doublets φ_S, φ_D:

$$V = -\frac{1}{2}(m_{11}^2 x_1 + m_{22}^2 x_2) + \frac{1}{2}(\lambda_1 x_1^2 + \lambda_2 x_2^2) +$$
$$+ \lambda_3 x_1 x_2 + \lambda_4 x_3 x_3^\dagger + \frac{1}{2}\left(\lambda_5 x_3^2 + h.c\right),$$
$$x_1 = \varphi_S^\dagger \varphi_S,\ \ x_2 = \varphi_D^\dagger \varphi_D,\ \ x_3 = \varphi_S^\dagger \varphi_D\,.$$

V is invariant under a Z_2 symmetry transformation:

$$\varphi_S \xrightarrow{Z_2} \varphi_S, \quad \varphi_D \xrightarrow{Z_2} -\varphi_D.$$

The conservation of Z_2 parity gives ***the Dark Matter candidate from the Z_2-odd doublet φ_D.***
We set Yukawa interaction to Model I
(only φ_S couples to fermions).

Thermal evolution of V

The first order corrections to the potential due to the thermal evolution are given by the $\propto T^2$ contributions to the **mass terms** m_{ii}^2, while λ_i of the quartic terms are unchanged:

$$m_{ii}^2(T) = m_{ii}^2 - c_i T^2\,, \quad i = 1,2$$
$$c_1 = \frac{3\lambda_1 + 2\lambda_3 + \lambda_4}{12} + \frac{3g^2 + g'^2}{32} + \frac{(g_t^2 + g_b^2)}{8},$$
$$c_2 = \frac{3\lambda_2 + 2\lambda_3 + \lambda_4}{12} + \frac{3g^2 + g'^2}{32}.$$

g, g' – the EW gauge couplings, g_t, g_b – SM Yukawa couplings (fermionic contribution).

Extrema

The most general EWSB solution:

$$\langle\varphi_S\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle\varphi_D\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u \\ v_D \end{pmatrix}$$

gives three neutral ($u = 0$) extrema:

$$I_1: v_D = 0, \quad v_S^2 = v^2 = m_{11}^2/\lambda_1,$$

Inert extremum – SM-like Higgs h from φ_S and DM candidate H from φ_D.

$$I_2: v_S = 0, \ \ v_D^2 = v^2 = m_{22}^2/\lambda_2,$$

Inert-like extremum – with massless fermions (Model I) and no candidate for DM.

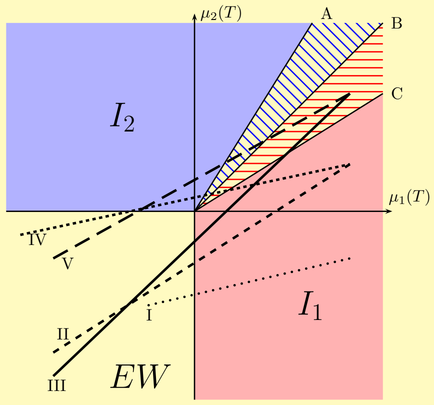
$$M: v_D, v_S \neq 0,\ v^2 = v_S^2 + v_D^2,$$

Mixed extremum – the standard 2HDM type of extremum.
The extremum with lowest energy is the ground state of the system – the vacuum.

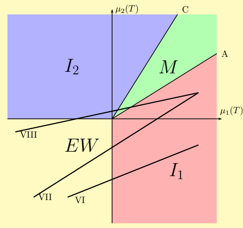
Possible sequences leading to Inert phase today

The possible sequences of phase transitions (different vacua) on (μ_1, μ_2) plane :

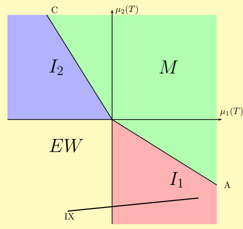
$$\mu_1(T) = m_{11}^2(T)/\sqrt{\lambda_1}, \quad \mu_2(T) = m_{22}^2(T)/\sqrt{\lambda_2}, \quad R = \lambda_{345}/\sqrt{\lambda_1\lambda_2}, \quad \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5.$$



a) $R > 1$



b) $0 < R < 1$



c) $-1 < R < 0$

red hatch – I_1 vacuum and I_2 local minimum, blue hatch – I_2 vacuum and I_1 local minimum;
$A: \mu_2(T) = \mu_1(T)R, \quad B: \mu_2(T) = \mu_1(T), \quad C: \mu_2(T) = \mu_1(T)R^{-1}.$

The possible sequences ("rays") that start in EW symmetric phase: $\mu_1(T), \mu_2(T) < 0$ and lead to the Inert phase (**I_1 being the global minimum**) today:

***EW $\to$ I$_1$*:**

- rays **I, VI, IX** – I_2 is not an extremum. For $R < 0$ ray **IX** is the only possible ray which corresponds to EW symmetry in the past
- rays **II, VII** – I_2 is an extremum, but never was a (local) minimum
- ray **III** – I_2 is a local minimum, but never was a global minimum

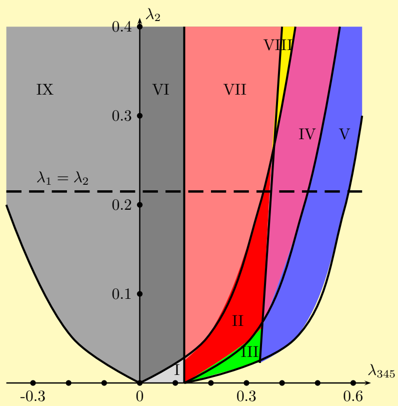
***EW $\to$ I$_2$ $\to$ I$_1$*:**

- ray **IV** – I_2 is not a local minimum, but was a global minimum in the past
- ray **V** – I_2 is a local minimum, it was a global minimum in the past

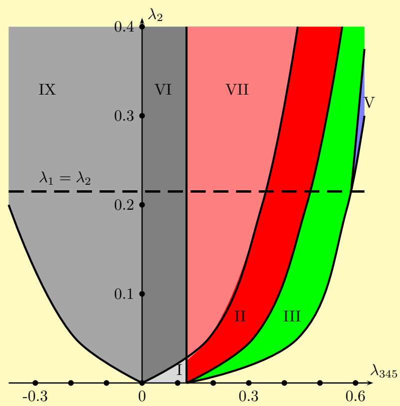
***EW $\to$ I$_2$ $\to$ M $\to$ I$_1$*:**

- ray **VIII** – I_2, M were global minima in the past

Example ($M_h = 120$ GeV, $M_H = 60$ GeV, $M_A = 68$ GeV, $M_{H^\pm} = 110$ GeV):



d) $(\lambda_{345}, \lambda_2)$ plot **with** fermions



e) $(\lambda_{345}, \lambda_2)$ plot **without** fermions

The different sequences (rays I-IX) leading to Inert phase with **Dark Matter particle *H***.
Fermionic contribution important! For example, for $\boldsymbol{\lambda_2 \leq \lambda_1}$ different type of vacuum in the past possible only if the fermionic part of $\boldsymbol{c_1}$ included.

References

[1] I. Ginzburg, I. Ivanov, K. Kanishev, *The Evolution of vacuum states and phase transitions in 2HDM during cooling of Universe*, Phys.Rev.D81:085031,2010

[2] I. Ginzburg, K. Kanishev, M. Krawczyk, D. Sokołowska *Evolution of the Universe to the present Inert phase*, (in prep.)