

On IDM, dark matter and evolution of the Universe

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collaboration with I.F. Ginzburg , K.A. Kanishchev and M. Krawczyk
[Phys.Rev.D82:123533,2010, arXiv:hep-ph/1009.5099, 1104.3326, 1107.1991]

Motivation

T.D. Lee, '73; Deshpande, Ma, '78

Barbieri, Hall, Rychkov '06; Cao, Ma, Rajasekaran '07

Two Higgs Doublet Model (2HDM):

- two scalar $SU(2)_W$ doublets Φ_S, Φ_D with the same hypercharge $Y = 1$
- CP violation in the scalar sector (explicit or spontaneous violation)
- different types of extrema (possible violation of $U(1)_{EM}$)
 \Rightarrow evolution of vacuum state in the past
- 2HDM with an exact Z_2 symmetry: Inert Doublet Model (IDM)
 \rightarrow candidate for the dark matter
- Testing Inert Doublet Model:
 - properties of SM-like Higgs h_S (light and heavy)
 - properties of dark scalars D_H, D_A, D^\pm
 - collider constraints
 - astrophysical data

2HDM

We consider scalar potential V with an explicit D -symmetry of Z_2 type:

$$D : \quad \Phi_S \rightarrow \Phi_S, \quad \Phi_D \rightarrow -\Phi_D, \quad \text{SM fields} \rightarrow \text{SM fields}$$

$$V = -\frac{1}{2} \left[m_{11}^2 \Phi_S^\dagger \Phi_S + m_{22}^2 \Phi_D^\dagger \Phi_D \right] + \frac{1}{2} \left[\lambda_1 \left(\Phi_S^\dagger \Phi_S \right)^2 + \lambda_2 \left(\Phi_D^\dagger \Phi_D \right)^2 \right] \\ + \lambda_3 \left(\Phi_S^\dagger \Phi_S \right) \left(\Phi_D^\dagger \Phi_D \right) + \lambda_4 \left(\Phi_S^\dagger \Phi_D \right) \left(\Phi_D^\dagger \Phi_S \right) + \frac{1}{2} \lambda_5 \left[\left(\Phi_S^\dagger \Phi_D \right)^2 + \left(\Phi_D^\dagger \Phi_S \right)^2 \right]$$

- All parameters $\in \mathbf{R}$ – no CP violation
- Model I – only Φ_S couples to fermions

The positivity constraints are required to have a stable vacuum:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad R + 1 > 0, \quad R_3 + 1 > 0$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad R = \lambda_{345} / \sqrt{\lambda_1 \lambda_2}, \quad R_3 = \lambda_3 / \sqrt{\lambda_1 \lambda_2}$$

Positivity constraints \rightarrow extremum with the lowest energy is
the global minimum (vacuum).

Other constraints: perturbativity, unitarity

Spontaneous Symmetry Breaking

The EW symmetric extremum:

$$\langle \Phi_S \rangle = \langle \Phi_D \rangle = 0$$

local minimum if $m_{11,22}^2 < 0$.

Barroso et al., '05

The general type of EWSB v.e.v:

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

$u \neq 0 \implies U(1)_{EM}$ broken:

- charge breaking extremum (Ch)

$u = 0 \implies U(1)_{EM}$ conserved:

- $v_{S,D} \neq 0$ neutral mixed extremum (M)
- $v_D = 0$ neutral inert extremum (I_1)

Deshpande, Ma, '78; Barbieri, Hall, Rychkov, '06

- $v_S = 0$ neutral inertlike extremum (I_2)

Extrema: charge breaking and mixed

Charge breaking extremum Ch :

$$\langle \Phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ 0 \end{pmatrix}$$

- $U(1)_{EM}$ symmetry broken by $u \neq 0$ – **massive photon**
- not a case that is realized now, **a possible vacuum in the past if**

$$\lambda_4 \pm \lambda_5 > 0, \quad R_3 < 1$$

- requires a charged “dark matter” particle – excluded

Ginzburg, Kanishchev, Krawczyk, Sokolowska '10

Mixed extremum M :

$$\langle \Phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}$$

- **CP conserving**, $\tan \beta = v_D/v_S$
- **massive Z^0, W^\pm , massless photon**, 5 physical Higgs bosons H^\pm, A, H, h
- no DM candidate

$$R < 1, \quad \lambda_4 + \lambda_5 < 0, \quad \lambda_5 < 0$$

Extrema: inert and inertlike

Deshpande, Ma, '78, Barbieri et al., '06

Inert extremum I_1 :

$$\langle \Phi_S \rangle = \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \quad \langle \Phi_D \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- Φ_S as in SM (SM-like Higgs boson h_S)
- Φ_D – ”dark” or inert doublet with 4 dark scalars (D_H, D_A, D^\pm), no interaction with fermions
- **exact D -symmetry** – both in Lagrangian and in the extremum
- only Φ_D has odd D -parity
 - **the lightest scalar is a candidate for the dark matter**

Inertlike extremum I_2 :

$$\langle \Phi_S \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad \langle \Phi_D \rangle = \begin{pmatrix} 0 \\ v_D \end{pmatrix}$$

- Φ_S and Φ_D exchange roles
- fermions massless at tree-level (Model I, only Φ_S couples to fermions)
- no DM candidate

Evolution of the Universe

Ivanov '08; Ginzburg, Kanishchev, Ivanov '09

Ginzburg, Kanishchev, Krawczyk, Sokołowska '10

- we assume that today **Inert Model** is realized, however, in the past some other extrema could have been lower
- we consider evolution of the Universe due to the thermal corrections to the potential
- At finite T ground state is given by minimum of Gibbs potential:

$$V_G(T) = \text{Tr}(V e^{-H/T}) / \text{Tr}(e^{-H/T}) \equiv V(T=0) + \Delta V(T)$$

- $\Delta V(T)$ – leading corrections $\propto T^2$ given by diagrams:



\Rightarrow fixed quartic terms, quadratic (mass) terms change with T

$$\Delta V(T) = \frac{1}{2} c_1 T^2 \Phi_S^\dagger \Phi_S + \frac{1}{2} c_2 T^2 \Phi_D^\dagger \Phi_D$$

Evolution of the Universe

From scalar, **bosonic** and **fermionic** contributions to $\Delta V \rightarrow m_{ii}^2(T)$:

$$m_{11}^2(T) = m_{11}^2 - c_1 T^2, \quad m_{22}^2(T) = m_{22}^2 - c_2 T^2$$

$$c_1 = \frac{3\lambda_1 + 2\lambda_3 + \lambda_4}{6} + \frac{3g^2 + g'^2}{8} + \frac{g_t^2 + g_b^2}{2}, \quad c_2 = \frac{3\lambda_2 + 2\lambda_3 + \lambda_4}{6} + \frac{3g^2 + g'^2}{8}$$

- **fermionic contribution** in c_1 (Model I)
- $c_1 + c_2 > 0$ from positivity constrains
- c_1 and c_2 **positive** to restore EW symmetry in the past

For a given T we determine:

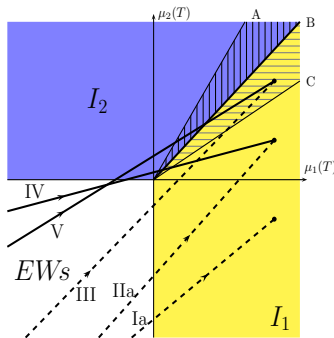
- sign of $v_i^2|_{I_1, I_2, M} \rightarrow$ possible existence of a given extremum
- values of λ_i (fixed) \rightarrow existence of a given local minimum
- value of **extremum energy** \rightarrow global minimum

\Rightarrow **sequences of possible phase transitions**

Possible rays

The possible sequences of phase transitions (**rays**) on $(\mu_1(T), \mu_2(T))$ plane:

$$\mu_1(T) = m_{11}^2(T)/\sqrt{\lambda_1}, \quad \mu_2(T) = m_{22}^2(T)/\sqrt{\lambda_2}.$$



$R > 1$

horizontal hatch – I_1 global, I_2 local min,
vertical hatch – I_2 global, I_1 local min;

$$A : \mu_2(T) = \mu_1(T)R,$$

$$B : \mu_2(T) = \mu_1(T),$$

$$C : \mu_2(T) = \mu_1(T)/R$$

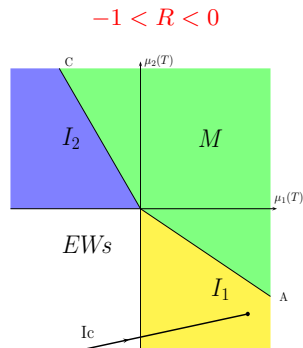
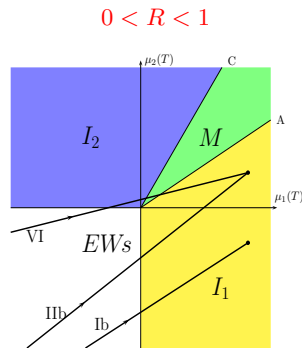
$EWs \rightarrow I_1$

- ray **Ia** – I_2 is not an extremum
- ray **IIa** – 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

$EWs \rightarrow I_2 \rightarrow I_1$

- 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

Possible rays



$$EWs \rightarrow I_1$$

- rays **Ib**, **Ic** – I_2 is not an extremum
- rays **IIb** – I_2 is an extremum, but never was a (local) minimum

$$EWs \rightarrow I_2 \rightarrow M \rightarrow I_1$$

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

Physical parameters

$$(\mu_1, \mu_2, R, c_1, c_2) \rightarrow (M_{h_S}, M_{D_H}, M_{D_A}, M_{D^\pm}, \lambda_{345}, \lambda_2)$$

λ_{345} – triple and quartic coupling: $D_H D_H h_S$ and $D_H D_H h_S h_S$

- main annihilation channel $D_H D_H \rightarrow h_S \rightarrow f \bar{f}$:

$$\sigma \propto \lambda_{345}^2 / (M_{D_H}^2 - M_{h_S}^2)^2 \Rightarrow \text{constraints from relic density data}$$

- DM-nucleon elastic scattering via h_S :

$$\sigma_{DM,N} \propto \lambda_{345}^2 / (M_{D_H} + M_N)^2 \Rightarrow \text{direct detection experiments}$$

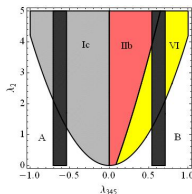
λ_2 – quartic self-coupling $D_H D_H D_H D_H$

- no influence on DM relic density
- non-accessible in the colliders
- limits λ_{345} through positivity constraints

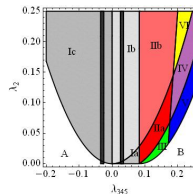
$(\lambda_{345}, \lambda_2)$ phase space

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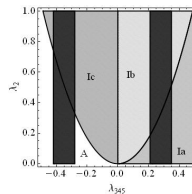
- **fixed** scalar masses, λ_{345} and λ_2 vary
- conditions for $(\mu_1, \mu_2) \rightarrow$ conditions for $(\lambda_{345}, \lambda_2)$
- each ray in separate region
- change of $M_{D_H} \rightarrow$ different rays possible



low DM mass



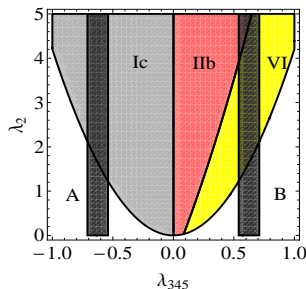
medium DM mass



high DM mass

Low DM mass region

- low DM mass $M_{D_H} \approx (3 - 8)$ GeV
- large mass splittings: $M_{D_A} \approx M_{D^\pm} \approx 100$ GeV
- no coannihilation
- fits DAMA/Libra and CoGent signal, mimics singlet DM
- recent XENON100 data – excluded by direct detection measurements



- limited number of rays
- large λ_2 needed, rather large λ_{345}
- T of final phase transition lower for large $\lambda_{345} \Rightarrow$ next order of correction to V needed

A – excluded by positivity constraints

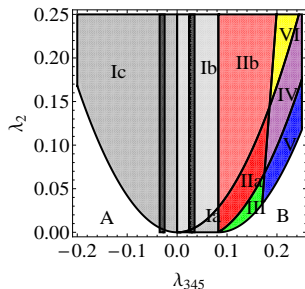
B – I_2 is a global minimum

vertical bounds – WMAP-allowed region

$$M_{D_H} = 5 \text{ GeV}, M_{D_A} = 105 \text{ GeV}, M_{D^\pm} = 110 \text{ GeV}, M_{h_S} = 120 \text{ GeV}$$

Medium DM mass region

- medium DM mass $M_{D_H} \approx (45 - 160)$ GeV
- large (D_H, D^\pm) mass splittings: $M_{D^\pm} - M_{D_H} \approx (50 - 90)$ GeV
 - **large** (D_H, D_A) mass splitting: $M_{D_A} - M_{D_H} \approx (50 - 90)$ GeV
 \Rightarrow **no coannihilation**
 - **small** (D_H, D_A) mass splitting: $M_{D_A} - M_{D_H} < 8$ GeV
 \Rightarrow **coannihilation**



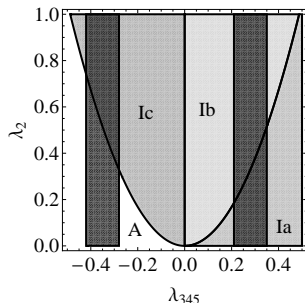
- **all rays possible** for all masses
- $\Omega_{DM} h^2$: strong dependence on M_{D_H} and $(M_{D_A} - M_{D_H})$
- for rays VI, IV, V – low T of final phase transition possible
- **rays IV and V – 1st order phase transition**

A – excluded by positivity constraints
 B – I_2 is a global minimum
 vertical bounds – WMAP-allowed region

$$M_{D_H} = 50 \text{ GeV}, M_{D_A} = 120 \text{ GeV}, M_{D^\pm} = 120 \text{ GeV}, M_{h_S} = 120 \text{ GeV}$$

High DM mass region

- high DM mass $M_{D_H} \approx (500 - 1000)$ GeV
- **small mass splittings:** $M_{D_H} \approx M_{D_A} \approx M_{D^\pm}$
- **coannihilation between all dark particles**
- only light Higgs h_S possible (EWPT)



- **only rays Ia, Ib, Ic**
- other rays require $\lambda \approx O(20)$
- further limits from unitarity

A – excluded by positivity constraints
vertical bounds – WMAP-allowed region

$$M_{D_H} = 800 \text{ GeV}, M_{D_A} = 801 \text{ GeV}, M_{D^\pm} = 801 \text{ GeV}, M_{h_S} = 120 \text{ GeV}$$

Conclusions

- Today – Inert Model (dark matter).
- Different types of extrema can be realized in the past.
- Possible sequences of phase transitions:

$$EWs \rightarrow I_2 \rightarrow M \rightarrow I_1$$

$$EWs \rightarrow I_2 \rightarrow I_1$$

$$EWs \rightarrow I_1$$

- λ_2 important for the evolution.
- Different behaviour for low, medium and high DM mass region.
- Need for the further corrections to V .