Dark Matter in multi-inert doublet models

Venus Keus

University of Helsinki & Helsinki Institute of Physics

Based on
and work in progress
with
S. King & S. Moretti & D. Sokolowska
J. Hernandez & A. Cordero & D. Rojas

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1 Introduction and motivation

2 I(1+1)HDM: the Inert doublet model

3 I(2+1)HDM: extending the Inert doublet model

4 Conclusions and outlook
Higgs particle discovered

- 2012 – a Higgs boson discovered at the LHC
  
  \[ \text{ATLAS: } M_h = 125.36 \text{ GeV} \]
  \[ \text{CMS: } M_h = 125.03 \text{ GeV} \]

- very SM-like

- yet we do expect some New Physics to exist
  
  - Dark Matter
  - baryon asymmetry and baryogenesis
  - extra source of CP violation
  - vacuum stability
  - ...

Dark Matter (DM)

around 25 % of the Universe is:

- cold
- non-baryonic
- neutral
- very weakly interacting

⇒ Weakly Interacting Massive Particle

- stable due to the discrete symmetry

\[
\begin{align*}
\text{DM} & \rightarrow \text{SM, } \text{pair annihilation} \\
\text{DM} & \not\rightarrow \text{SM, } \text{stable}
\end{align*}
\]
Higgs-portal DM

Simplest realisation: the SM with $\Phi_{SM} + Z_2$-odd scalar $S$:

$$S \rightarrow -S, \quad \text{SM fields} \rightarrow \text{SM fields}$$

$$L = L_{SM} + \frac{1}{2} (\partial S)^2 - \frac{1}{2} m_{DM}^2 S^2 - \lambda_{DM} S^4 - \lambda_{hDM} \Phi_{SM}^2 S^2$$

Higgs-portal interaction:

![Diagram showing Higgs-portal interaction]

given by the same coupling
The Inert Doublet Model

$I(1+1)\text{HDM}$

2HDM with 1 Inert and 1 Higgs doublet
A two Higgs Doublet Model

Two Higgs Doublet Model (2HDM):

- two scalar $SU(2)_W$ doublets $\Phi_1, \Phi_2$ with the hypercharge $Y = +1$
- rich phenomenology: different types of vacua, hierarchy in Yukawa couplings, CP violation in the scalar sector, baryogenesis, ...

- a 2HDM with an exact $Z_2$ symmetry: the Inert Doublet Model
  $\rightarrow$ SM-like Higgs boson
  $\rightarrow$ a Dark Matter candidate
The Inert Doublet Model

Scalar potential $V$ invariant under a $Z_2$-transformation:

$$
Z_2 : \quad \Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2, \quad \text{SM fields} \rightarrow \text{SM fields}
$$

$$
V = -\frac{1}{2} \left[ m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 \right] + \frac{1}{2} \left[ \lambda_1 \left( \Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left( \Phi_2^\dagger \Phi_2 \right)^2 \right]
+ \lambda_3 \left( \Phi_1^\dagger \Phi_1 \right) \left( \Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left( \Phi_1^\dagger \Phi_2 \right) \left( \Phi_2^\dagger \Phi_1 \right) + \frac{1}{2} \lambda_5 \left[ \left( \Phi_1^\dagger \Phi_2 \right)^2 + \left( \Phi_2^\dagger \Phi_1 \right)^2 \right]
$$

- The potential is explicitly $Z_2$-symmetric
- Only $\Phi_1$ couples to fermions
- All parameters are real – no CP violation
The Inert minimum

\[ \langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix} \]

- The whole Lagrangian is explicitly \( Z_2 \)-symmetric
- \( \Phi_1 \) – active as in SM (SM-like Higgs boson \( h \))
- \( \Phi_2 \) “dark” or inert doublet with 4 dark scalars \((H, A, H^\pm)\), no interaction with fermions
- only \( \Phi_2 \) has odd \( Z_2 \)-parity
  \[\rightarrow \] the lightest scalar is a candidate for the dark matter

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Constraints

(1) **Vacuum stability**: scalar potential $V$ bounded from below

(2) **Existence of the Inert vacuum**: a *global* minimum of $V$

(3) **Perturbative unitarity**: eigenvalues $\Lambda_i$ of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$

(4) **Higgs mass**: $M_h = 125$ GeV

\[
(1) - (4) \Rightarrow m_{22}^2 \lesssim 9 \cdot 10^4 \text{ GeV}^2, \quad \lambda_1 = 0.258, \quad \lambda_2 < 8.38, \quad \lambda_3, \lambda_{345} > -1.47,
\]

(5) **EWPT & LEP**: bounds on masses of the scalars

\[
M_{H^\pm} \gtrsim 70 - 90 \text{ GeV}
\]

\[
\delta_A = M_A - M_H < 8 \text{ GeV} \Rightarrow M_H + M_A > M_Z
\]

excluded: $M_H < 80$ GeV, $M_A < 100$ GeV and $\delta_A > 8$ GeV
Relic density constraints

(6) **$H$ as DM candidate:** $M_H < M_A, M_{H \pm}$ with proper $\Omega_{DM} h^2$

$$0.1118 < \Omega_{DM} h^2 < 0.128$$

$$\lambda_{345} \sim g_{HHh} \text{ and } M_i$$

- **Strongly constrained by LHC and DD:**
  - low DM mass $M_H \lesssim 10$ GeV, $\lambda_{345} \sim \mathcal{O}(0.5)$
  - medium DM mass $M_H \approx (40 - 160)$ GeV, $\lambda_{345} \sim \mathcal{O}(0.05)$

- **DD sensitivity very low:**
  - high DM mass $M_H \gtrsim 500$ GeV, $\lambda_{345} \sim \mathcal{O}(0.1)$
LHC constraints from $h \rightarrow \gamma\gamma$

- $h\gamma\gamma$ not present at tree level
- At loop level in the SM

In the IDM – additional $H^\pm$

- Experiment: signal strength $R_{\gamma\gamma} \approx 1$
Summary of the I(1+1)HDM

\[ Br(h \rightarrow \text{inv}) + R_{\gamma\gamma} + \Omega_{DM} h^2 \Rightarrow \text{strong limits on IDM} \]

- Low DM mass excluded
- \( M_H < M_h/2 \Rightarrow R_{\gamma\gamma} > 1 \)
- \( M_h/2 < M_H < M_W \ & H \text{ constitutes } 100\% \text{ of DM} \Rightarrow R_{\gamma\gamma} < 1 \)
- Heavy DM \Rightarrow R_{\gamma\gamma} \approx 1
Extending the Inert doublet model

I(2+1)HDM

3HDM with 2 Inert and 1 Higgs doublet
Three-Higgs Doublet Models (3HDMs)

Three-Higgs Doublet Models:

- three $SU(2)$ doublets, $\phi_1, \phi_2, \phi_3$
  - one Higgs doublet per family
  - with the SM-Higgs doublet quantum numbers

- richer symmetry groups than the 2HDMs
  - discrete, continuous, CP, Generalised CP

- richer particle spectrum
  - 3 scalars, 2 pseudo-scalars, 2 charged
I(2+1)HDM

$Z_2$-symmetry in I(2+1)HDM:

$\phi_1 \rightarrow -\phi_1$, $\phi_2 \rightarrow -\phi_2$, $\phi_3 \rightarrow \phi_3$, SM fields $\rightarrow$ SM fields

$Z_2$-invariant potential:

$$V = \sum_{i}^{3} \left[ -|\mu_i|^2 (\phi_i^\dagger \phi_i) + \lambda_{ii}(\phi_i^\dagger \phi_i)^2 \right]$$

$$+ \sum_{ij}^{3} \left[ \lambda_{ij}(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right]

+ \left( -\mu_{12}^2(\phi_1^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_2)^2 + \lambda_2(\phi_2^\dagger \phi_3)^2 + \lambda_3(\phi_3^\dagger \phi_1)^2 + h.c. \right)$$

- All parameters real
- Only $\phi_3$ couples to fermions
- Explicit $Z_2$-symmetry
DM in I(2+1)HDM

$Z_2$-invariant vacuum state:

$$
\phi_1 = \left( \begin{array}{c} H_1^+ \\ H_0^0 + iA_1^0 \\ \sqrt{2} \end{array} \right), \quad \phi_2 = \left( \begin{array}{c} H_2^+ \\ H_0^0 + iA_2^0 \\ \sqrt{2} \end{array} \right), \quad \phi_3 = \left( \begin{array}{c} G^+ \\ v + h + iG_0^0 \\ \sqrt{2} \end{array} \right)
$$

- $\phi_3$ – SM-like doublet with SM-like Higgs $h$
- $Z_2$-odd doublets $\phi_1$ and $\phi_2$ mix:

$$
H_1 = \cos \alpha_H H_1^0 + \sin \alpha_H H_2^0, \quad H_2 = \cos \alpha_H H_2^0 - \sin \alpha_H H_1^0
$$

(similar for $A_i$ and $H_i^{\pm}$)

- 4 neutral and 2 charged $Z_2$-odd particles (double the IDM)
- $H_1$ – DM candidate, other dark particles heavier
Dark Matter Annihilation

- **annihilation through Higgs into fermions;** dominant channel for $M_{DM} < M_h/2$

- **annihilation to gauge bosons;** crucial for heavier masses

- **coannihilation;** when particles have similar masses
DM Annihilation Scenarios

Low mass region:

(A) **no coannihilation effects:**

$$M_{H_1} < M_{H_2,A_1,A_2,H_1^\pm,H_2^\pm}$$

(D) **coannihilation with** $H_2,A_{1,2}$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} < M_{H_1^\pm,H_2^\pm}$$

Heavy mass region:

(G) **coannihilation with** $H_2,A_{1,2},H_{1,2}^\pm$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} \approx M_{H_1^\pm,H_2^\pm}$$

(H) **coannihilation with** $A_1,H_1^\pm$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_1^\pm} < M_{H_2,A_2,H_2^\pm}$$
LHC vs Planck $M_{DM} < M_h/2$

- $\frac{1}{2} M_{DM} < M_h$

**Case A**: $M_{DM} \gtrsim 53 \text{ GeV}$

- $\text{Br}(h \rightarrow \text{inv}) < 37\%$ & $\Omega_{DM} h^2 \Rightarrow$

**Case D**: most masses are OK
Planck constraints: $M_{DM} > M_h/2$

Relic density values are dominated by three couplings:

$g_{DMVV}$, $g_{hVV}$, $g_{H_1H_1h}$
Direct detection limits

Case D: new region in agreement with LUX with respect to Case A
Heavy mass regime $M_{DM} > M_W$

- **case H** – like the I(1+1)DM: $M_{H_1} \gtrsim 525$ GeV
- **case G** – new region: $M_{H_1} \gtrsim 360$ GeV
Direct detection limits

Case G: new region in agreement with LUX with respect to Case H
LHC signals: monojet channels

Monojet channels \( gg \rightarrow g H_1 H_1, \ q\bar{q} \rightarrow g H_1 H_1, \ qg \rightarrow q H_1 H_1 \)

![Graph showing cross section \( \sigma \) vs. mass \( m_{H_1} \)]
LHC signals: dijet channels

- Vector Boson Fusion: \( q_i q_j \rightarrow H_1 H_1 q_k q_l \)
- Higgs-Strahlung: \( q_i \bar{q}_j \rightarrow V^* H_1 H_1 \)

HS: charged channels

![Graph showing the cross-section in HS processes in terms of the DM mass.](image)
### Summary

- **I(1+1)DM**
  - a good DM model with rich phenomenology, however, *very constrained*.

- **I(2+1)HDM**
  - viable DM candidate
  - large dark sector
    - In the light mass region: $46 \text{ GeV} \lesssim m_{DM} \lesssim 62 \text{ GeV}$
    - In the heavy mass region: $360 \text{ GeV} \lesssim m_{DM} \lesssim 525 \text{ GeV}$
  - Observable at the LHC
Outlook

- **CP-Violation in I(2+1)HDM**
  - SM-like active sector: \( H_3 \equiv h^{SM} \)
  - CPV in the inert sector: \( H_{1,2}, A_{1,2} \rightarrow S_{1,2,3,4} \) CPV DM
  - New observables at the LHC: \( S_i S_j Z \) vertices

- **CP-Violation in I(1+2)HDM**
  - IDM-like inert sector: CPC DM
  - CPV in the active sector: \( \tilde{H}_1, \tilde{H}_2, \tilde{H}_3 \)
  - Interesting LHC phenomenology
CP-mixed DM

![Relic density constraints graph]

**Case A**
- Excluded

**Preliminary**

-M$_{S_1}$ [GeV]
BACKUP SLIDES
Indirect searches

- **I(1+1)HDM:** indirect detection signatures: internal bremsstrahlung in the processes of $H_1 H_1 \rightarrow W^+ W^- \gamma$ mediated by a charged scalar in the $t$-channel.

- **I(2+1)HDM**
  same signature generated through the exchange of any of the two charged scalars $H_1^\pm$.

The signal could even be **stronger for scenario G** with **larger** scalar couplings.
LHC signals: monojet channels $pp \rightarrow H_1 H_1 + \text{jet}$
LHC signals: dijet channels $pp \rightarrow H_1 H_1 + 2$ jets

![VBF diagrams with dijet final states](image)
Low DM mass

\[ M_H \lesssim 10 \text{ GeV}, \quad M_A \approx M_{H\pm} \approx 100 \text{ GeV} \]

\( h \to AA \) channel closed, \( h \to HH \) channel open

main annihilation channel: \( HH \to h \to b\bar{b} \)

- Correct relic density

\[ 0.1118 < \Omega_{DM} h^2 < 0.128 \Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5) \]

- CDMS-II reported event:

\[ M_H = 8.6 \text{ GeV} \Rightarrow |\lambda_{345}| \approx (0.3 - 0.4) \]

- \( Br(h \to inv) \lesssim 0.4 \Rightarrow |\lambda_{345}| \lesssim 0.02 \)

Low DM mass excluded
Medium DM mass – $HH$ channel open

\[ 50 \text{ GeV} < M_H < M_h/2 \text{ GeV}, \quad M_A = M_{H^\pm} = 120 \text{ GeV} \]

Red bound: $\Omega_{DM} h^2$ in agreement with Planck

Black line: $Br(h \rightarrow inv) \approx 0.4$
Medium DM mass – $HH$ channel closed

\[ \frac{M_h}{2} < M_H < 83 \text{ GeV}, \quad M_A = M_{H^\pm} = M_H + 50 \text{ GeV} \]

Red bound: $\Omega_{DM} h^2$ in agreement with Planck
High DM mass

\[ M_H \gtrsim 550 \text{ GeV}, \quad M_A = M_{H\pm} = M_H + 1 \text{ GeV} \]

Red bound: \( \Omega_{DM} h^2 \) in agreement with Planck
The ratio of decay rates of $\tilde{H}_1$ to those of the SM Higgs boson $h_{SM}$ as a function of $\lambda_5^i$. 

\[ \sin(\beta-\alpha) = 1 \]
\[ \tan \beta = 5 \]

\[ \tan \beta = 10 \]
The ratio of decay rates of $\tilde{H}_1$ to those of the SM Higgs boson $h_{SM}$ as a function of $\lambda_5^i$. 

\[\sin(\beta - \alpha) = 0.98\]
\[\tan\beta = 5\]
\[\tan\beta = 10\]
The coefficient of the gauge-gauge-scalar type couplings as a function of $\lambda_5^i$. 

$\sin(\beta - \tilde{\alpha}) = 1$
$\tan\beta = 5$

$\sin(\beta - \tilde{\alpha}) = 1$
$\tan\beta = 10$
The coefficient of the gauge-gauge-scalar type couplings as a function of $\lambda_5^i$. 

\[\sin(\beta-\alpha) = 0.98\]
\[\tan \beta = 5\]

\[\sin(\beta-\alpha) = 0.98\]
\[\tan \beta = 10\]