# Investigating stability of the inert vacuum in the light of the LHC and Planck results

Bogumiła Świeżewska

Faculty of Physics, University of Warsaw

03.09.2014
Lisbon, Portugal

Workshop on Multi-Higgs Models

in collaboration with M. Krawczyk, D. Sokołowska, P. Swaczyna,
PRD 88 (2013) 035019, PRD 88 (2013) 055027, JHEP 09 (2013) 055
**work in progress**

# Why Inert Doublet Model?

- Simple extension of the SM with two $SU(2)$ doublets
- Rich phenomenology

# Why Inert Doublet Model?

- Simple extension of the SM with two $SU(2)$ doublets
- Rich phenomenology
  - SM-like Higgs boson


from PhD comics

# Why Inert Doublet Model?

- Simple extension of the SM with two $SU(2)$ doublets
- Rich phenomenology
  - **SM-like Higgs boson**
  - **Viable DM candidate**


from PhD comics


from particlezoo.net

# Why Inert Doublet Model?

- Simple extension of the SM with two $SU(2)$ doublets
- Rich phenomenology
  - **SM-like Higgs boson**
  - **Viable DM candidate**
- Thermal evolution of the Universe + some conditions for baryogenesis (strong first-order PT for $275\,\mathrm{GeV} \lesssim M_{H^\pm}, M_A \lesssim 380\,\mathrm{GeV},\ M_H \sim 65\,\mathrm{GeV}$)
  [P. Chankowski, G. Gil, M. Krawczyk, PLB 717 (2012) 396-402]

from PhD comics

from particlezoo.net

# Inert Doublet Model (IDM)

[N. G. Deshpande, E. Ma, PRD 18 (1978) 2574, J. F. Gunion, H. E. Haber, G. Kane, S. Dawson, *The Higgs Hunter's Guide*, 1990 Addison-Wesley, R. Barbieri, L. J. Hall, V. S. Rychkov, PRD 74 (2006) 015007, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, PRD 82 (2010) 123533]

IDM – a 2HDM with the scalar potential (real parameters) for $\phi_S$ and $\phi_D$ doublets:

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

- $\mathbb{Z}_2$-type symmetry **D**: $\phi_D \to -\phi_D$, $\phi_S \to \phi_S$
- Yukawa interactions: type I (only $\phi_S$ couples to fermions)
- $\mathcal{L}$ – **D-symmetric**
- **D-symmetric vacuum state** $\langle\phi_S\rangle = \frac{v}{\sqrt{2}}$, $\langle\phi_D\rangle = 0$

$\Rightarrow$ **EXACT D-symmetry**

# Particle spectrum of IDM

[E. M. Dolle, S. Su, Phys. Rev. D 80 (2009) 055012, L. Lopez Honorez, E. Nezri, F. J. Oliver, M. Tytgat, JCAP 0702 (2007) 028, D. Sokołowska, arXiv:1107.1991 [hep-ph]]


$\phi_S$: $h$ – SM-like Higgs boson

- tree-level couplings to fermions and gauge bosons like in the SM
- **deviation from SM in loop couplings possible!**

# Particle spectrum of IDM

[E. M. Dolle, S. Su, Phys. Rev. D 80 (2009) 055012, L. Lopez Honorez, E. Nezri, F. J. Oliver, M. Tytgat, JCAP 0702 (2007) 028, D. Sokołowska, arXiv:1107.1991 [hep-ph]]


$\phi_S$: $h$ – SM-like Higgs boson

- tree-level couplings to fermions and gauge bosons like in the SM
- **deviation from SM in loop couplings possible!**

$\phi_D$: $H$ – scalar, $A$ – pseudoscalar, $H^\pm$ – charged

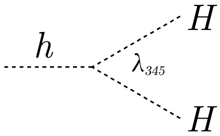
- $D$ symmetry **exact** $\Rightarrow$ lightest $D$-odd particle stable $\Rightarrow$ **DM candidate**
- DM= **H**, so $M_H < M_{H^\pm}, M_A$
- "Higgs portal" DM – coupling to fermions through Higgs

# Constraints

- **Vacuum stability:** positivity, stability of Inert vacuum
- **Perturbative unitarity**: eigenvalues $\Lambda_i$ of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$
- **Electroweak Precision Tests** (EWPT): $S$ and $T$ within $2\sigma$ ($S = 0.03 \pm 0.09$, $T = 0.07 \pm 0.08$, with correlation of 87%)
- **LEP bounds** on the scalars' masses
- **LHC:** $M_H = 125\,\text{GeV}$, $\text{Br}(h \to \text{inv})$, $\Gamma(h)$, $R_{\gamma\gamma}$
- **DM constraints:** Planck results on DM relic density

# Invisible decays of the Higgs boson in the IDM

- $h \to HH$ – invisible decay ($H$ is stable)
- augmented total width of the Higgs boson, $\Gamma(h \to HH) \sim \lambda_{345}^2$

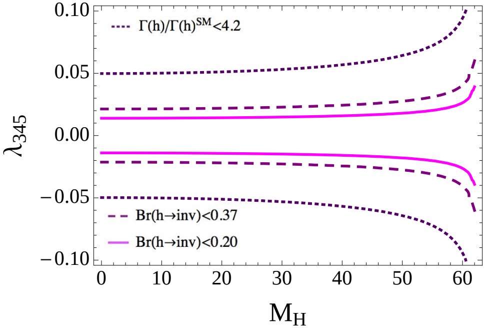



LHC:

- $\mathrm{Br}(h \to \mathrm{inv}) < 37\%$,
- $\Gamma(h)/\Gamma(h)^{\mathrm{SM}} < 4.2$

global fit:

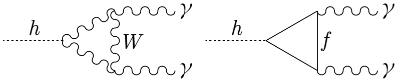
- $\mathrm{Br}(h \to \mathrm{inv}) \lesssim 20\%$



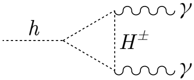

[G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, PLB 723 (2013) 340; ATLAS-CONF-2014-010, 2014; CMS-PAS-HIG-14-002]

# Two-photon decay of the Higgs boson

- At the loop level in the SM




- In the IDM – additional $H^{\pm}$




$\Rightarrow$ **Modified h $\rightarrow \gamma\gamma$ width**

**$R_{\gamma\gamma}$ – signal strength**

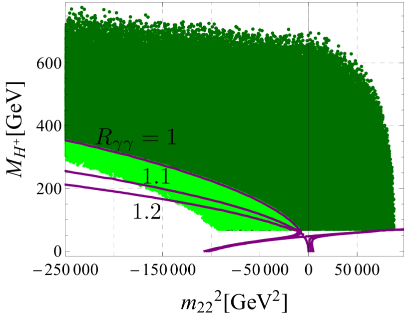
$$R_{\gamma\gamma} = \frac{\sigma(pp \rightarrow h \rightarrow \gamma\gamma)^{IDM}}{\sigma(pp \rightarrow h \rightarrow \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \rightarrow \gamma\gamma)^{IDM}}{\Gamma(h \rightarrow \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}$$

For now: $R_{\gamma\gamma} = 1.17 \pm 0.27$ (ATLAS), $R_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}$ (CMS)

[see the talks by M. Kenzie and S. Laplace at ICHEP 2014; ATLAS CERN-PH-EP-2014-198]

# $R_{\gamma\gamma} > 1$ and the masses of the dark scalars

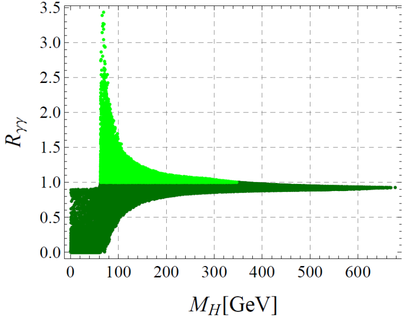
Mass of the charged scalar




If $R_{\gamma\gamma} > 1.2$:

- $M_H,\ M_{H^\pm} \lesssim 154$ GeV.
- **Fairly light charged scalar**

Mass of the DM

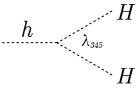


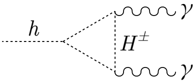

If $R_{\gamma\gamma} > 1$:

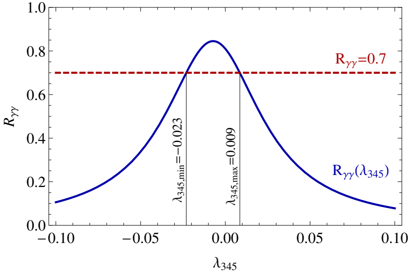
- $M_H > M_h/2$
- **Light** ($\lesssim 63$ GeV) **DM excluded**

[A. Arhrib, R. Benbrik, N. Gaur, PRD 85 (2012) 095021, BŚ, M. Krawczyk, PRD 88 (2013) 035019]

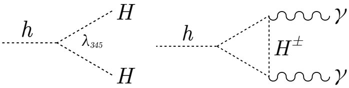
# $R_{\gamma\gamma}$ and relic density

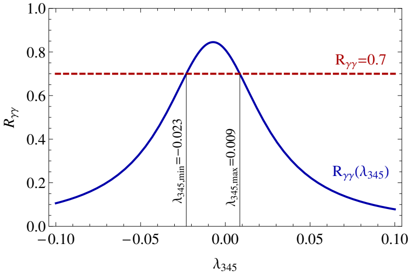


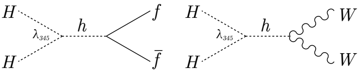



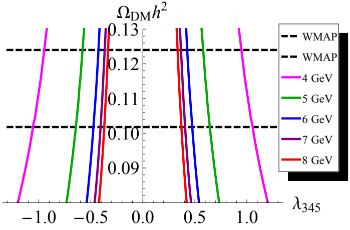



# $R_{\gamma\gamma}$ and relic density

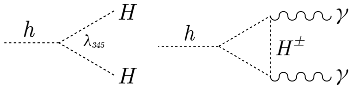



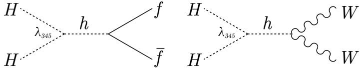



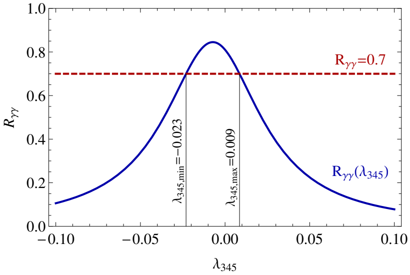



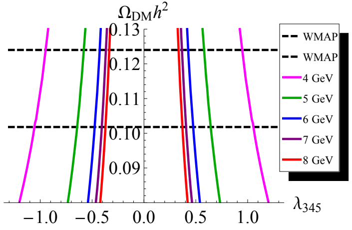

From D. Sokołowska, arXiv:1107.1991

# $R_{\gamma\gamma}$ and relic density



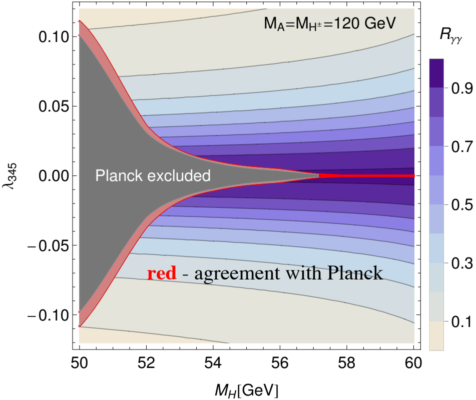

From D. Sokołowska, arXiv:1107.1991

**Does $R_{\gamma\gamma} > 0.7$ agree with the Planck measurements?**

# Results for the DM

[Planck update: D. Sokołowska, P. Swaczyna, 2014]

$h \to HH$ open

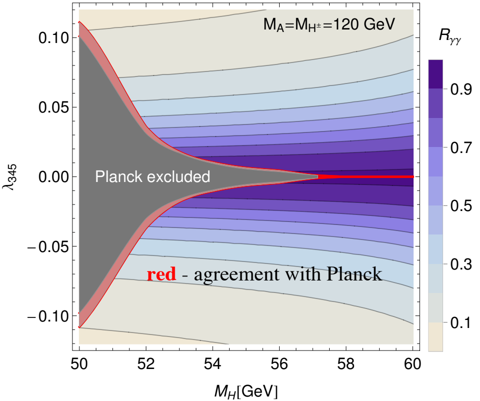



$50\,\mathrm{GeV} < M_H < M_h/2$, $M_A = M_{H^\pm} = 120\,\mathrm{GeV}$

# Results for the DM

[Planck update: D. Sokołowska, P. Swaczyna, 2014]

$h \to HH$ open



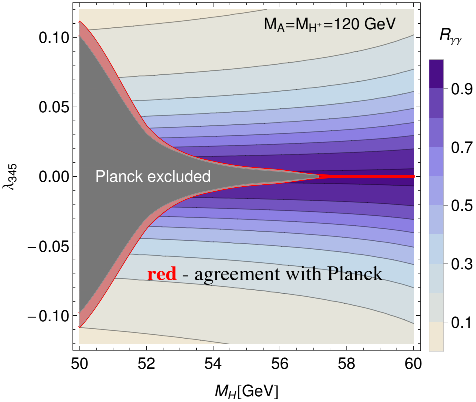

$50\,\mathrm{GeV} < M_H < M_h/2,\ M_A = M_{H^\pm} = 120\,\mathrm{GeV}$

- **intermediate DM 1**
  $(50\,\mathrm{GeV} < M_H < M_H/2)$
  $\Longrightarrow M_H > 53\,\mathrm{GeV}$

# Results for the DM

[Planck update: D. Sokołowska, P. Swaczyna, 2014]

$h \to HH$ open



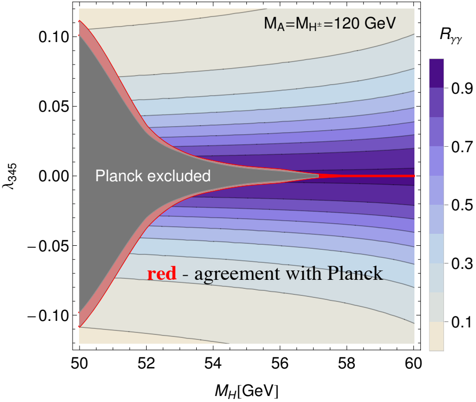

$50\,\text{GeV} < M_H < M_h/2$, $M_A = M_{H^\pm} = 120\,\text{GeV}$

- **light DM** ($M_H < 10\,\text{GeV}$) $\Longrightarrow$ excluded
- **intermediate DM 1** ($50\,\text{GeV} < M_H < M_H/2$) $\Longrightarrow M_H > 53\,\text{GeV}$

# Results for the DM

[Planck update: D. Sokołowska, P. Swaczyna, 2014]

$h \to HH$ open



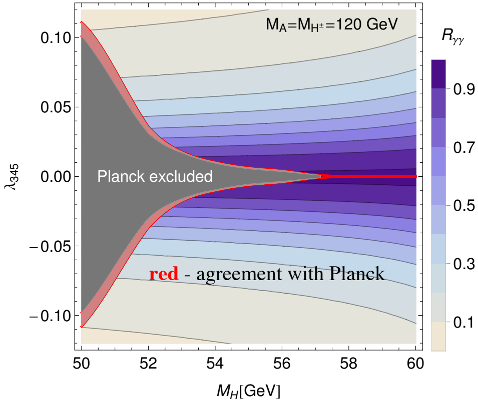

$50\,\mathrm{GeV} < M_H < M_h/2$, $M_A = M_{H^\pm} = 120\,\mathrm{GeV}$

- **light DM** ($M_H < 10\,\mathrm{GeV}$) $\Longrightarrow$ excluded
- **intermediate DM 1** ($50\,\mathrm{GeV} < M_H < M_H/2$) $\Longrightarrow M_H > 53\,\mathrm{GeV}$
- **intermediate DM 2** ($M_h/2 < M_H \lesssim 82\,\mathrm{GeV}$) $\Longrightarrow R_{\gamma\gamma} < 1$

# Results for the DM

[Planck update: D. Sokołowska, P. Swaczyna, 2014]

$h \to HH$ open



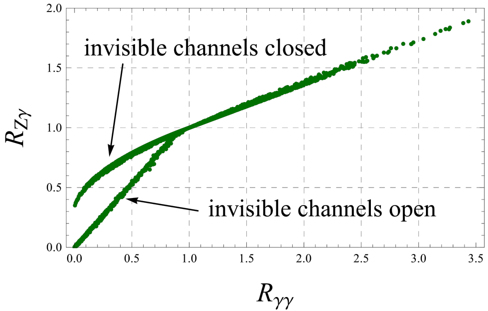

$50\,\text{GeV} < M_H < M_h/2$, $M_A = M_{H^\pm} = 120\,\text{GeV}$

- **light DM** ($M_H < 10\,\text{GeV}$) $\Rightarrow$ excluded
- **intermediate DM 1** ($50\,\text{GeV} < M_H < M_H/2$) $\Rightarrow M_H > 53\,\text{GeV}$
- **intermediate DM 2** ($M_h/2 < M_H \lesssim 82\,\text{GeV}$) $\Rightarrow R_{\gamma\gamma} < 1$
- **heavy DM** ($M_H > 500\,\text{GeV}$) $\Rightarrow R_{\gamma\gamma} \approx 1$

# $h \to \gamma\gamma$ vs $h \to Z\gamma$

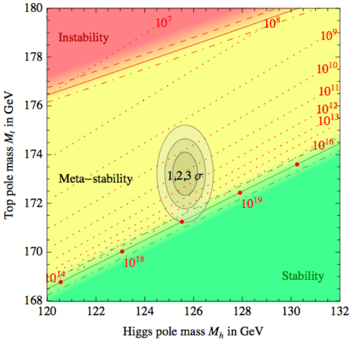
[BŚ, M. Krawczyk, Phys. Rev. D 88 (2013) 035019, formulas for $h \to Z\gamma$: A. Djouadi, Phys.Rept. 459 (2008) 1, C.-S. Chen, C.-Q. Geng, D. Huang, L.-H. Tsai, Phys.Rev.D 87 (2013) 075019]

- Sensitivity to invisible channels
- $R_{\gamma\gamma}$ and $R_{Z\gamma}$ positively correlated
- $R_{\gamma\gamma} > 1 \Leftrightarrow R_{Z\gamma} > 1$



# Vacuum stability – the SM picture

- measurement of the Higgs mass allows to localize the SM in the phase diagram
- SM vacuum – metastable but with long lifetime
- new interactions modify the picture
- what is the impact of additional scalars?




from: Butazzo et al., JHEP 1312 (2013) 089

[see also: V. Branchina et al., PRL 111 (2013) 241801, arXiv:1407.4112, arXiv:1408.5302 ]

# Vacuum stability – the IDM picture

1. $V$ has to be bounded from below

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0,$$

[M. Krawczyk et al., PRD 82 (2010) 123533, see also: A. Barroso et al., JHEP 1306 (2013) 045, J.Phys.Conf.Ser. 447 (2013) 012051, [1305.1235]]

# Vacuum stability – the IDM picture

1. $V$ has to be bounded from below

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0,$$

2. The Inert state has to be a minimum of the potential

$$M^2_{\text{scalar}} \geqslant 0$$

[M. Krawczyk et al., PRD 82 (2010) 123533, see also: A. Barroso et al., JHEP 1306 (2013) 045, J.Phys.Conf.Ser. 447 (2013) 012051, [1305.1235]]

# Vacuum stability – the IDM picture

1. $V$ has to be bounded from below

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0,$$

2. The Inert state has to be a minimum of the potential

$$M^2_{\text{scalar}} \geqslant 0$$

3. The Inert state has to be the **global minimum** of the potential

[M. Krawczyk et al., PRD 82 (2010) 123533, see also: A. Barroso et al., JHEP 1306 (2013) 045, J.Phys.Conf.Ser. 447 (2013) 012051, [1305.1235]]

# Possible extrema of the potential

[N. G. Deshpande, E. Ma, PRD 18 (1978) 2574, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, PRD 82 (2010) 123533, see also: P. M. Ferreira, R. Santos, A. Barroso, Phys.Lett.B 603 (2004), Phys.Lett. B632 (2006) 684-687 ]

**Not realized at present**

EW symmetric, Charge breaking

# Possible extrema of the potential

[N. G. Deshpande, E. Ma, PRD 18 (1978) 2574, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, PRD 82 (2010) 123533, see also: P. M. Ferreira, R. Santos, A. Barroso, Phys.Lett.B 603 (2004), Phys.Lett. B632 (2006) 684-687 ]

## Not realized at present

EW symmetric, Charge breaking

## Mixed extremum (M)

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

"standard" choice for 2HDM (MSSM), no DM candidate

# Possible extrema of the potential

[N. G. Deshpande, E. Ma, PRD 18 (1978) 2574, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, PRD 82 (2010) 123533, see also: P. M. Ferreira, R. Santos, A. Barroso, Phys.Lett.B 603 (2004), Phys.Lett. B632 (2006) 684-687 ]

## Not realized at present

EW symmetric, Charge breaking

## Mixed extremum (M)

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

"standard" choice for 2HDM (MSSM), no DM candidate

## Inert extremum ($I_1$)

$$\langle \phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \langle \phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

our choice, DM candidate

# Possible extrema of the potential

[N. G. Deshpande, E. Ma, PRD 18 (1978) 2574, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, PRD 82 (2010) 123533, see also: P. M. Ferreira, R. Santos, A. Barroso, Phys.Lett.B 603 (2004), Phys.Lett. B632 (2006) 684-687 ]

## Not realized at present

EW symmetric, Charge breaking

## Mixed extremum (M)

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

"standard" choice for 2HDM (MSSM), no DM candidate

## Inert extremum ($I_1$)

$$\langle \phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \langle \phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

our choice, DM candidate

## Inert-like extremum ($I_2$)

$$\langle \phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \langle \phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

massless fermions

# Phase diagram and coexistence of minima

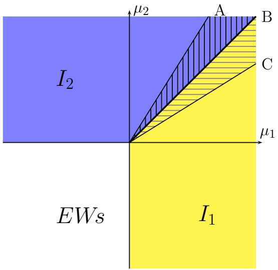
[BŚ, PRD 88 (2013) 055027]

- Inert and Inert-like minima can coexist (at the tree level)
- demand that Inert is global minimum ⇒ compare energies

$$\frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}} \xrightarrow{+\text{constr.}} m_{22}^2 \leqslant 9 \cdot 10^4\,\text{GeV}^2$$

$$(M_h^2 = m_{11}^2 = \lambda_1 v^2)$$

- or possibility of metastability at the tree-level




$R > 1$

from D. Sokołowska, PoS ICHEP2010:457

# Tree-level absolute stability and phenomenology

[B.Ś., M. Krawczyk, PRD 88 (2013) 035019]

If invisible channels closed $R_{\gamma\gamma} > 1$ can be solved analytically.

- **Constructive interference**
  - $m_{22}^2 < -2M_{H^\pm}^2$
  - with LEP bound on $M_{H^\pm}$ $\Rightarrow m_{22}^2 < -9.8 \cdot 10^3\,\mathrm{GeV}^2$
- **Destructive interference**
  - IDM contribution $\geqslant 2\times$ SM contribution
  - big $m_{22}^2$ required: $m_{22}^2 \gtrsim 1.8 \cdot 10^5\,\mathrm{GeV}^2$
  - **excluded by the condition for the Inert vacuum** $m_{22}^2 \lesssim 9 \cdot 10^4\,\mathrm{GeV}^2$

$\Rightarrow$ for $m_{22}^2 \gtrsim 9 \cdot 10^4\,\mathrm{GeV}^2$ Inert and Inert-like minima can coexist – **necessary computation of the Inert vacuum lifetime**

# Stability beyond tree-level – work in progress

- *common sense:* "scalar contribution to the effective potential is positive, so IDM vacuum should be more stable than in the SM" – is it true?

# Stability beyond tree-level – work in progress

- *common sense:* "scalar contribution to the effective potential is positive, so IDM vacuum should be more stable than in the SM" – is it true?
- *simple approach:* consider the tree level positivity conditions with running couplings inserted

$$\lambda_1(\mu) > 0, \quad \lambda_2(\mu) > 0, \quad \lambda_3(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)} > 0,$$

$$\lambda_{345}(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)} > 0,$$

$\Longrightarrow$ the instability scale is higher than in the SM

[A. Goudelis, B. Herrmann, O. Stål, JHEP 09 (2013) 106]

# Stability beyond tree-level – work in progress

- *common sense:* "scalar contribution to the effective potential is positive, so IDM vacuum should be more stable than in the SM" – is it true?
- *simple approach:* consider the tree level positivity conditions with running couplings inserted

$$\lambda_1(\mu) > 0, \quad \lambda_2(\mu) > 0, \quad \lambda_3(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)} > 0,$$

$$\lambda_{345}(\mu) + \sqrt{\lambda_1(\mu)\lambda_2(\mu)} > 0,$$

$\Rightarrow$ the instability scale is higher than in the SM

[A. Goudelis, B. Herrmann, O. Stål, JHEP 09 (2013) 106]

- *refined approximate approach:* consider effective potential of the IDM, keeping only one vev $\neq 0$ (additional scalars are "integrated out")

# Stability beyond tree-level – work in progress

*final goal* – consider full 1-loop effective potential of the IDM
[some results: P. Chankowski, G. Gil, M. Krawczyk, PLB 717 (2012) 396-402]

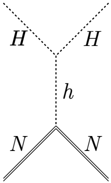
- is it bounded from below?
- what is the vacuum structure?
- can DM stabilize the SM vacuum?
- what is the lifetime of the inert vacuum?
- what is the impact on phenomenology?

# Summary

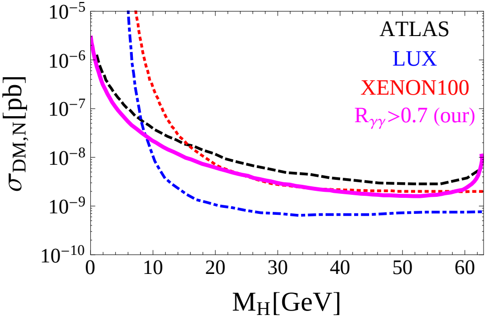
- IDM is consistent with present experimental results
- It provides a viable DM candidate
- Measurements of Higgs properties constrain $H^{\pm}$ and DM masses
- When Higgs results combined with Planck $\Longrightarrow$ stringent constraints on DM scenarios
- Interesting issue of metastability in the IDM – work in progress

# Backup slides

# Direct detection – comparison with XENON/LUX

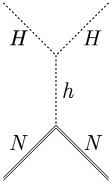



- DM-nucleon scattering cross section $\sigma_{\mathrm{DM,N}} \sim \lambda_{345}^2$
- $R_{\gamma\gamma}$ bounds on $\lambda_{345}$ translated to $(M_H, \sigma_{\mathrm{DM},N})$ plane

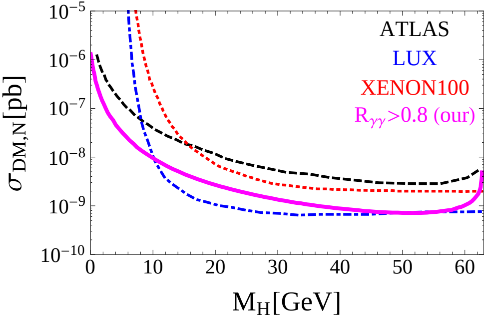



Limits stronger/comparable to those from XENON100

# Direct detection – comparison with XENON/LUX




- DM-nucleon scattering cross section $\sigma_{\mathrm{DM,N}} \sim \lambda_{345}^2$
- $R_{\gamma\gamma}$ bounds on $\lambda_{345}$ translated to $(M_H,\ \sigma_{\mathrm{DM},N})$ plane




and to those from LUX (stronger for $M_H < 10\,\mathrm{GeV}$)

# Direct detection – dependence on $f_N$.

DM-nucleon scattering cross section $\sigma_{\mathrm{DM},N} \sim \lambda_{345}^2$

$$\sigma_{\mathrm{DM,N}} = \frac{\lambda_{345}^2}{4\pi M_h^4} \frac{m_N^4}{(m_N + M_H)^2} f_N^2$$

Depends on the value of $f_N$, no agreement on its precise value.
$f_N \in (0.014,\ 0.66)$. We use $f_N = 0.326$ – the middle value.