Stability of the inert vacuum state beyond tree level

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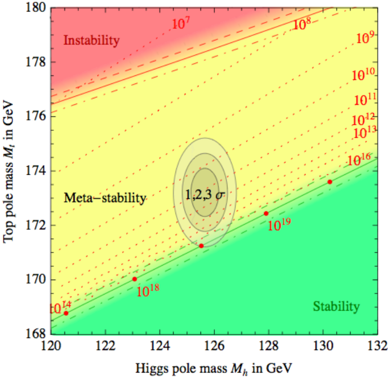
6.12.2015
SCALARS 2015, Warsaw, Poland

based on: BŚ, JHEP 1507 (2015) 118,
P. M. Ferreira (ISEL and CFTC, Lisbon), BŚ, arXiv:1511.02879

Aim of the talk

There is a Higgs boson with mass $M_h \approx 125\,\mathrm{GeV}$!

- measurement of the Higgs mass allows to localize the SM in the phase diagram
- new interactions modify the picture
- **what is the influence of additional scalars on the vacuum structure?**



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

[see also: V. Branchina et al., PRL 111 (2013) 241801, Z. Lalak, M. Lewicki, P. Olszewski, JHEP 1405 (2014) 119]

Inert Doublet Model and vacuum stability

IDM = a two-Higgs-doublet model with an **exact $\mathbb{Z}_2$ symmetry**

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$\longrightarrow$ one-loop SM potential, with corrections from heavy scalars

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How does loop-level vacuum structure look like?

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→ one-loop SM potential, with corrections from heavy scalars

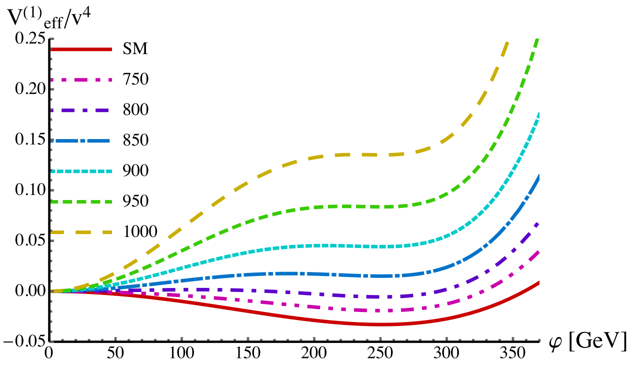
How does loop-level vacuum structure look like?

→ compare values of the full one-loop potential at different minima

Vacuum stability with heavy scalars

[BŚ, JHEP 1507 (2015) 118]

M_H = 550 GeV, hhHH coupling fixed (= -0.1)



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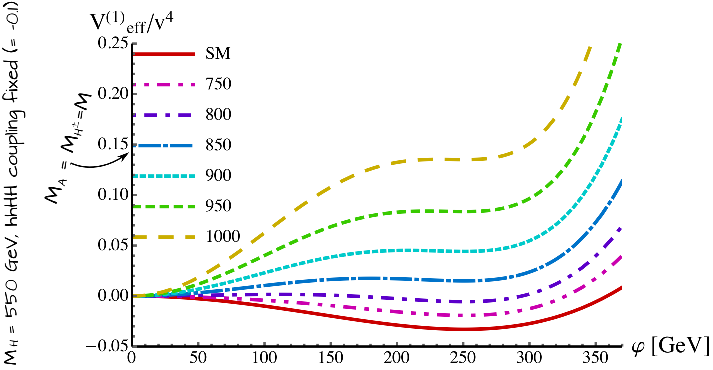

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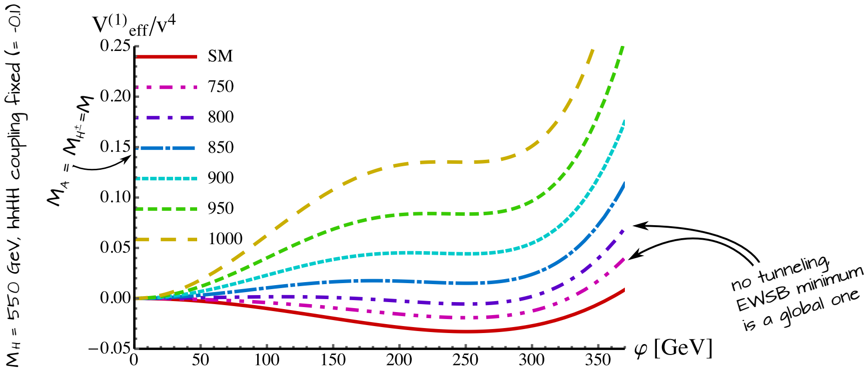

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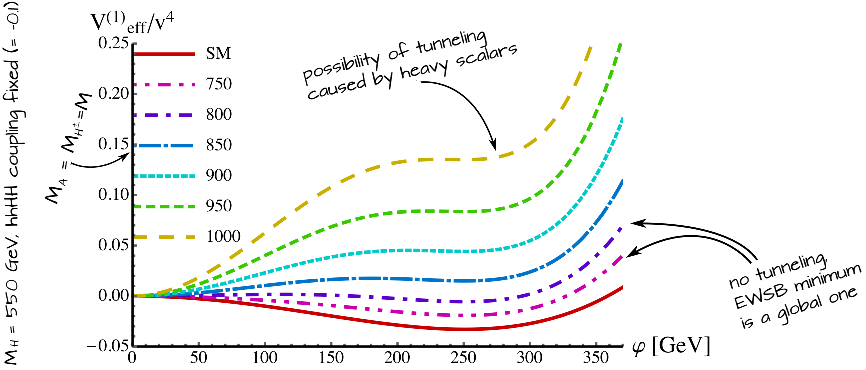

- maximum at $\varphi = 0$ becomes a minimum

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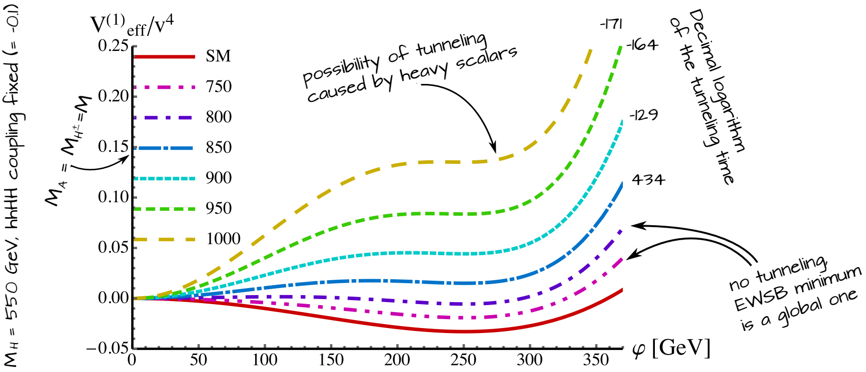

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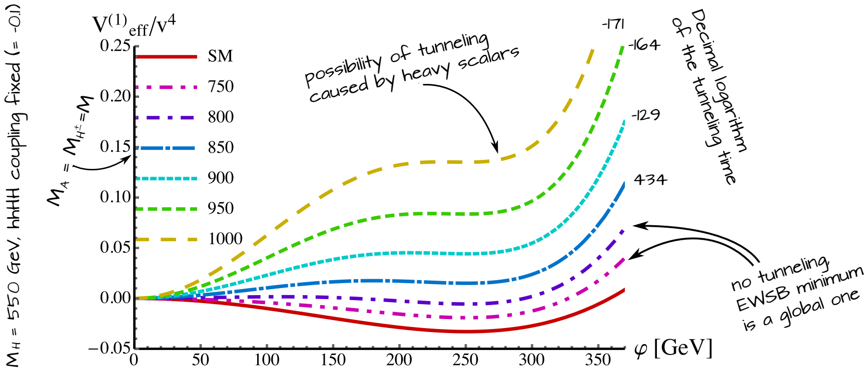

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- **for heavy inert scalars – EWSB minimum is highly unstable**

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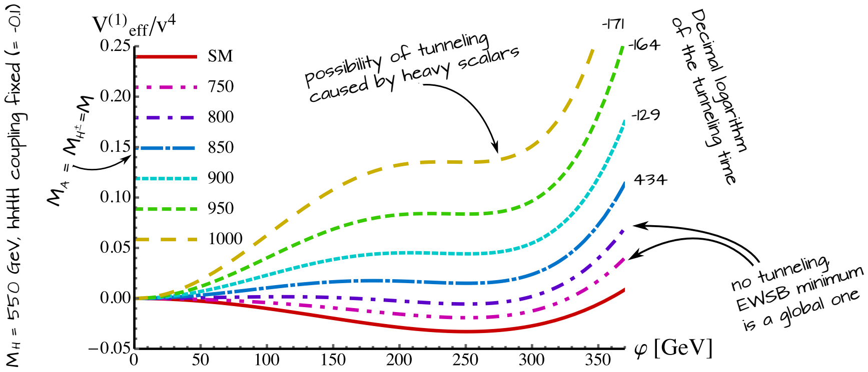

- maximum at $\varphi = 0$ becomes a minimum
- **for heavy inert scalars – EWSB minimum is highly unstable**
- instability only when big splittings among inert scalars – in IDM excluded by EWPT and DM relic density

Vacuum structure: inert vs inert-like

Inert extremum

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

Inert-like extremum

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

Can tree-level vacuum structure be inverted by loop corrections?

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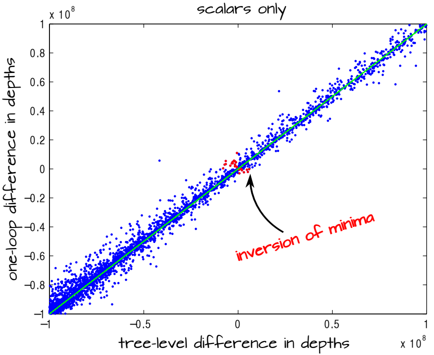

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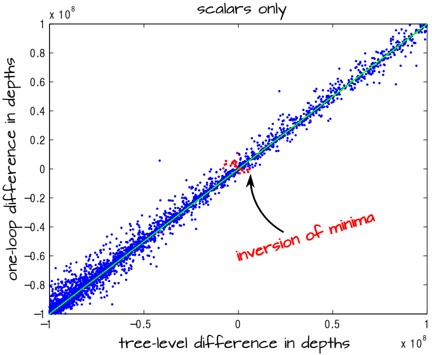
Can tree-level vacuum structure be inverted by loop corrections?

- the minima can be inverted by loop corrections
- it only happens when they are close in energies



[P.M. Ferreira, BŚ, arXiv:1511.02879]

Conclusions

- Additional scalars do influence the vacuum structure of a model
- Loop contributions may destabilize the SM-like vacuum – not the case in the IDM but has to be checked
- In multi-scalar models the vacuum structure can be rearranged at loop level – sometimes it is crucial to use the one-loop effective potential

Bakup slides

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 ϕ_S and ϕ_D doublets:

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

$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D) + \lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{1}{2}\lambda_5\left[(\phi_S^\dagger\phi_D)^2 + (\phi_D^\dagger\phi_S)^2\right]$$

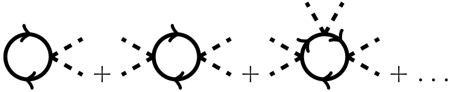
- $\mathbb{Z}_2$-type symmetry **D**: $\phi_D \to -\phi_D$, $\phi_S \to \phi_S$
- Yukawa interactions: type I (only ϕ_S couples to fermions)
- $\mathcal{L}$ – **D-symmetric**
- **D-symmetric vacuum state** $\langle\phi_S\rangle = \frac{v}{\sqrt{2}}$, $\langle\phi_D\rangle = 0$

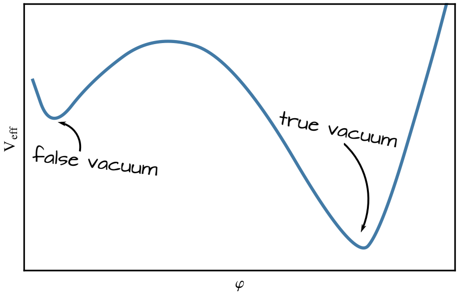
$\Longrightarrow$ **EXACT D-symmetry**

Constraints

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

Motivation

$\delta V_{\rm eff} =$ 



[in the IDM: A. Goudelis, B. Herrmann, and O. Stål, JHEP 1309 (2013) 106, M. Kadastik, K. Kannike, A. Racioppi, and M. Raidal, JHEP 1205 (2012) 061, N. Khan and S. Rakshit, arXiv:1503.03085.]

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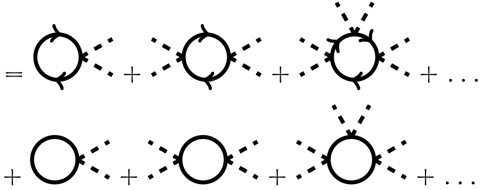
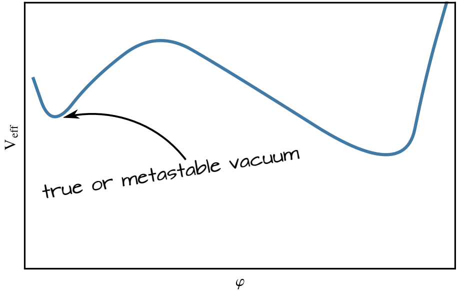


Idea: introduce new scalars to balance the top contribution at large energies



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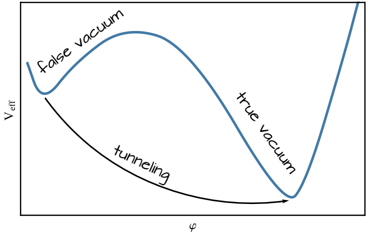
Vacuum stability

vacuum = ground state of a theory

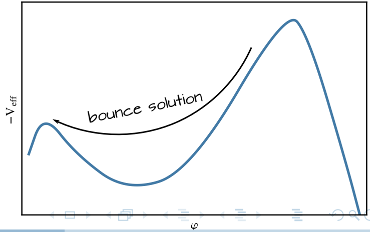
- **true** vacuum = global minimum of the potential
- **metastable** vacuum = local minimum with long* lifetime
- **unstable** vacuum = local minimum with short* lifetime

*short/long = shorter/longer than the age of the Universe, $T_U \approx 14 \cdot 10^9$ years



If more than one minimum – tunneling possible

- described semi-clasically
- τ lifetime of vacuum, in units of T_U



Tunneling time

- Bounce equation:

$$\ddot{\varphi} + \frac{3}{s}\dot{\varphi} = \frac{\partial V_{\text{eff}}^{(1)}(\varphi)}{\partial \varphi},$$

boundary conditions: $\dot{\varphi}_B(0) = 0$, and $\varphi_B(\infty) = v$.

- solved numerically by the **undershoot–overshoot method**
- lifetime of a vacuum

$$\tau = \frac{e^{S_E}}{\varphi_0^4 T_U^4},$$

where $\varphi_0 = \varphi(0)$, and

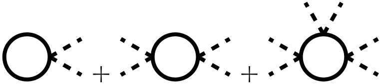
$$S_E = 2\pi^2 \int dss^3 \left[\frac{1}{2}\dot{\varphi}_B^2(s) + V(\varphi_B(s))\right].$$

Effective potential

[S. R. Coleman, E. J. Weinberg, PRD 7 (1973) 1888, G. Gil, P. Chankowski, and M. Krawczyk, PLB 717 (2012) 396]

To take into account quantum corrections we analyse one-loop effective potential

$$V_{\text{eff}} = V^{(0)} + \delta V = V^{(0)} +$$



$$+ \dots$$

- in 2HDM – in principle all scalar fields allowed on external legs
  $\Rightarrow$ V_{eff} – multivariable function
- **assumption: inert scalars are heavy, can be integrated out**
  $\Rightarrow$ inert scalars allowed only in the loops, Higgs field on external legs
- on-shell (OS) renormalized potential

Effective potential in OS scheme

The effective potential:

$$V_{\text{eff}}^{(1)} = V_{\text{eff}}^{(0)} + \delta V_{\text{CW}} + \delta V + const.$$

- $V_{\text{eff}}^{(0)}$ – tree-level effective potential

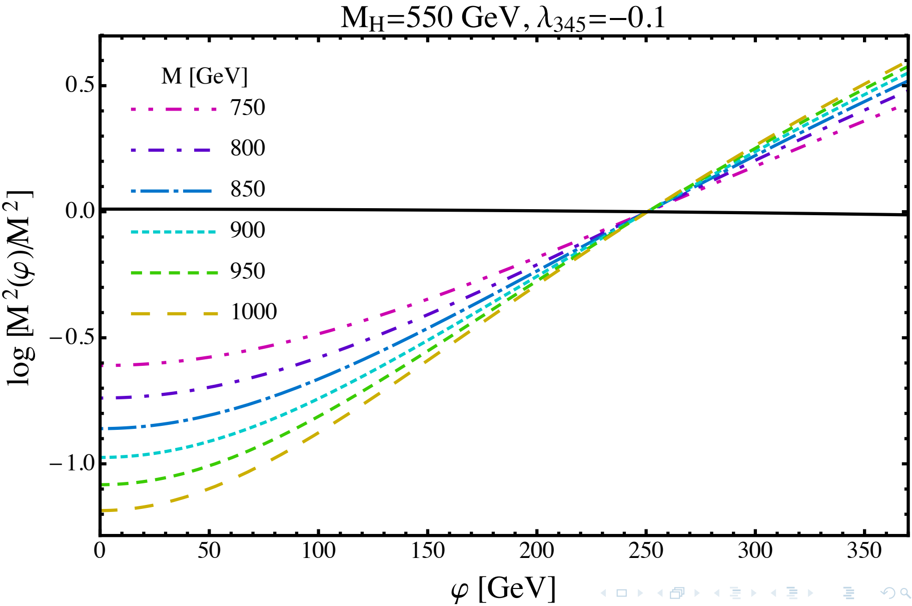
$$V_{\text{eff}}^{(0)} = -\frac{1}{4} m_{11}^2 \varphi^2 + \frac{1}{8} \lambda_1 \varphi^4,$$

- δV_{CW} – CW potential

$$\delta V_{\text{CW}} = \sum_i \frac{f_i}{64\pi^2} M_i(\varphi)^4 \left[-\frac{2}{\epsilon} + \gamma_E - C_i + \log\left(\frac{M_i(\varphi)^2}{4\pi\mu^2} \right) \right],$$

- δV – counterterm potential in OS scheme
  OS scheme: one-loop tadpole of h is cancelled, the Higgs propagator has a pole at M_h with a residue equal to i

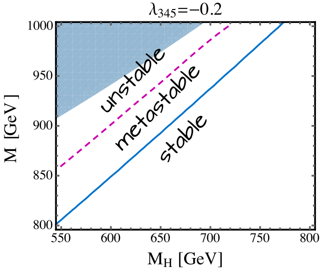
Perturbativity of the expansion



EW metastability in the IDM parameter space

Where in the parameter space is metastability realised?

For $M_A = M_{H^\pm} = M$



[T. Hambye, F.-S. Ling, L. Lopez Honorez, and J. Rocher, JHEP 0907 (2009) 090, arXiv:0903.4010]

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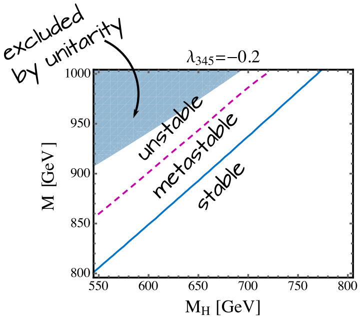
- meta/instability when relatively large splitting between M_H and M, $M^2 - M_H^2 \sim \lambda_{\text{scalar}} v^2$
  $\Rightarrow$ some scalar couplings large
- consistent with perturbative unitarity
- EWPT not constraining $(T = 0)$
- however, DM relic abundance requires small splittings, $\mathcal{O}(10\,\text{GeV})$
  $\rightarrow$ **inconsistent with Planck measurements for heavy DM**



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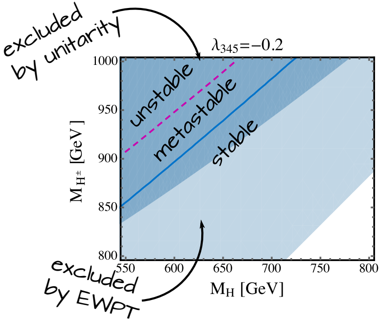
EW metastability in the IDM parameter space

For $M_A = M_H + 1$, $M_{H^\pm}$ – free

- large splitting required
- excluded by unitarity, EWPT, and relic density



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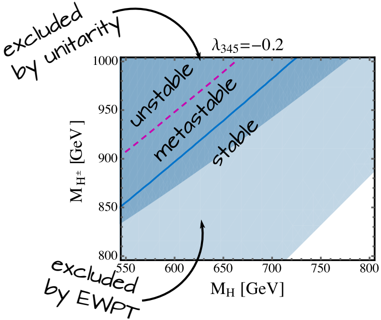

If IDM is in agreement with theoretical and experimental constraints
$\Longrightarrow$ it is free from meta- or unstable vacuum around the EW scale.

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]]

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

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

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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

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Not realized at present

EW symmetric, Charge breaking

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

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our choice, DM candidate

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Inert-like extremum (I_2)

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massless fermions

Phase diagram and coexistence of minima

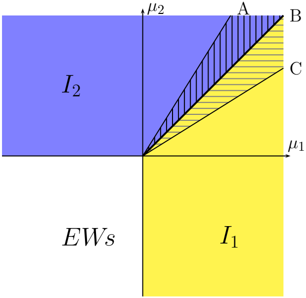
[BŚ, PRD 88 (2013) 055027]

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

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

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

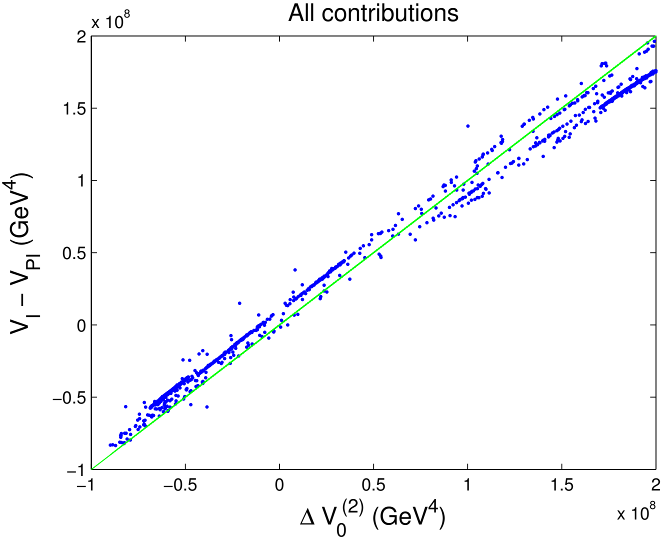
- or possibility of metastability at the tree-level



$R > 1$

from D. Sokołowska, PoS ICHEP2010:457

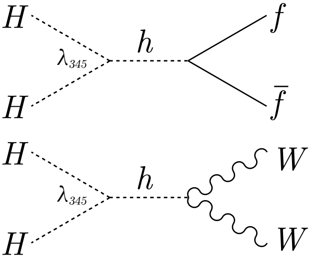
All contributions included

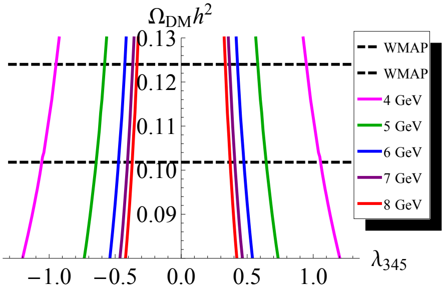


Relic density constraints

[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]]

$$0.1118 < \Omega_{DM} h^2 < 0.1280 \quad (3\sigma, \mathrm{PLANCK})$$



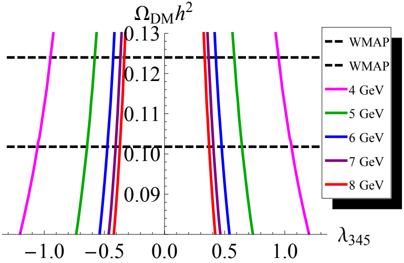


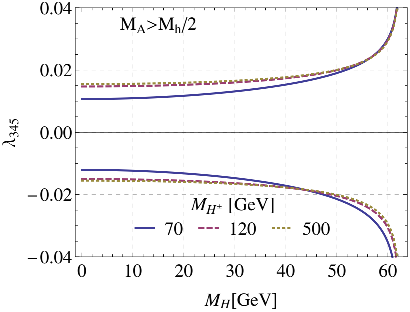
From D. Sokołowska, arXiv:1107.1991

Possible masses:

- **light DM**: $M_H \lesssim 10\,\mathrm{GeV}$
- **intermediate DM**: $40\,\mathrm{GeV} \lesssim M_H \lesssim 160\,\mathrm{GeV}$
- **heavy DM**: $M_H \gtrsim 500\,\mathrm{GeV}$

Light DM, $M_H \lesssim 10\,\mathrm{GeV}$



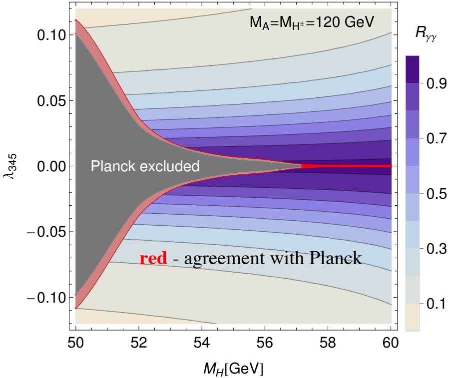


- correct relic density $\Rightarrow |\lambda_{345}| \sim \mathcal{O}(0.5)$
- too small $\lambda_{345} \Rightarrow$ overclosing the Universe
- $R_{\gamma\gamma} > 0.7 \Rightarrow |\lambda_{345}| < 0.04$

Light DM exlucded

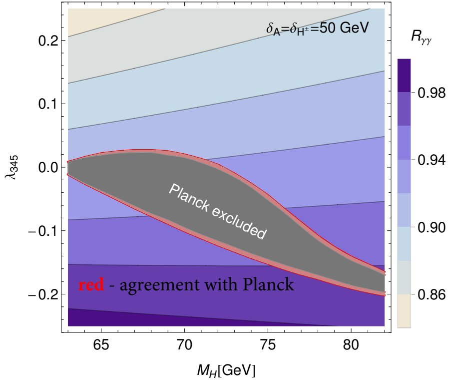
[Planck update: D. Sokołowska, P. Swaczyna, 2014]

$h \to HH$ open



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

$h \to HH$ closed



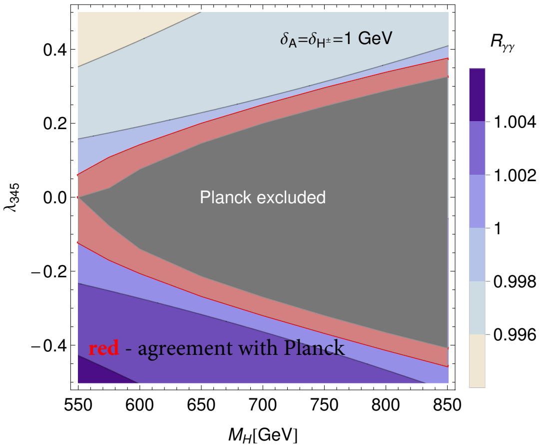
$M_h/2 < M_H < 83\,\mathrm{GeV},\ M_A = M_{H^\pm} = M_H + 50\,\mathrm{GeV}$

$\mathrm{R}_{\gamma\gamma} > 0.7$ & PLANCK
$\Longrightarrow \mathrm{M_H} > 53\,\mathrm{GeV}$

agreement with PLANCK and
$\mathrm{R}_{\gamma\gamma} > 0.7$, but then $\mathrm{R}_{\gamma\gamma} < 1$

Heavy DM

$M_H > 500\,\mathrm{GeV}$, $M_A = M_{H^\pm} = M_H + 1\,\mathrm{GeV}$ (because of S, T)



Agreement with PLANCK and $R_{\gamma\gamma} \approx 1$.