MultiHiggs Workshop

Lisbon 29.08.2012

Inert Doublet Model and Strong First Order Phase Transition

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Plan

General introduction

Higgs and Dark sector in IDM

Diffrent phases of Universe

Termal T2 evolution (short)

Beyond T2 evolution

(effective potential approach)

→ strenght of the phase transition
towards electroweak baryogenesis

2HDM- great laboratory of BSM

- Inert Doublet Model (IDM) provides DM and it is in agreement with present astrophysical and collider data including the 125 GeV Higgs boson
- If today (T=0) Universe in the Inert phase what was in the past ?
- We have studied temperature dependent Z2 sym. 2HDM potential → evolution of the inert vacuum and sequences of different vacua in the past (one, two and three phase transitions)

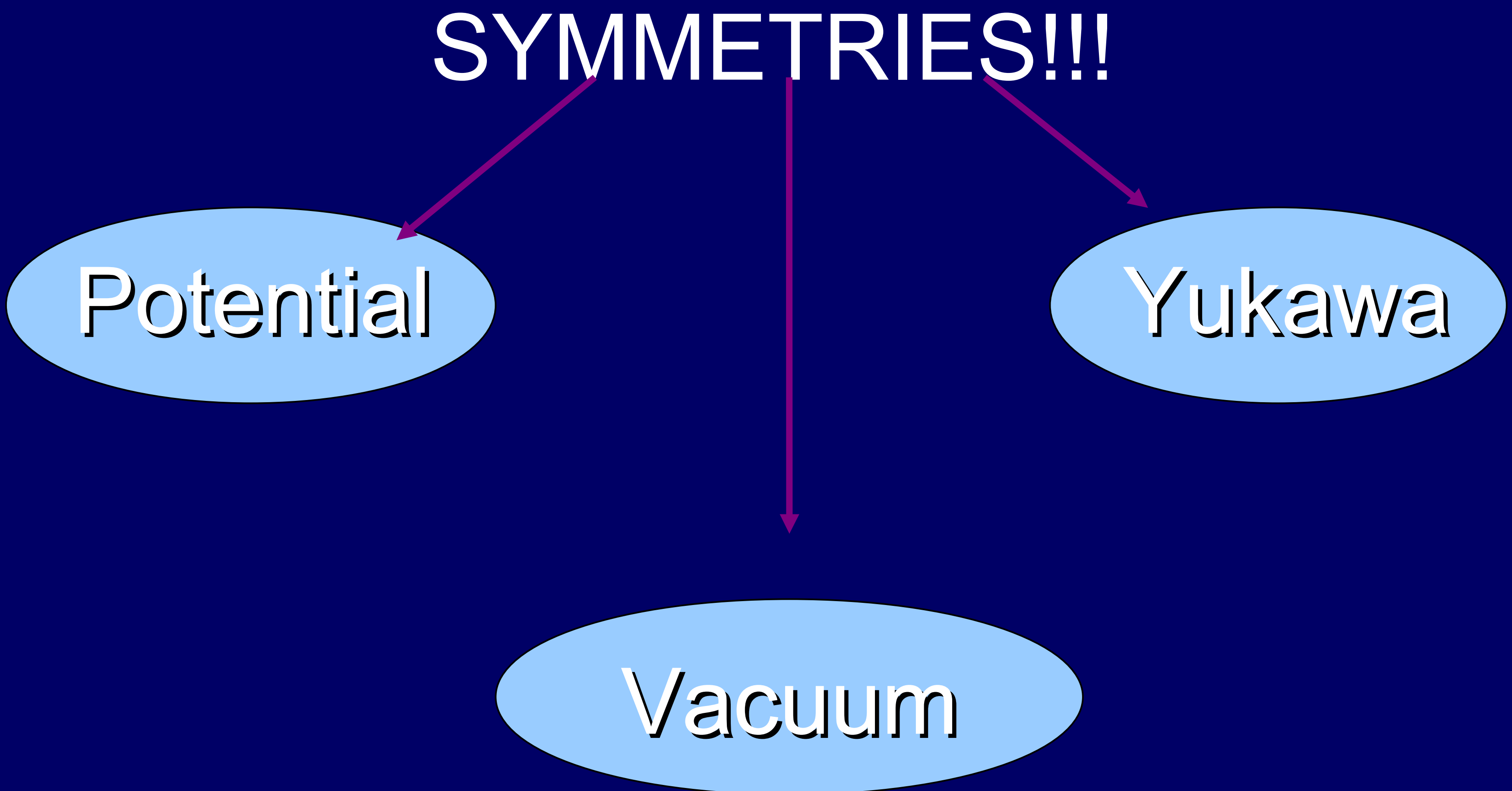
 - with leading T2 corrections (only m^2_{ii} (T^2))

(PRD 82(2010) GKKS, I. Ginzburg and D. Sokołowska talks here)

 - beyond T2 corrections (to find strong enough first-order phase transition needed for baryogenesis)

(G. Gil Thesis'2011, G.Gil, P. Chankowski, MK 1207.0084 [hep-ph])

2HDM's



Various models of Yukawa inter.

typically with some Z2 type symmetry to avoid FCNC

Model I - only one doublet interacts with fermions

Model II – one doublet with down-type fermions d , l

other with up-type fermions u

Model III - both doublets interact with fermions

Model IV (X) - leptons interacts with one doublet, quarks with the other

Model Y - one doublet with down-type quarks d

other with up-type quarks u and leptons

Top 2HDM – top only with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs

+ Extra dim 2HDM models

2HDM Potential (Lee'73)

$$V = \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \tfrac{1}{2}\,[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c]$$

$$+ [(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2))(\Phi_1^\dagger\Phi_2) + h.c]$$

$$- \tfrac{1}{2}m^2_{11}(\Phi_1^\dagger\Phi_1) - \tfrac{1}{2}m^2_{22}(\Phi_2^\dagger\Phi_2) - \tfrac{1}{2}[m^2_{12}(\Phi_1^\dagger\Phi_2) + h.c.]$$

Z_2 symmetry transformation: $\Phi_1 \rightarrow \Phi_1 \quad \Phi_2 \rightarrow -\Phi_2$

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term (Re $m^2_{12} = \mu^2$)

Explicit Z_2 symmetry in V: λ_6, λ_7, $m^2_{12} = 0$

Possible extrema (vacuum) states

The most general state **for V with explicit Z_2**

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

v_S, v_D, u - real

v_S, $u \geq 0$

$v^2=v_S{}^2+v_D{}^2+u^2=(246\ \mathrm{GeV})^2$

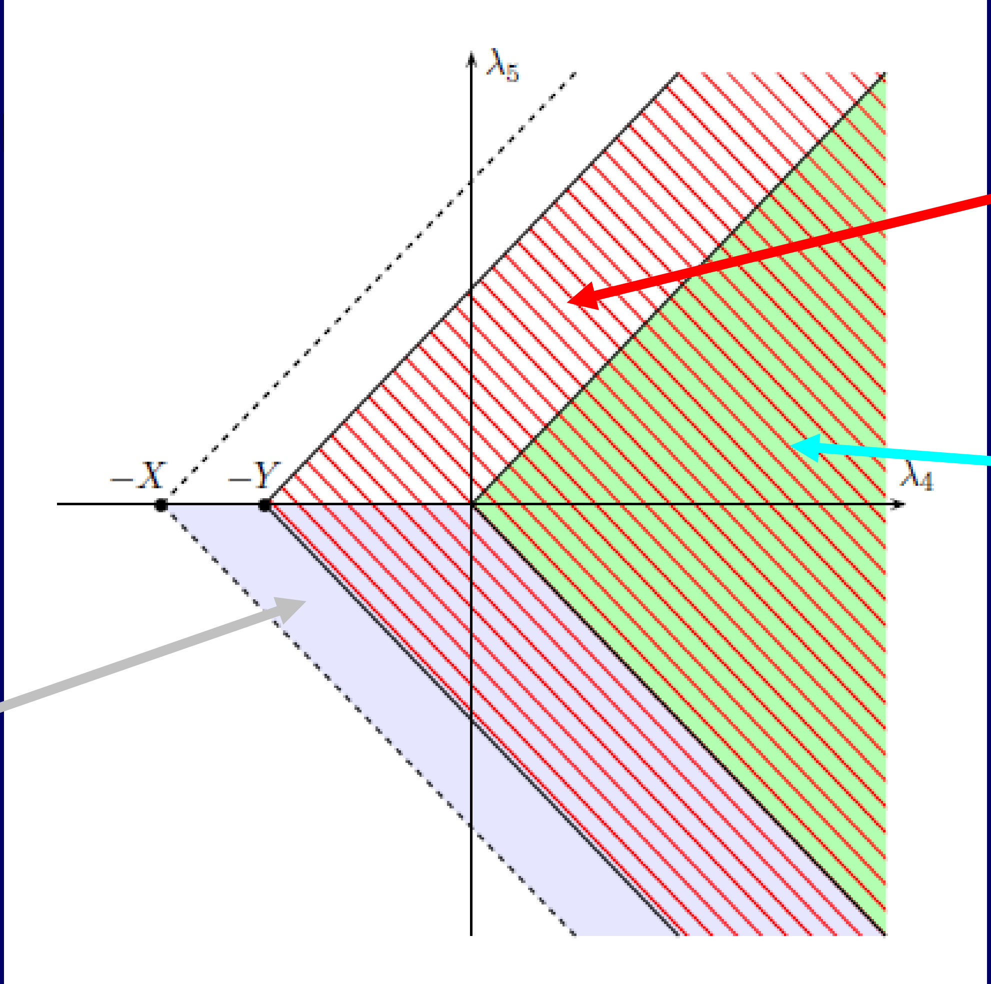
EWs	EWs	$u=0 \quad v_D=v_S=0$
Inert	I_1	$u=0 \quad v_D=0$
Inert-like	I_2	$u=0 \quad v_S=0$
Mixed (Normal, MSSM like)	M	$u=0$
Charge Breaking	Ch	$u\neq 0 \quad v_D=0$

Various extrema (vacua) on (λ_4 , λ_5) plane

Positivity constrains: $\lambda_4 \pm \lambda_5 > - X \quad X=\sqrt{\lambda_1 \lambda_2}+\lambda_3>0$

Inert (Inert-like)

$Y = M_{H+}^2 \, 2/v^2$



Charge Breaking Ch

Mixed

Note the overlap of the Inert with M and Ch !

TODAY

2HDM with explicit Z_2 (D) symmetry

$\Phi_S \rightarrow \Phi_S \quad \Phi_D \rightarrow - \Phi_D$

Model I (Yukawa int. with Φ_S only)

- Charge breaking phase Ch?

  photon is massive, el.charge is not conserved...

  $\rightarrow$ No

- Neutral phases:

  Mixed M ok, many data, but no DM

  Inert I1 OK! In agreement with accelerator and astrophysical data (neutral DM)

  Inert-like I2 No, all fermions massless, no DM

Inert Doublet Model

Ma'78
Barbieri'06

Symmetry under Z_2 transf. $\Phi_S \to \Phi_S \quad \Phi_D \to - \Phi_D$

both in L (V and Yukawa interaction = Model I only Φ_S)

and in the vacuum:

$<\Phi_S> = v \qquad <\Phi_D> = 0$ Inert vacuum I_1

Today?

Φ_S as in SM (BEH), with Higgs boson h (SM-like)

Φ_D has no vev, with 4 scalars (no Higgs bosons!)

no interaction with fermions (inert doublet)

Here Z_2 symmetry exact $\to Z_2$ parity, only Φ_D has odd Z_2-parity

$\to$ The lightest scalar stable -a dark matter candidate

(Φ_D dark doublet with dark scalars) .

$\Phi_1 \to \Phi_S$ Higgs doublet S $\qquad \Phi_2 \to \Phi_D$ Dark doublet D

Constraining Inert Doublet Model

- Positivity,extrema,vacua,pert. unitarity, S, T
- By considering properties of *(Ma'2006,..B. Świeżewska, Thesis2011, 1112.4356, 1112.5086[hep-ph] and talk)*

  - the SM-like h, $M^2_h = m_{11}^2 = \lambda_1 v^2$

  - the dark scalars D always in pairs!

$$M^2_{H^+} = -\frac{m^2_{22}}{2} + \frac{\lambda_3}{2}v^2$$

$$M^2_H = -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4+\lambda_5}{2}v^2$$

$$M^2_A = -\frac{m^2_{22}}{2} + \frac{\lambda_3+\lambda_4-\lambda_5}{2}v^2$$

λ_{345}

D couple to V = W/Z (eg. AZH, $H^- W^+ H$), not DVV!

Quartic selfcouplings D^4 proportional to λ_2

hopeless to be measured at colliders! *(→ D. Sokołowska talk)*

Couplings with Higgs: hHH ~ λ_{345} h H+H- = ~ λ_3

Evolution of the Universe in 2HDM– through different vacua in the past

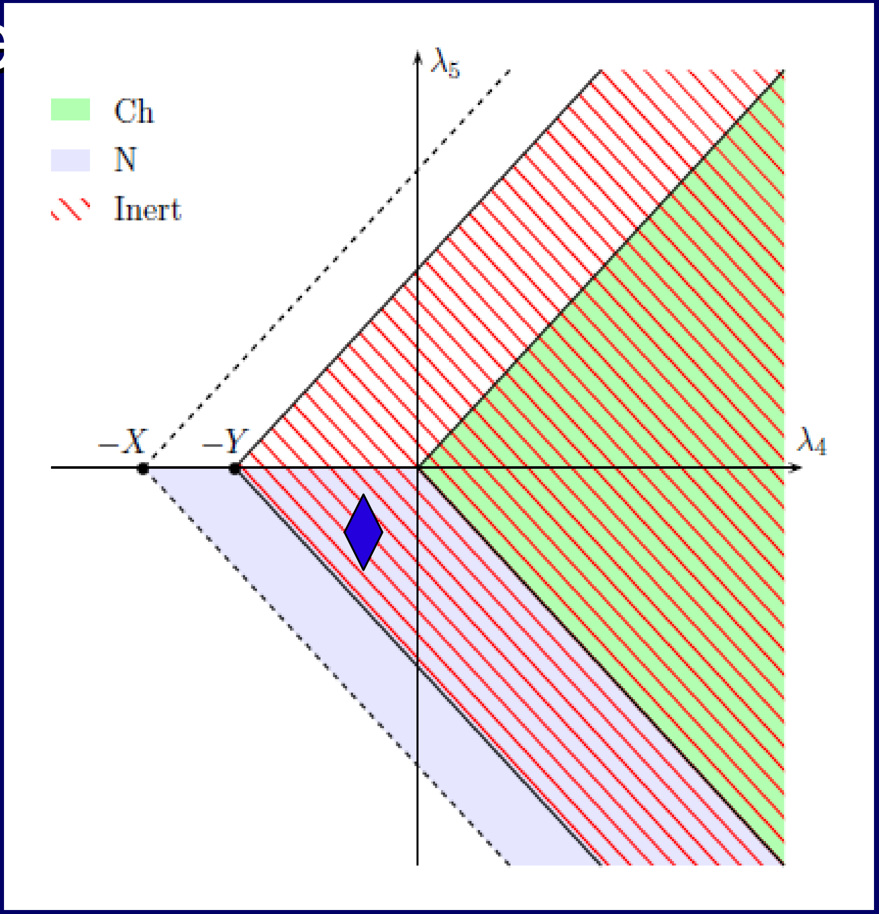
Ginzburg, Ivanov, Kanishev 2009
Ginzburg, Kanishev, Krawczyk, Sokołowska 2010, Sokołowska 2011

We consider 2HDM with an explicit D (Z_2) symmetry assuming that today the Inert Doublet Model describes reality

Yukawa interaction – Model I →
all fermions couple only to Φ_S

From the EW symmetric phase to the INERT phase in T2 approximation

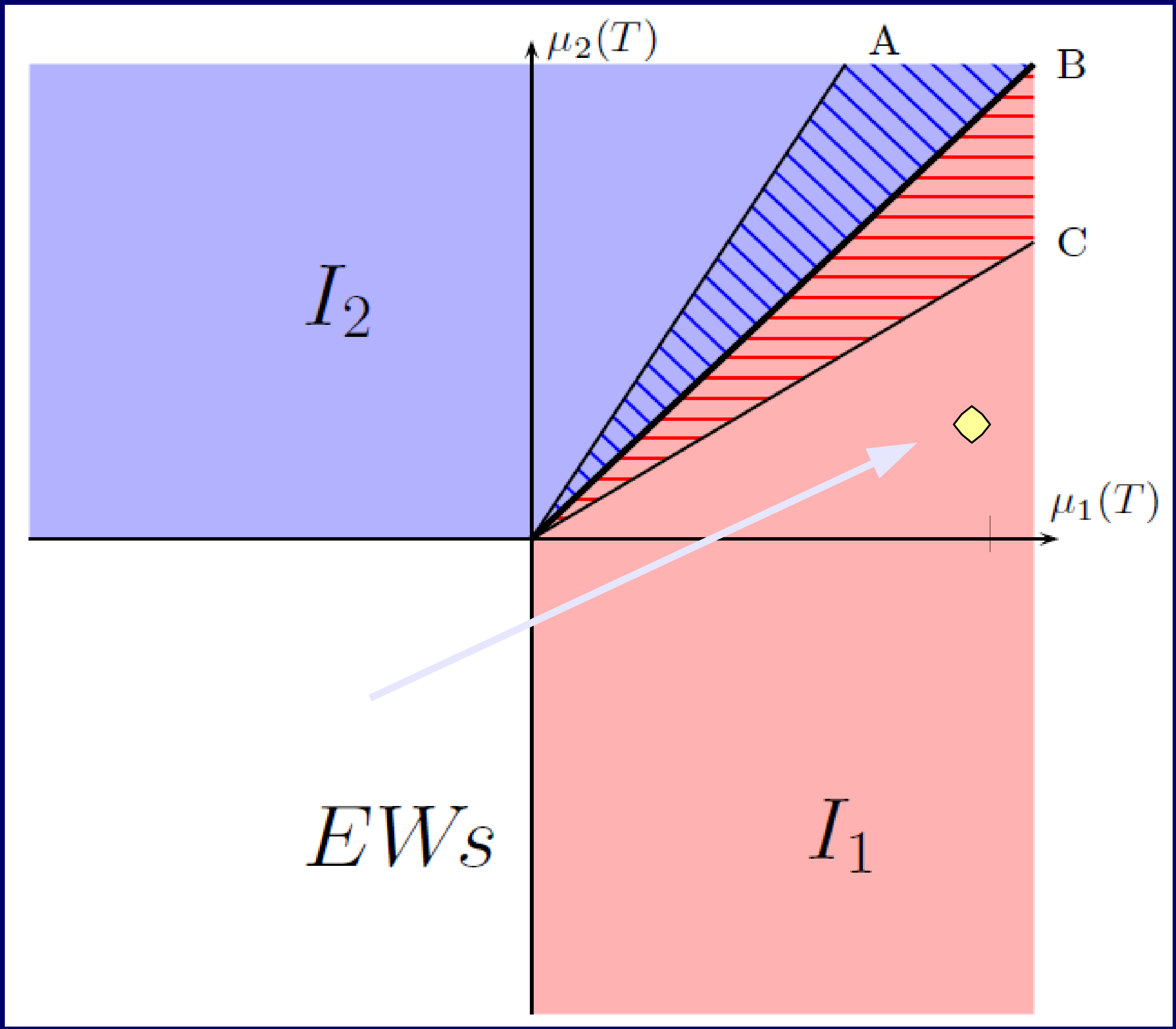
In the simplest T2 approximation only *mass terms* in V vary with temperature like T^2, while *lambdas* are fixed



Various scenarios possible in one, two or three steps, with 1st or 2nd type phase transitions → *Sokołowska talk*

Ginzburg, Kanishev, MK, Sokołowska Phys. Rev D 2010

Phase diagram (μ_1,μ_2)



$\mu_i = m_{ii}^2/\sqrt{\lambda_i}$

$$R + 1 > 0.$$

Stability condition

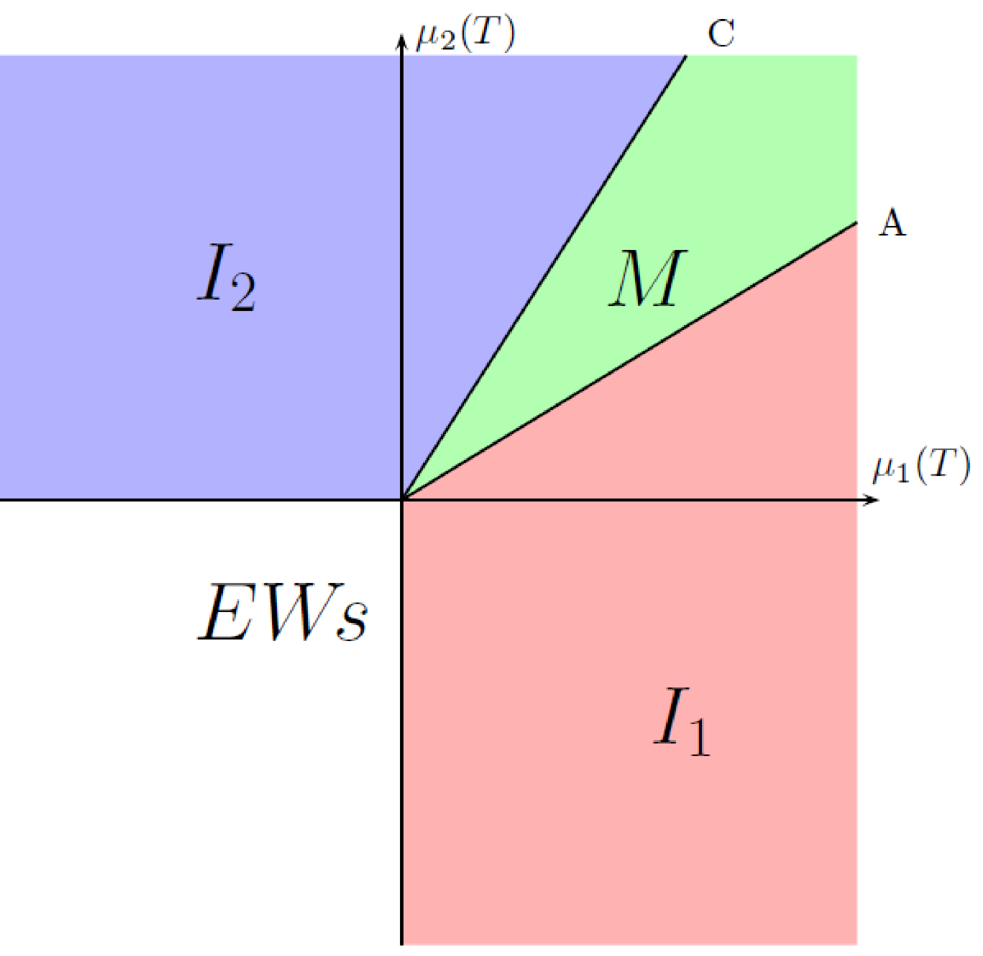
$$R = \frac{\lambda_{345}}{\sqrt{\lambda_1 \lambda_2}}.$$

3 regions of R

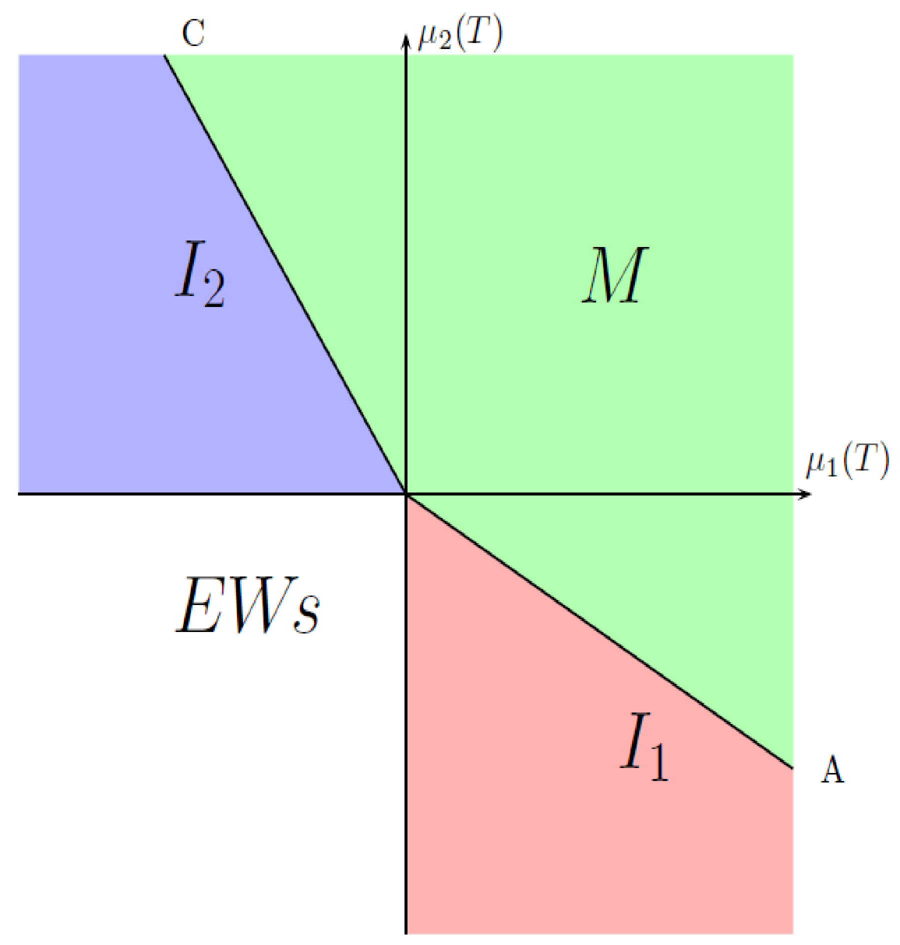
T2 corrections $\rightarrow$ rays from EW s to Inert phase

R>1

Phase diagrams



1>R>0



0>R>-1

Transitions to the Inert phase beyond T2 corrections

We applied one-loop effective potential at T=0 (Coleman-Wienberg term) and temperature dependent effective potential at T≠0 (with sum of ring diagrams)

$$V_T^{(1L)}(v_1, v_2) = V_{\text{eff}}^{(1L)}(v_1, v_2) + \Delta^{(1L)} V_{T\neq 0}(v_1, v_2).$$

The one-loop effective potential $V_{\text{eff}}(v_1, v_2)$ is given in the Landau gauge by standard formula

mass matrices

$$V_{\text{eff}}^{(1L)} = V_{\text{tree}} + \frac{1}{64\pi^2} \sum_{\text{fields}} C_s \left\{ \mathcal{M}_s^4 \left(\ln \frac{\mathcal{M}_s^2}{4\pi\mu^2} - \frac{3}{2} + \frac{2}{d-2} - \gamma_E \right) \right\} + \text{CT},$$

number of states

counter terms →

Fixing counterterms

We require that v1=v1(tree)

and that h field propagator has a pole for tree-level mass-squared M_h^2

Then we put conditions on λ_{345} (hHH), λ_2(HHHH)

On the other hand λ_2 cannot be directly measured in the foreseeable future[6] so its precise definition at the loop-level is not important. Here for simplicity we choose to subtract the divergences of $V_{\text{eff}}^{(1L)}$ proportional to v_2^4 and $v_1^2 v_2^2$ using the $\overline{\text{MS}}$ scheme. This fixes the combinations $\delta\lambda_2 + 2\lambda_2\delta Z_2$ and $\delta\lambda_{345} + \lambda_{345}(\delta Z_1 + \delta Z_2)$. Once the latter counterterm is fixed the last necessary combination $\delta m_{22}^2 + m_{22}^2 \delta Z_2$ is determined by renormalizing the H^0 propagator on-shell. The counterterms $\delta\lambda_3$ and $\delta\lambda_5$ can be then used to enforce that the tree-level masses M_{A^0} and $M_{H^\pm}$ remain unchanged by one-loop corrections (they do not need to be determined explicitly).

One-loop temperature dependent effective potential

$$\Delta^{(1L)} V_{T\neq 0} = \frac{T^4}{2\pi^2} \sum_{\text{fields}} C_s \int_0^\infty dx\, x^2 \ln\left[1 - (-1)^{2s} \exp\left(-\sqrt{x^2 + \mathcal{M}_s^2/T^2}\right)\right].$$

For $T^2 \gg \mathcal{M}_s^2$ the contribution of $\mathcal{M}_s^2$ to (12) can be expanded:

$$\left(\Delta^{(1L)} V_{T\neq 0}\right)_B = |C_s| \left\{ -\frac{\pi^2}{90} T^4 + \frac{1}{24} T^2 \mathcal{M}_s^2 - \frac{T}{12\pi} |\mathcal{M}_s^3| - \frac{\mathcal{M}_s^4}{64\pi^2} \left(\ln \frac{\mathcal{M}_s^2}{T^2} - C_B \right) \right.$$

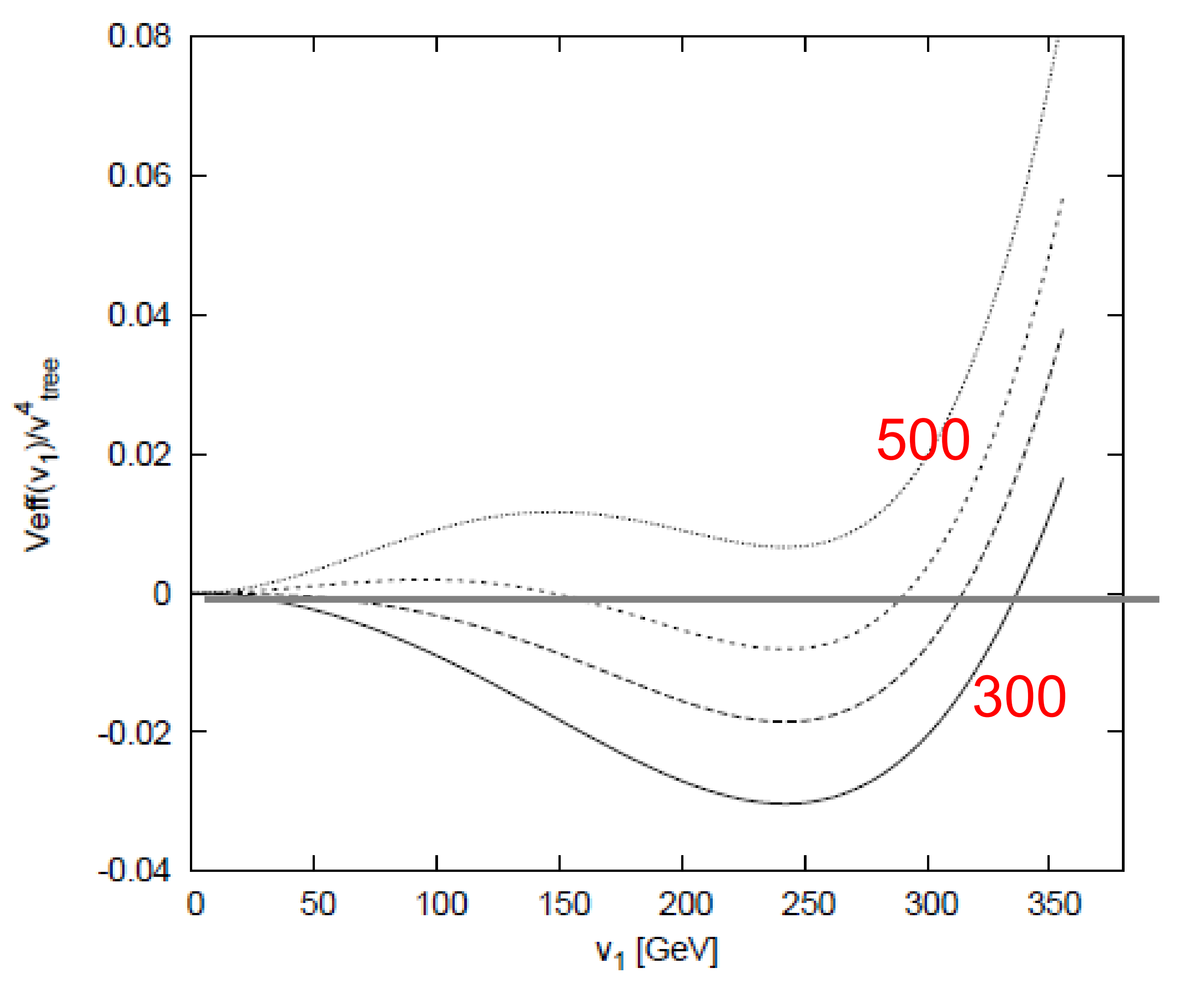
$$\left(\Delta^{(1L)} V_{T\neq 0}\right)_F = |C_s| \left\{ -\frac{7\pi^2}{720} T^4 + \frac{1}{48} T^2 \mathcal{M}_s^2 + \frac{\mathcal{M}_s^4}{64\pi^2} \left(\ln \frac{\mathcal{M}_s^2}{T^2} - C_F \right) \right\}$$

($C_B = 5.40762$, $C_F = 2.63503$). In the opposite limit $T^2 \ll \mathcal{M}_s^2$ one has

$$\left(\Delta^{(1L)} V_{T\neq 0}\right)_s = -|C_s|\, T^4 \left(\frac{|\mathcal{M}_s|}{2\pi T} \right)^{3/2} \left(1 + \frac{15}{8} \frac{T}{|\mathcal{M}_s|} + \dots \right) \exp\left(-\frac{|\mathcal{M}_s|}{T} \right),$$

both for B and F

Effective T=0 potential



Mh=125 GeV

MH=65 GeV

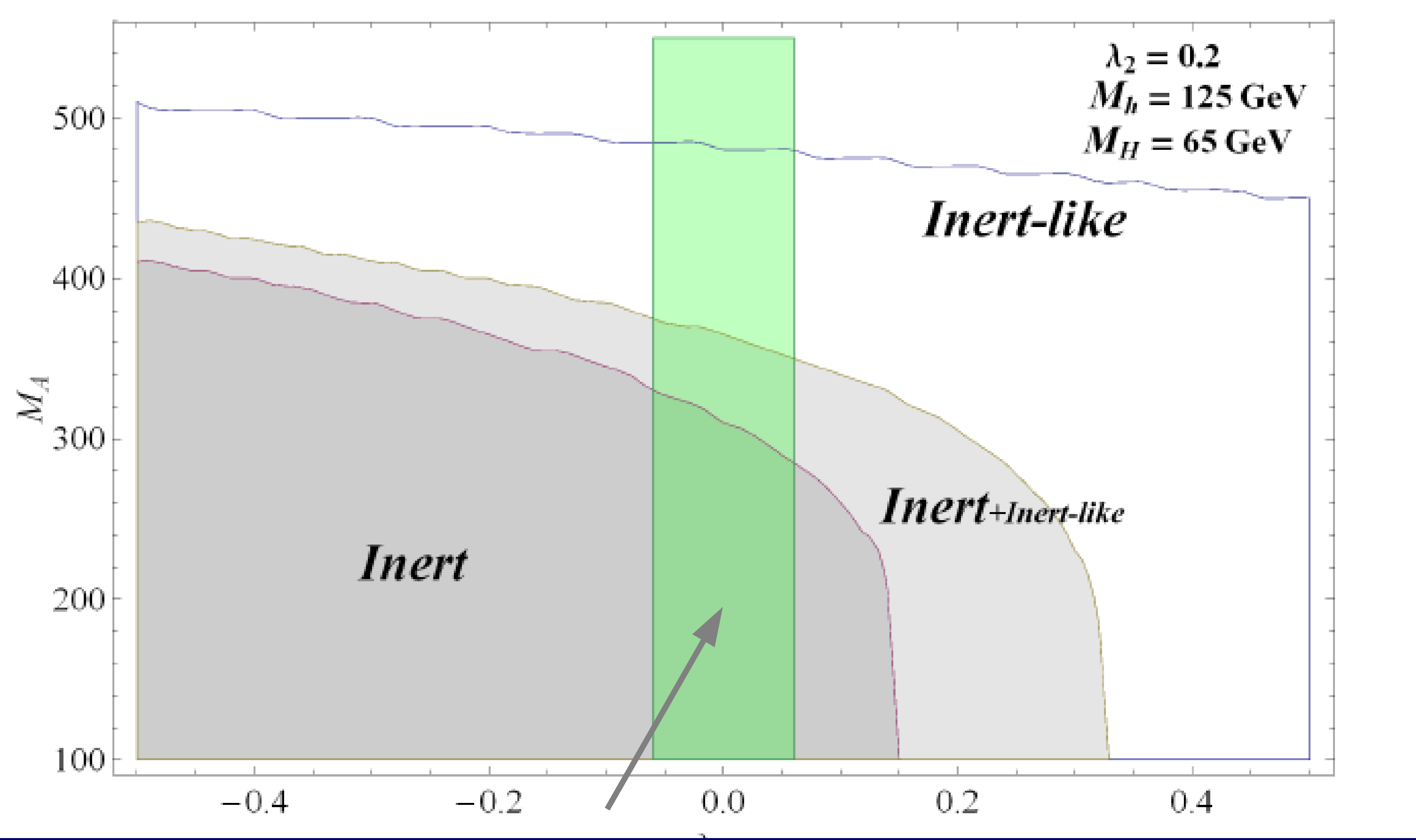
MH+=MA=
500,450,400,300
GeVṼ

λ_{345}=0.2,
λ_2=0.2

$v_{2(D)}$=0

Critical temperature T_{EW}: V at new minimum = V at $v_{1(s)}=v_{2(D)}=0$

Phases at T=0



Xenon100 bound

λ_{345}

Strength of the phase transition

$v(T_{EW})/T_{EW}$

We are looking for parameter space of IDM which allows for a strong first order phase transition

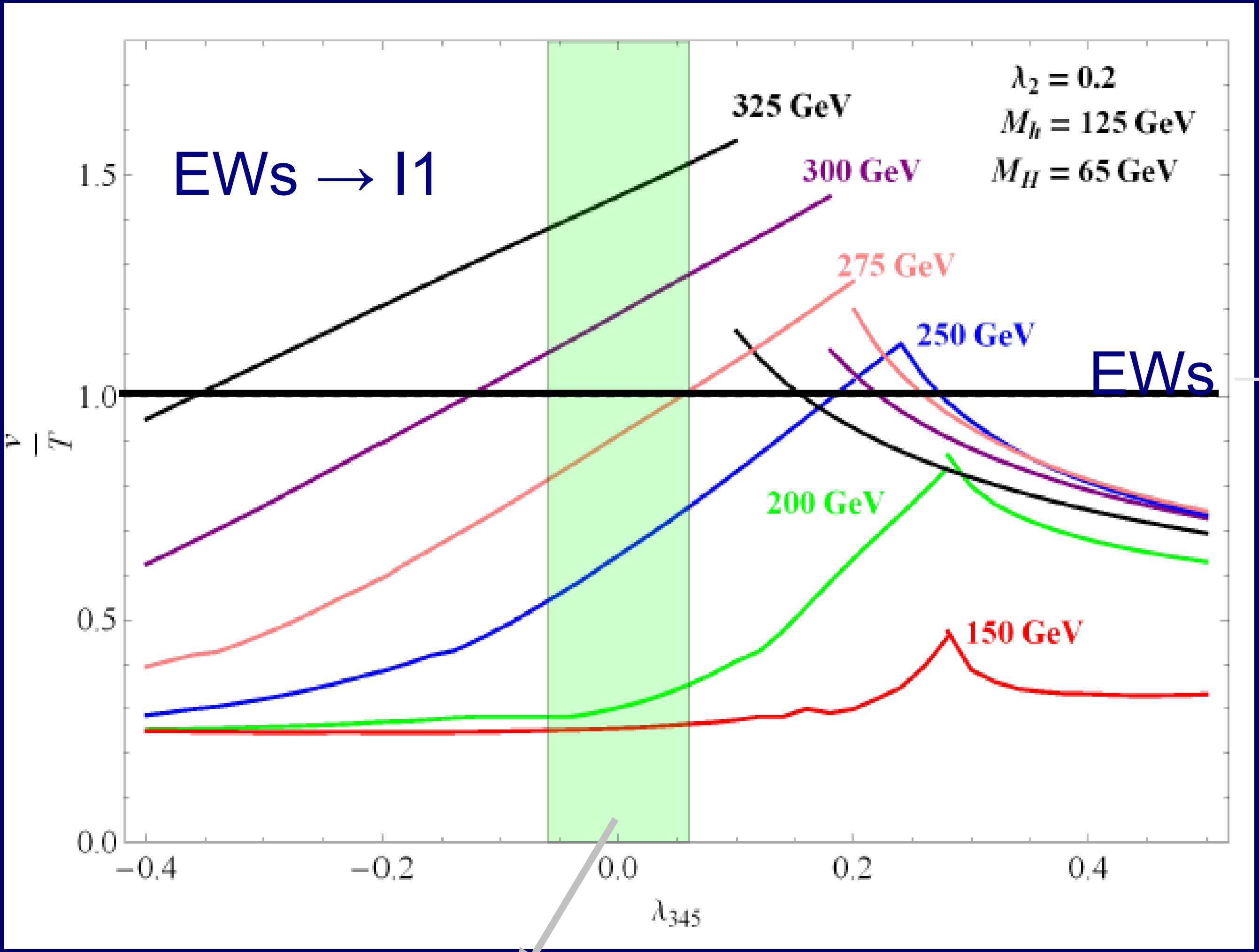
$v(T_{EW})/T_{EW} > 1$

being in agreement with collider and astro-physical data

We focus on medium DM, with MH « v,heavy degenerated A and H+ and M_h=125 GeV

Results for $v(T_{EW})/T_{EW}$

Mh=125 GeV, MH=65 GeV, λ2=0.2



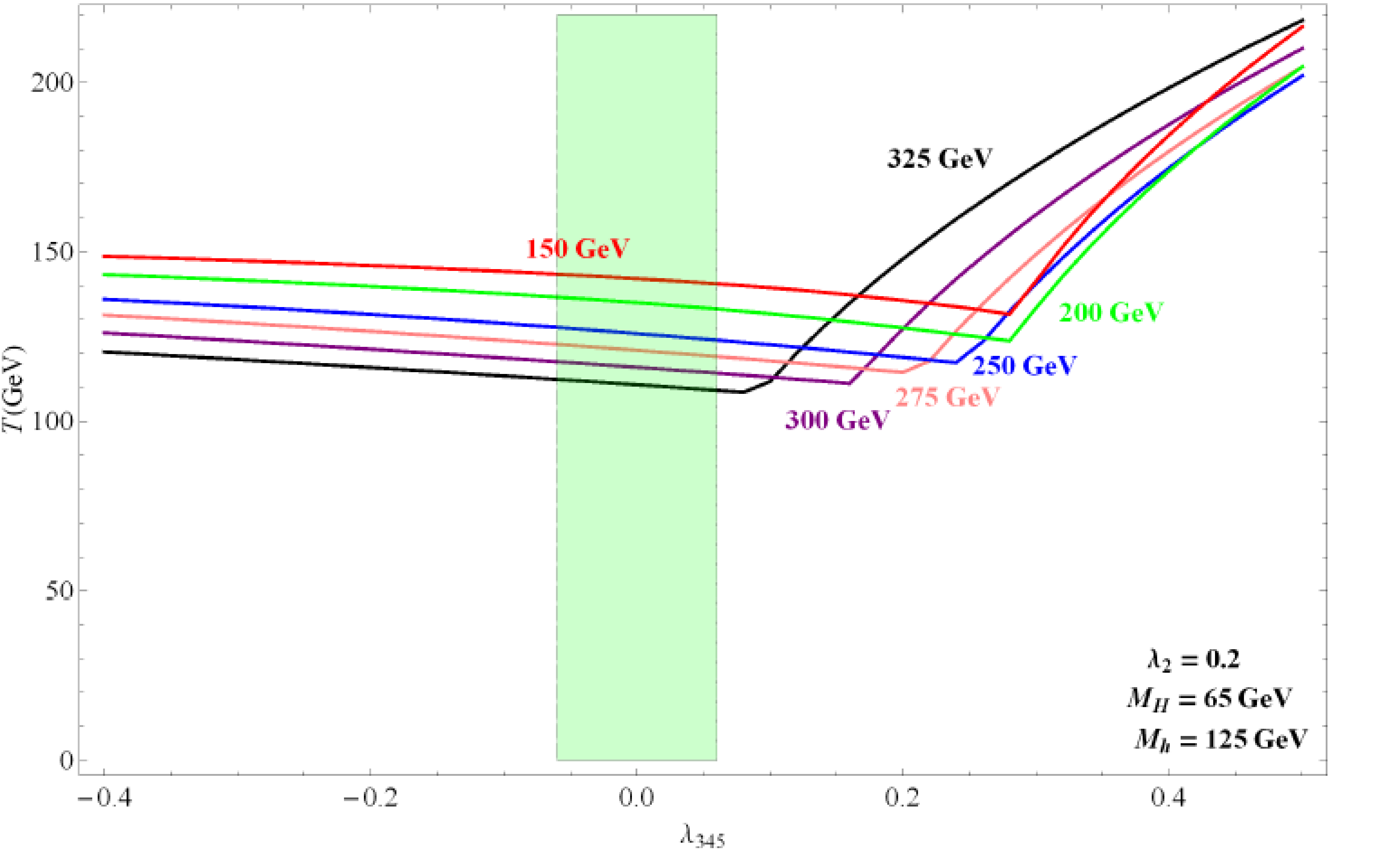
→ I2 → I1

Allowed MH+=MA between 275 and 380 GeV (one step)

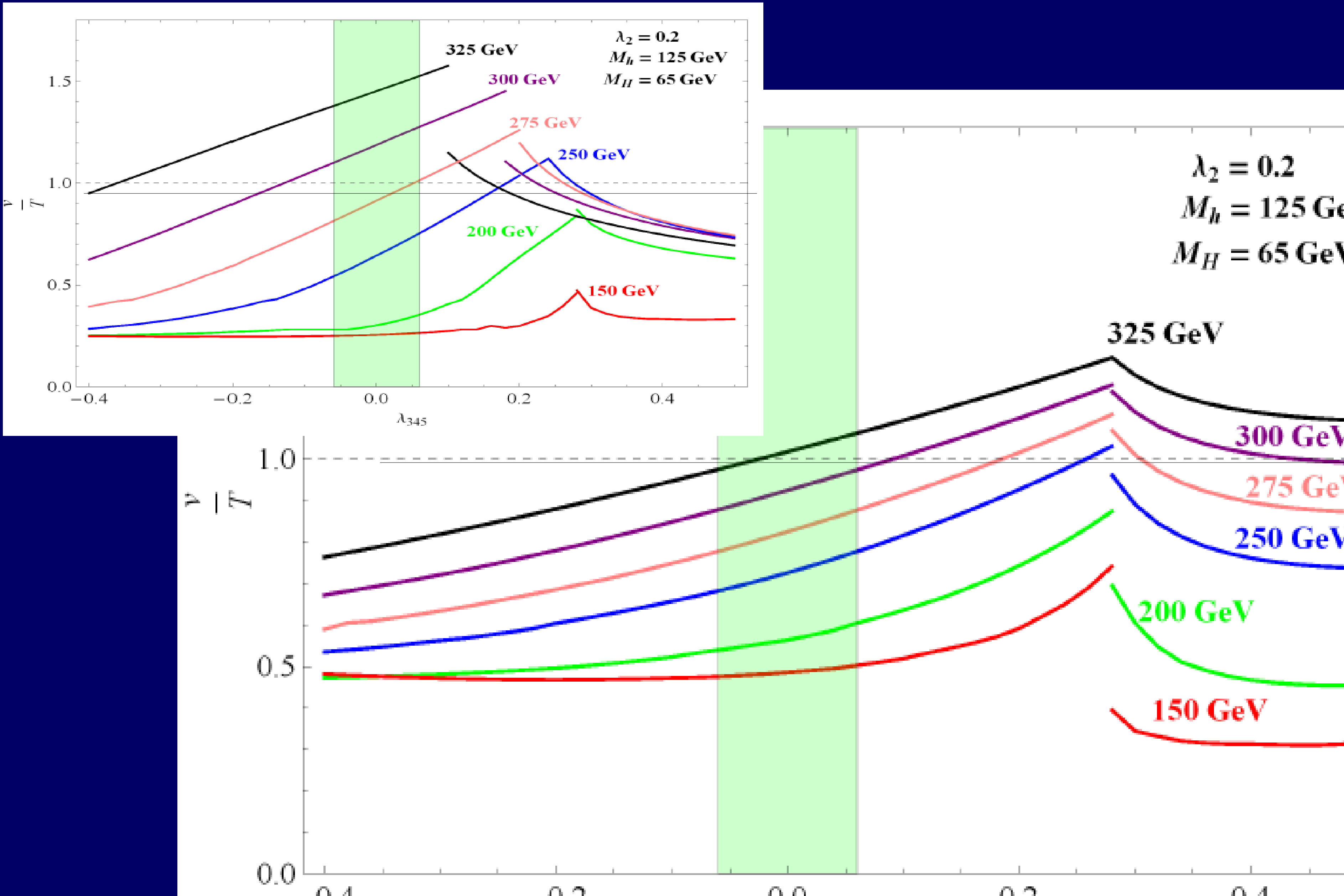
λ_{345}

Xenon100 bound

T_{EW} as a function of λ_{345}



Role of Coleman-Weinberg



Conclusion

Strong first order phase transition in IDM possible for realistic mass of Higgs boson (125 GeV)

and DM (~65 GeV) for

1/ heavy (degenerate) H+ and A with mass

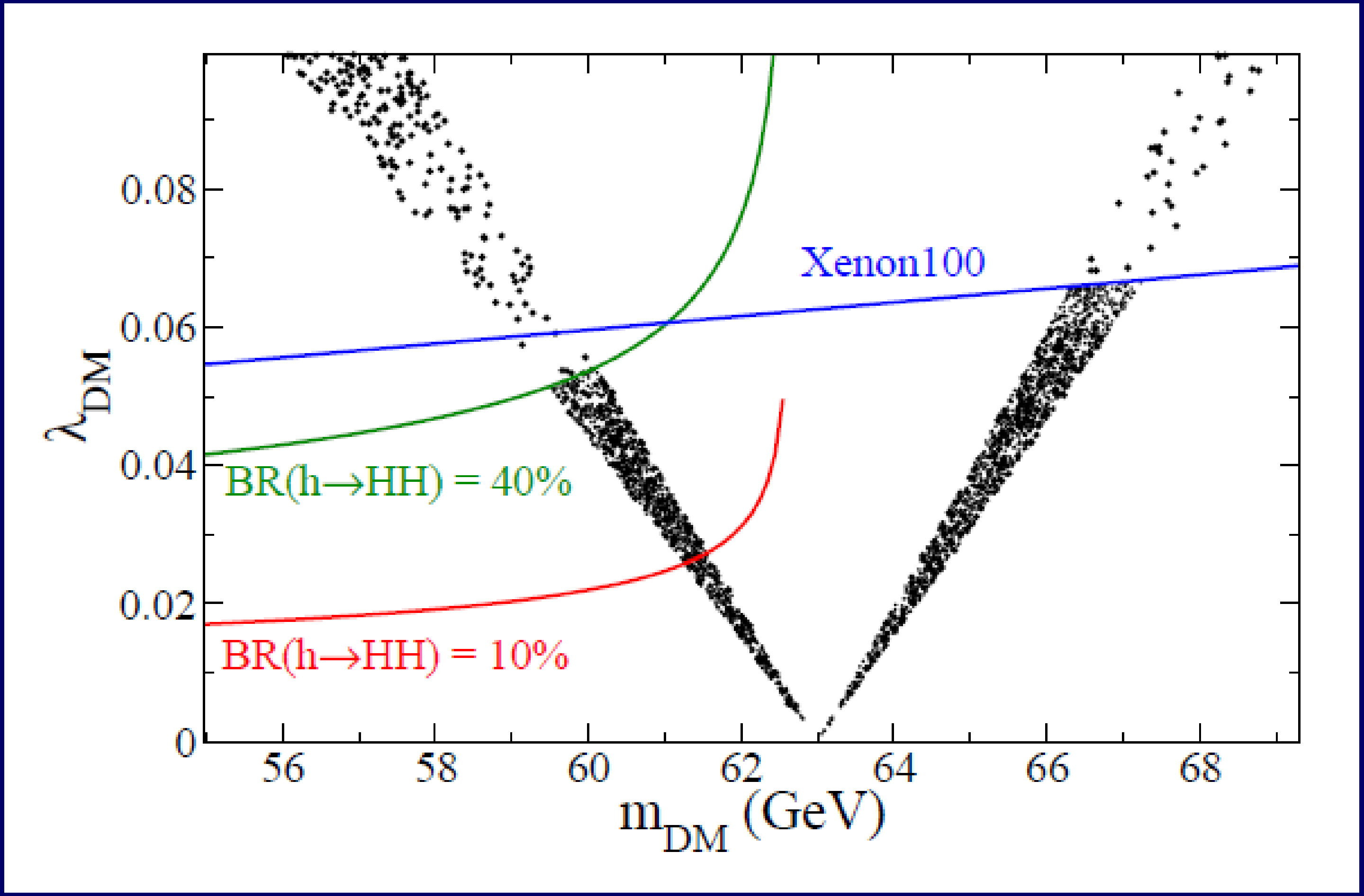
275 -380 GeV

2/ low value of hHH coupling $|\lambda_{345}| < 0.1$

3/ Coleman-Weinberg term important

Our results in agreement with recent papers on IDM
Borach, Cline 1204.4722
Chowdhury et al 1110.5334 (DM as a trigger of strong EW PT)
(on 2HDM Cline et al, 1107.3559 and Kozhusko..1106.0790)

D. Borach, J. Cline
Inert Doublet DM with Strong EW phase transition 1204.4722[hep-ph]



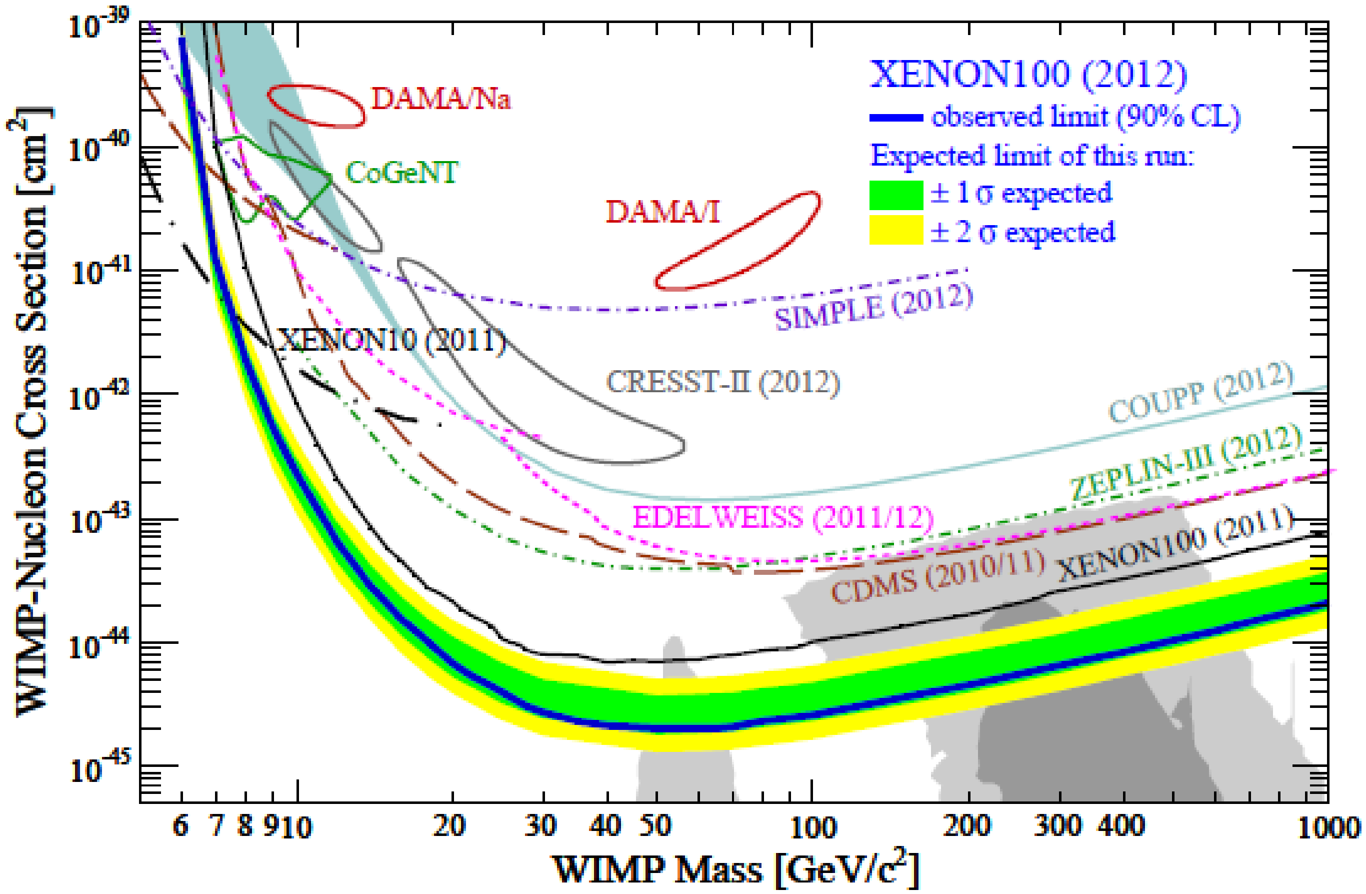
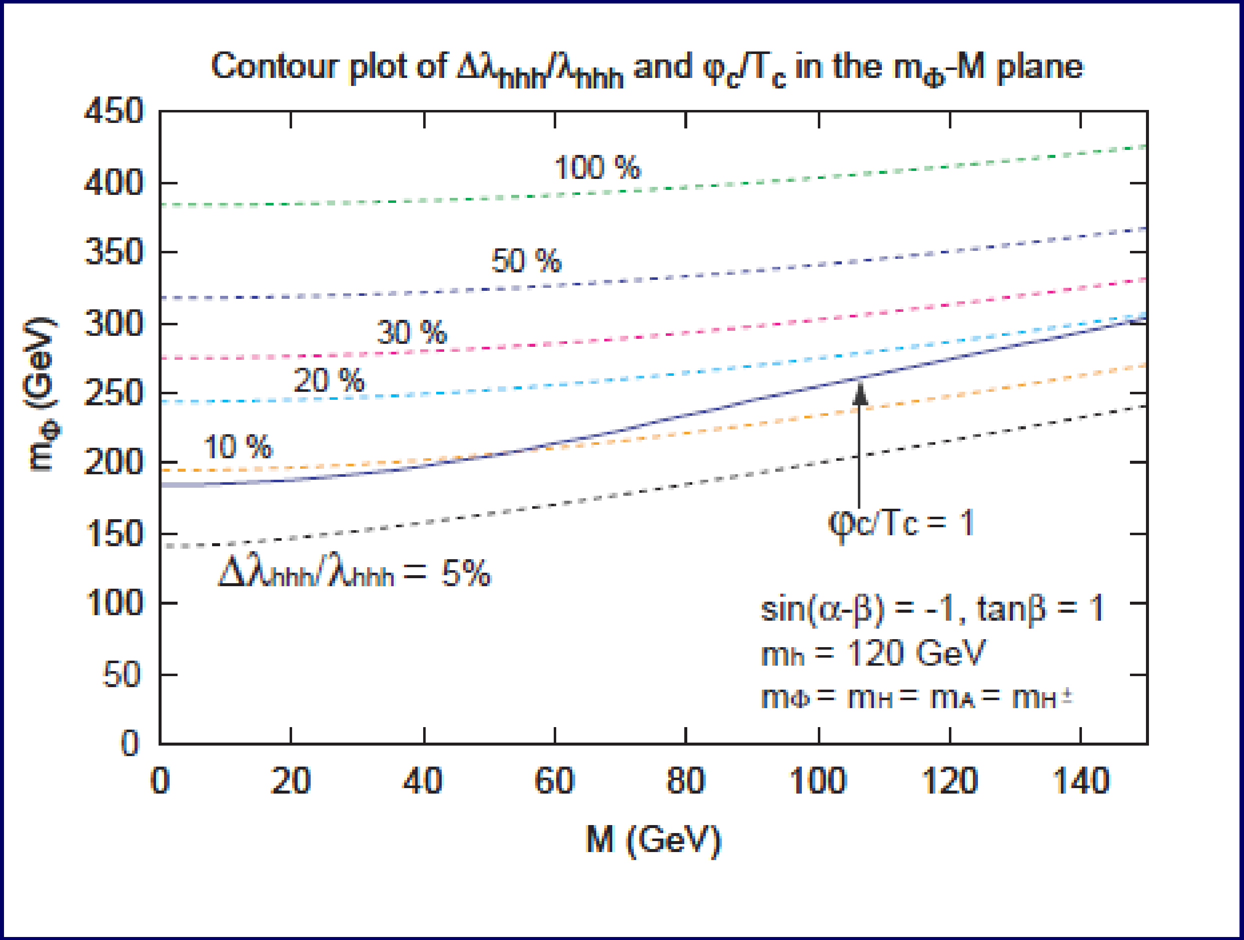


FIG. 3: New result on spin-independent WIMP-nucleon scattering from XENON100: The expected sensitivity of this run is shown by the green/yellow band ($1\sigma/2\sigma$) and the resulting exclusion limit (90% CL) in blue. For comparison, other experimental results are also shown [19–22], together with



Contour plot of $\Delta\lambda_{hhh}/\lambda_{hhh}$ and φ_c/T_c in the m_Φ-M plane
100 %
50 %
30 %
20 %
10 %
$\varphi_c/T_c = 1$
$\Delta\lambda_{hhh}/\lambda_{hhh} = 5\%$
$\sin(\alpha-\beta) = -1$, $\tan\beta = 1$
$m_h = 120$ GeV
$m_\Phi = m_H = m_A = m_{H^\pm}$
m_Φ (GeV)
M (GeV)
0
50
100
150
200
250
300
350
400
450
20
40
60
80
100
120
140