Fate of electroweak symmetry in the early Universe: Non-restoration and trapped vacua in extended Higgs sectors

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[2103.12707 and tbp]

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DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

EW symmetry in the early universe

Standard Model

EW symmetry conserved in early universe

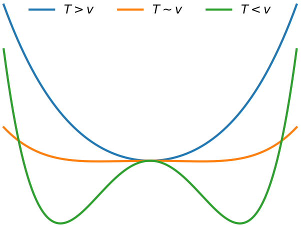
$\downarrow$

EW (cross over) phase transition at $T \sim v$

$\downarrow$

EW symmetry broken at $T = 0$

Each step is a model-dependent feature!



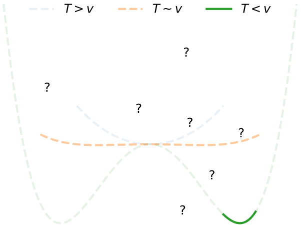
Models with extended scalar sectors

Other possiblities:

- $\rightarrow$ EW symmetry non-restoration (SnR)
- $\rightarrow$ EW 1st-order phase transitions (FOEWPT)
- $\rightarrow$ Vacuum trapping

Classify parameter space

Phenomenological consequences



Early universe ↔ Today's phenomenology

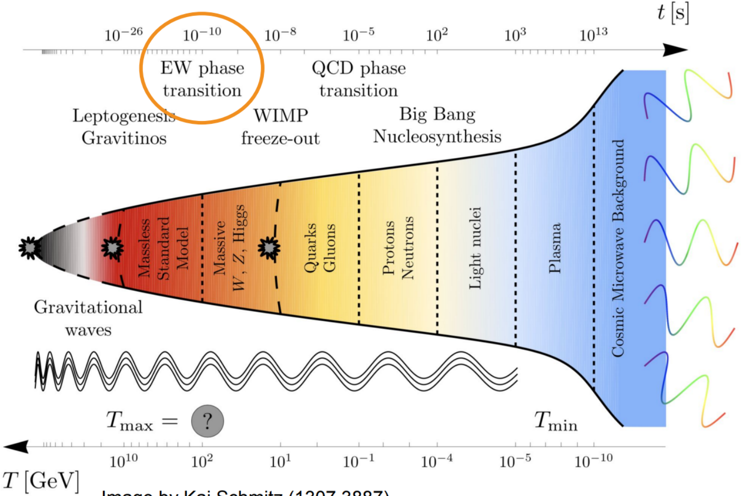
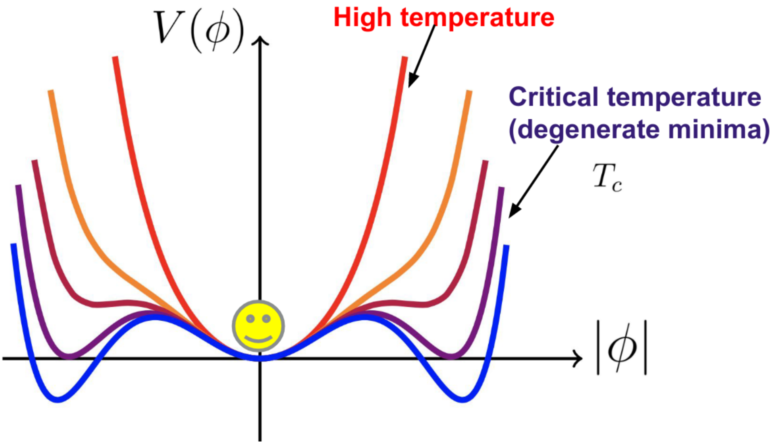


Image by Kai Schmitz (1307.3887)

EW baryogenesis
Gravitational waves } Require first-order EW phase transition

First-order EW phase transition

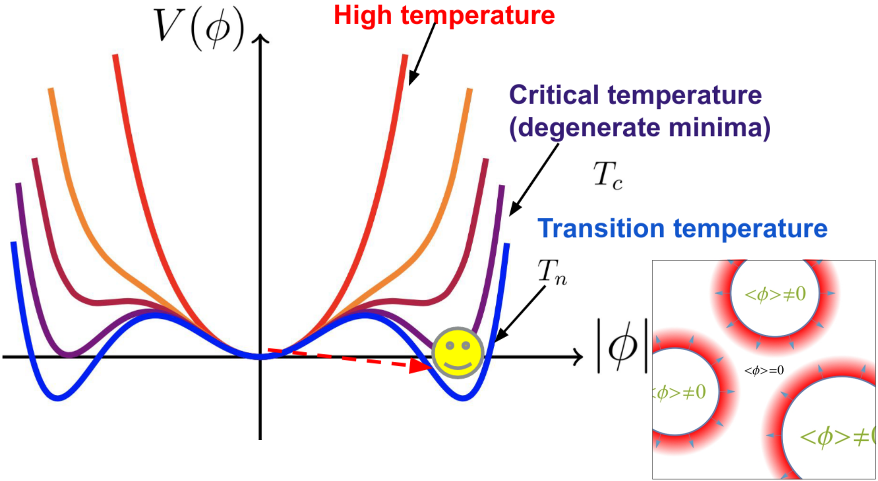
[Slide: Olalla Olea, Susy2021]



"False" minimum and "true" (EW) minimum separated by potential barrier

First-order EW phase transition

[Slide: Olalla Olea, Susy2021]

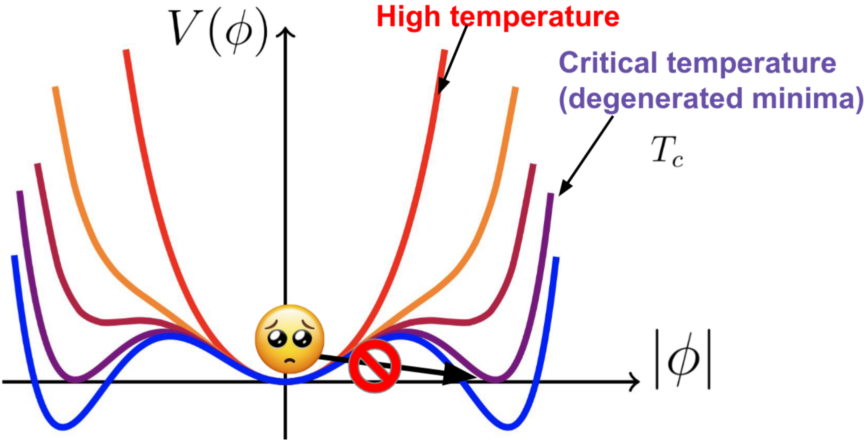


[Jose Miguel No]

"Strong" first-order phase transition: $v_n/T_n > 1$

Vacuum trapping

[Slide: Olalla Olea, Susy2021]

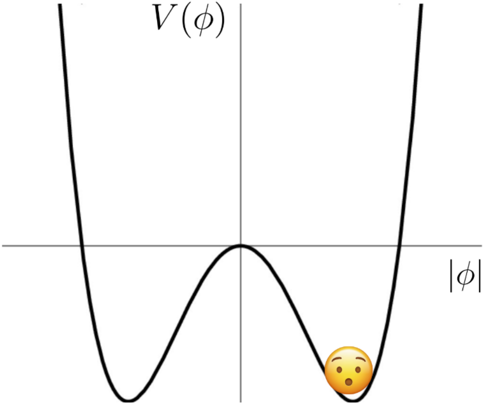


Phenomenologically not viable $\rightarrow$ exclusions even tough EW min. is global min.

EW symmetry non-restoration

[Slide: Olalla Olea, Susy2021]

$T >$ EW scale:



Non-standard cosmological history, high-scale EW baryogenesis

The (Next-to) 2 Higgs Doublet Model: (N)2HDM

$$\begin{aligned}\text{N2HDM} &= \text{SM}(\phi_1) + \text{Second Higgs Doublet}(\phi_2) + \text{Real Scalar Singlet}(\phi_s) \\ &= \text{2HDM}(\phi_1, \phi_2) + \text{Real Scalar Singlet}(\phi_s)\end{aligned}$$

Scalar tree-level potential

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.]$$
$$\left(+\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2\right)$$

Symmetries: Z_2: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$ and $\phi_s \to \phi_s$, only softly broken by m_{12}^2
(Z_2': $\phi_1 \to \phi_1$, $\phi_2 \to \phi_2$ and $\phi_s \to -\phi_s$, spontaneously broken by v_s)

Extension of Z_2 to Yukawa sector $\Rightarrow$ 4 types of the (N)2HDM

EW vacuum:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \rho_1 + i\sigma_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \rho_2 + i\sigma_2)/\sqrt{2} \end{pmatrix}, \quad \left(\Phi_S = (v_S + \rho_S + i\sigma_S)/\sqrt{2}\right)$$

BSM Particles:

CP-even scalars $h_1, h_2(, h_3)$, CP-odd scalar A, charged scalars $H^\pm$

Scalar potential at finite temperature

$$V_{\rm eff} = V_{\rm tree}(\rho_i) + V_{\rm CW}(\rho_i) + V_{\rm CT}(\rho_i) + V_{\rm T}(\rho_i, T) + V_{\rm daisy}(\rho_i, T)$$

$V_{\rm tree}$: Classical (tree-level) potential
$V_{\rm CW}$: Coleman-Weinberg potential → (one-loop) radiative corrections
$V_{\rm CT}$: UV-finite counterterm potential → OS conditions
$V_{\rm T}$: Finite-T corrections, explicitly depends on T
$V_{\rm daisy}$: Resummation of bosonic "Matsubara" zero modes (Arnold-Espinosa)

$$V_{\rm CW}(\phi_i) = \sum_j \frac{n_j}{64\pi^2} (-1)^{2s_i}\, m_j(\phi_i)^4 \left[\ln\left(\frac{|m_j(\phi_i)^2|}{\mu^2}\right) - c_j\right]$$

$$V_T(\phi_i) = \sum_j \frac{n_j\, T^4}{2\pi^2} J_\pm \left(\frac{m_j^2(\phi_i)}{T^2}\right)$$

$$V_{\rm daisy} = -\sum_k \frac{T}{12\pi}\left(\left(\bar{m}_k^2(\phi, T)\right)^{\frac{3}{2}} - \left(m_k^2(\phi)\right)^{\frac{3}{2}}\right)$$

[More details: M.Quiros, hep-ph/9901312]

Thermal history of vacuum configurations

Analysis strategy:

$\mathbf{T = 0}$ analysis: Generate viable parameter points

Theoretical constraints: (Meta-)stability of the EW vacuum, perturbativity, unitarity

Experimental constraints: h_{125}, collider searches, flavour physics, EW precision observables

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$\mathbf{T > 0}$ analysis: Track the vacuum adopted by the universe as a function of T

Minimization problem: Find the (co-existing minima) of the potential at each T

Determine (strong) first-order phase transitions: Nucleation (transition) temperature T_n

$$\Gamma(T) = A(T)\, e^{-S_3(T)/T} \quad \rightarrow \quad S_3(T_n)/T_n \sim 140$$

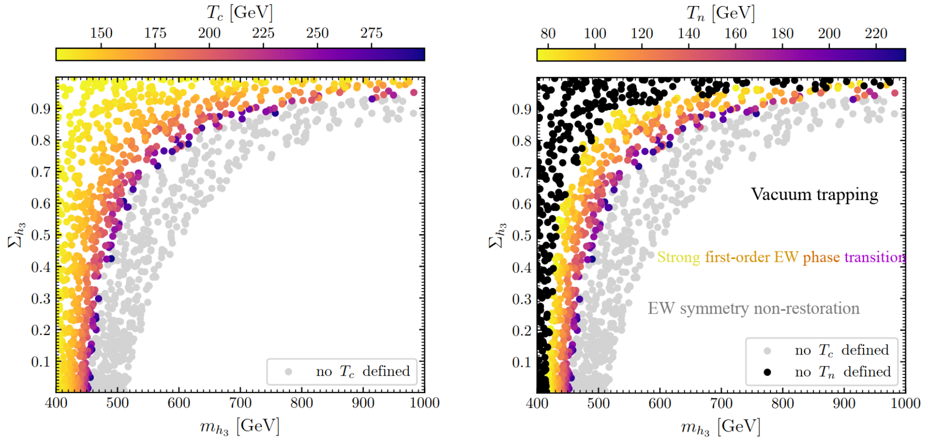
Categorize parameter space of the model

$\rightarrow$ First-order EW phase transitions $\rightarrow$ EW symmetry non-restoration $\rightarrow$ Vacuum trapping

FOEWPT, EW SnR and vacuum trapping in a box

[TB, S. Heinemeyer, J.M. No, O. Olea, G. Weiglein, 2103.12707]

N2HDM: Alignment limit, $\tan\beta = 2$, $m_{h_1} = 125\,\mathrm{GeV}$, $m_{h_2} = 400\,\mathrm{GeV}$, $m_A = m_{H^\pm} = 650\,\mathrm{GeV}$



Σ_{h_3}: Singlet admixture of h_3

$v_c/T_c > 1$ not a viable indicator of a FOEWPT

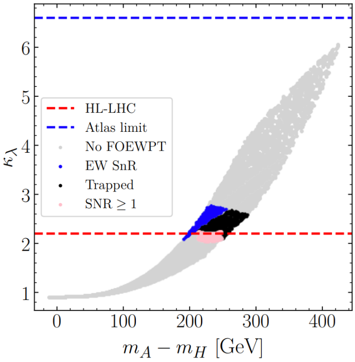
Presence of second Higgs doublet facilitates EW SnR

Future probes of the thermal history

[TB, S. Heinemeyer, J.M. No, O. Olea, G. Weiglein, tbp]

2HDM: Alignment limit, $\tan\beta = 3$, $m_H < m_A$, $600\,\mathrm{GeV} < m_A = m_{H^\pm} < 1000\,\mathrm{GeV}$

Colliders: HL-LHC

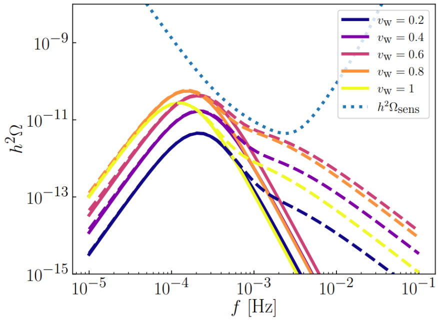


$$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$$

SNR: LISA Signal-to-noise ratio of GW signal

SnR: Symmetry non-restoration

GW signals from FOEWPT: LISA



$$h^2\Omega_{\mathrm{GW}}(f) = h^2\Omega_{\mathrm{sw}}(f) + h^2\Omega_{\mathrm{turb}}(f)$$

SNR $= \mathcal{O}(10\ldots100)$

depending on v_w: Bubble-wall velocity

Conclusions

Non-standard thermal histories in the (N)2HDM

→ **First-order EW phase transitions**

→ **EW symmetry non-restoration**

New constrains on the (N)2HDM from **vacuum trapping**

→ Presence of T_c not a sufficient indication for FOEWPT

→ Potential with global EW minimum at $T = 0$ might still be unphysical

Thermal analysis provides **guidance** as to where to look for new physics

→ Trilinear self-coupling of h_{125} (both EW SnR and FOEWPT)

→ Gravitational waves at LISA (FOEWPT)

Thanks!