Fate of the electroweak symmetry in the early Universe

Vacuum trapping and symmetry non restoration within the N2HDM

Based on 2103.12707

M. Olalla Olea Romacho

In collaboration with

T. Biekötter, S. Heinemeyer, J. M. No, G. Weiglein

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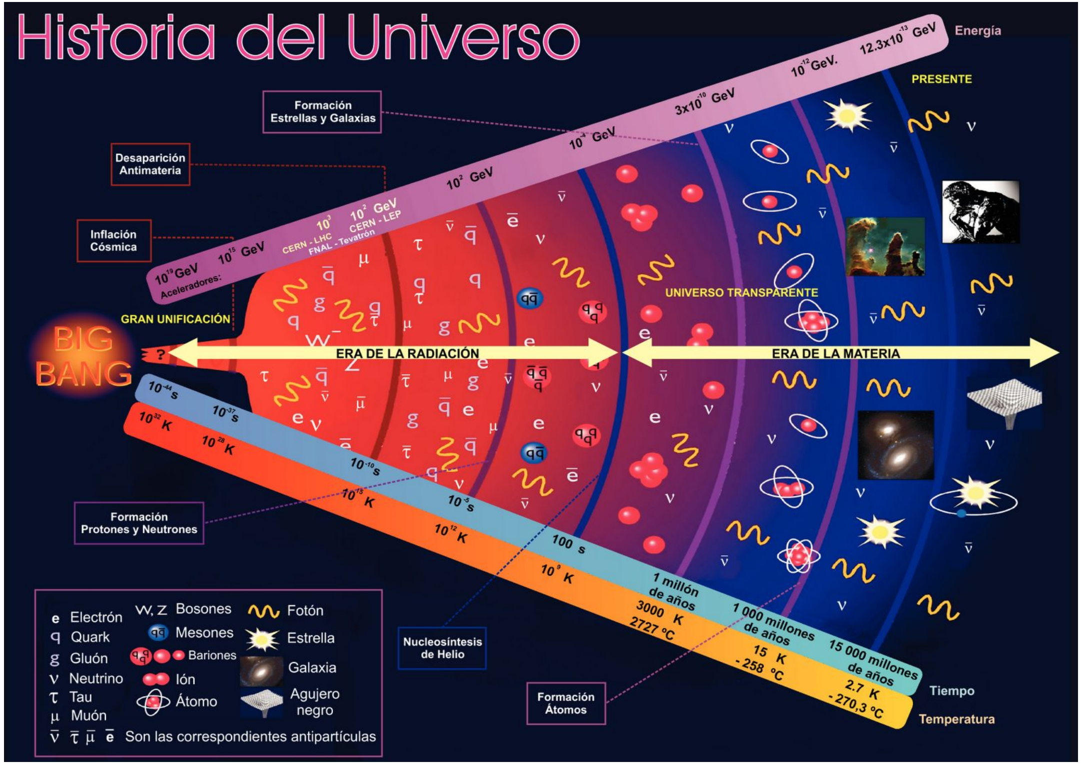
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

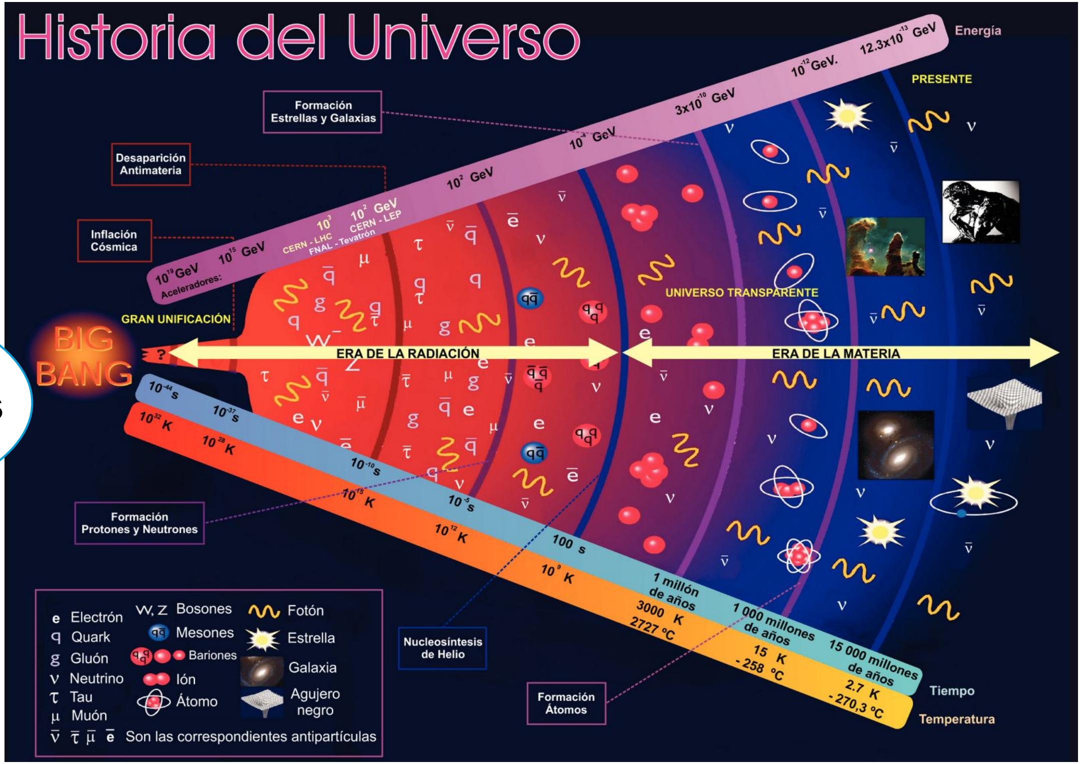
DESY.

Introduction



The first-order electroweak phase transition (FOEWPT) has been extensively studied in the literature

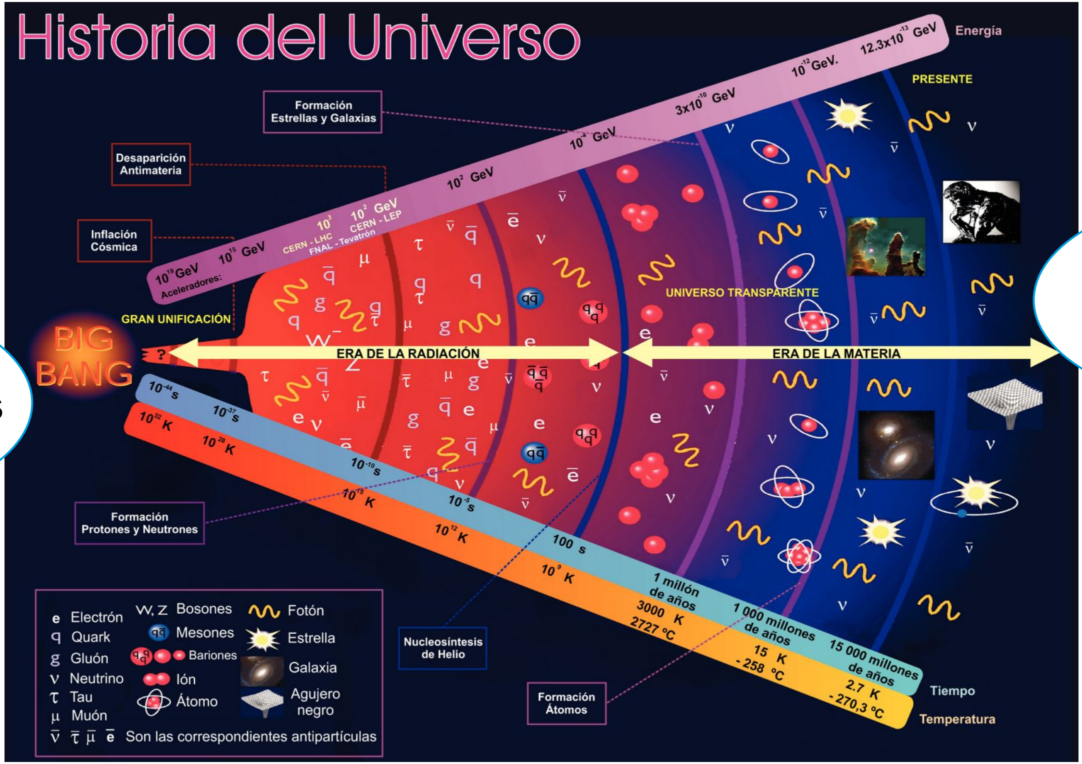
Introduction



EW Baryogenesis

The first-order electroweak phase transition (FOEWPT) has been extensively studied in the literature

Introduction



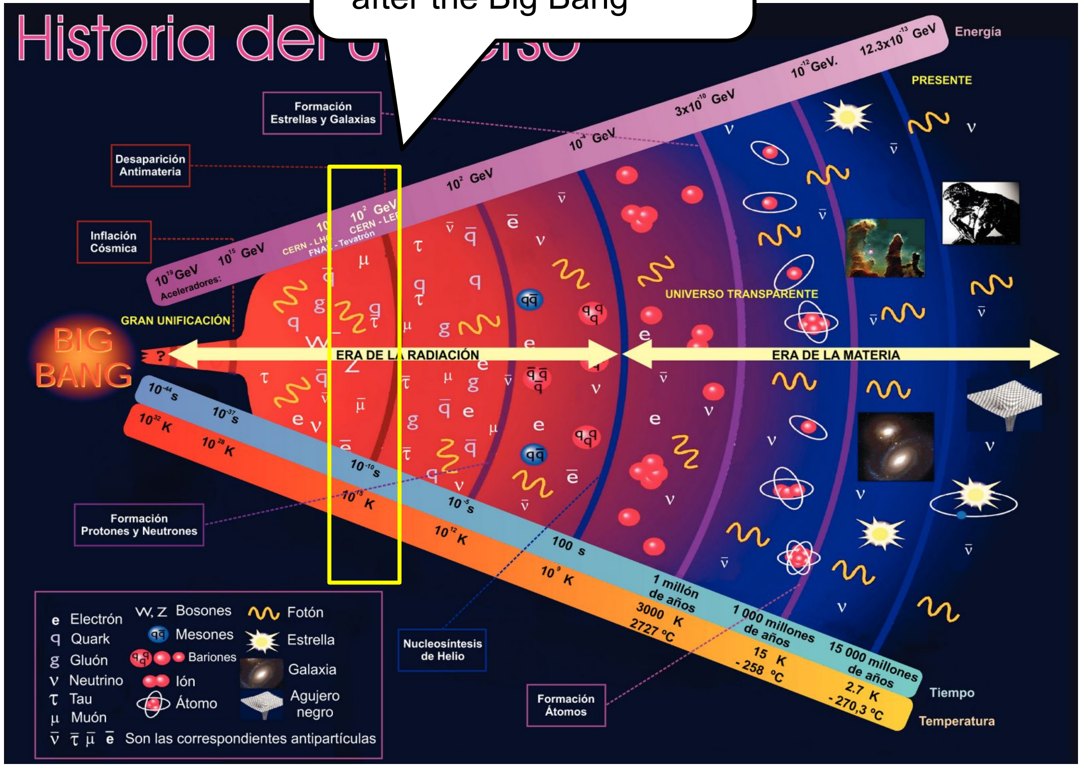
EW Baryogenesis

GW predictions

The first-order electroweak phase transition (FOEWPT) has been extensively studied in the literature

Introduction

FOEWPT could have happened 10^{-11} seconds after the Big Bang

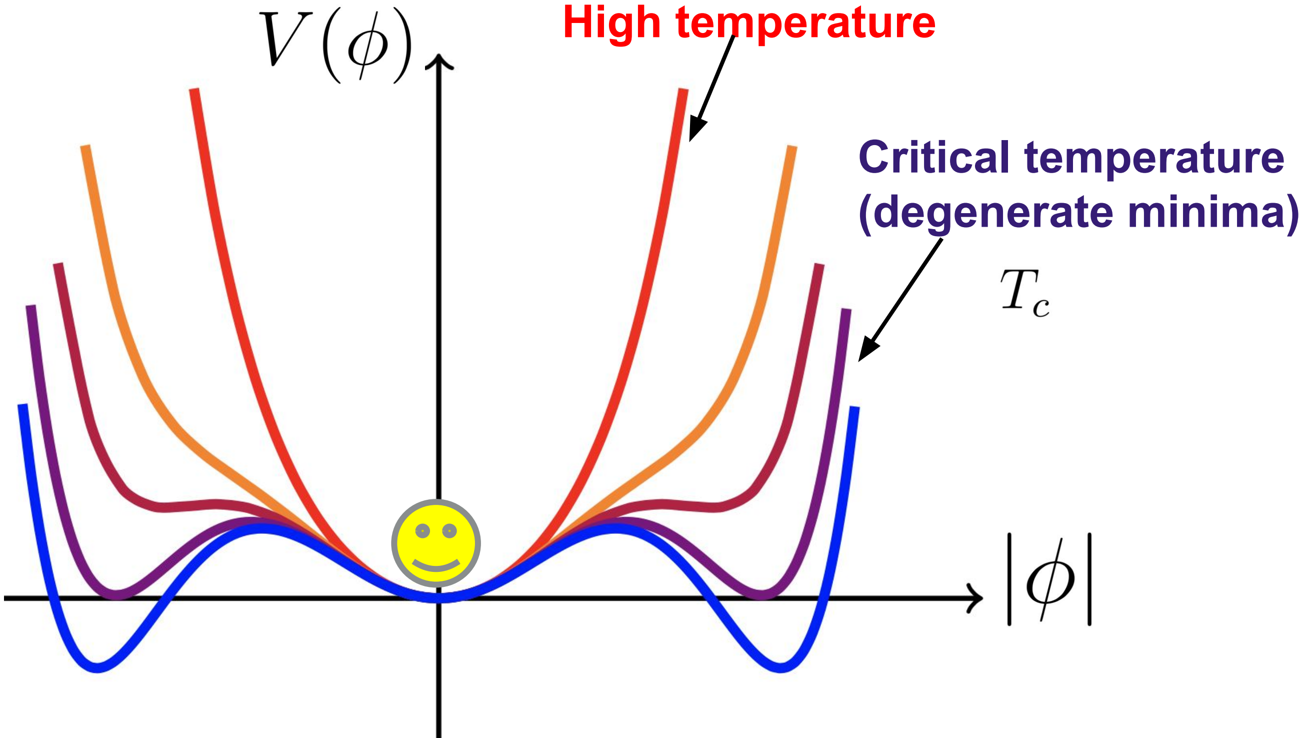


We are interested in other finite-temperature effects that may be relevant during the electroweak cosmological epoch

Introduction

What is a FOEWPT?

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$



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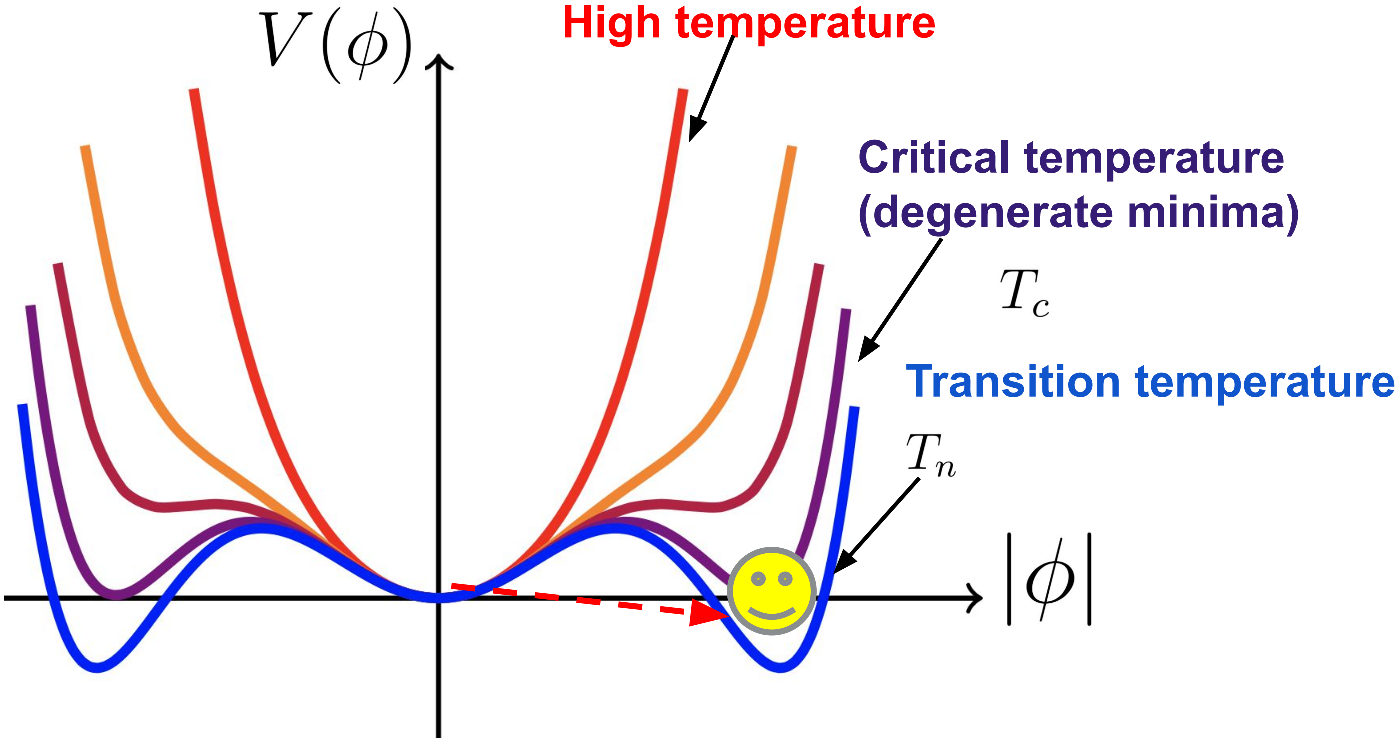

Introduction

- Baryogenesis requires three conditions to be accomplished (Sakharov conditions):
  - Baryon number violation.
  - CP violation.
  - **Departure from thermal equilibrium: FOEWPT**

If baryon and CP violating reaction in thermal equilibrium:
$A + B \rightleftarrows C + D$
The inverse reaction washes out the potential baryon asymmetry: we need to fall out of equilibrium.

Introduction

- The Standard Model (SM) does not feature a FOEWPT
- Need for Beyond the Standard Model Physics?
- **Extended Higgs sectors** are a popular choice that could accommodate a FOEWPT.
  - Active field: study of the FOEWPT in singlet extensions of the SM, doublet extensions…

Introduction

- Which other finite-temperature effects could occur to the thermal history of models with extended Higgs sectors?
- Two phenomena that bring new constraints to the parameter space of these models:
  - **Electroweak (EW) symmetry non-restoration (SNR) at high temperature**
  - **Vacuum trapping**

Introduction

- Which other finite-temperature effects could occur to the thermal history of models with extended Higgs sectors?
- Two phenomena that bring new constraints to the parameter space of these models:
  - **Electroweak (EW) symmetry non-restoration (SNR) at high temperature**
  - **Vacuum trapping**

Not always handled well in the literature

Model

The tree-level Next-to-2HDM (N2HDM)

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

Three fields are allowed to acquire a vev (assuming CP and charge conservation)

$$\boxed{\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \rho_1 + i\eta_1\right) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \rho_2 + i\eta_2\right) \end{pmatrix}, \quad \Phi_S = v_S + \rho_3,}$$

Model

The tree-level Next-to-2HDM (N2HDM)

- After spontaneous symmetry breaking we are left with 5 physical scalars:
  - 3 CP-even h_1, h_2, h_3
  - 1 CP-odd A
  - 2 charged scalars $H^\pm$
- Yukawa type II

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Model

Experimental and theoretical constraints at zero-temperature

Theoretical	Experimental
Perturbative Unitarity	Electroweak precision constraints
Boundeness from Below	Flavour Constraints
Vacuum Stability	Higgs Searches and Higgs measurements

EVADE

HiggsBounds and **HiggsSignals**

Model

The 1-loop effective potential

$\boxed{T = 0}$

$$V_{\text{eff}}^{T=0}(\rho_1, \rho_2, \rho_3) = V_{\text{tree}} + V_{\text{CW}}(\rho_1, \rho_2, \rho_3)$$

Coleman-Weinberg potential: sum of 1PI one-loop diagrams with arbitrary numbers of external ϱ_i and particles of the theory running in the loop.

$\boxed{T \neq 0}$ Finite Temperature Field Theory

Model

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$$V_{\text{eff}}^{T>0}(\rho_1, \rho_2, \rho_3) = V_{\text{tree}} + V_{\text{CW}}(\rho_1, \rho_2, \rho_3) + V_{\text{T}}(\rho_1, \rho_2, \rho_3, T)$$

Model

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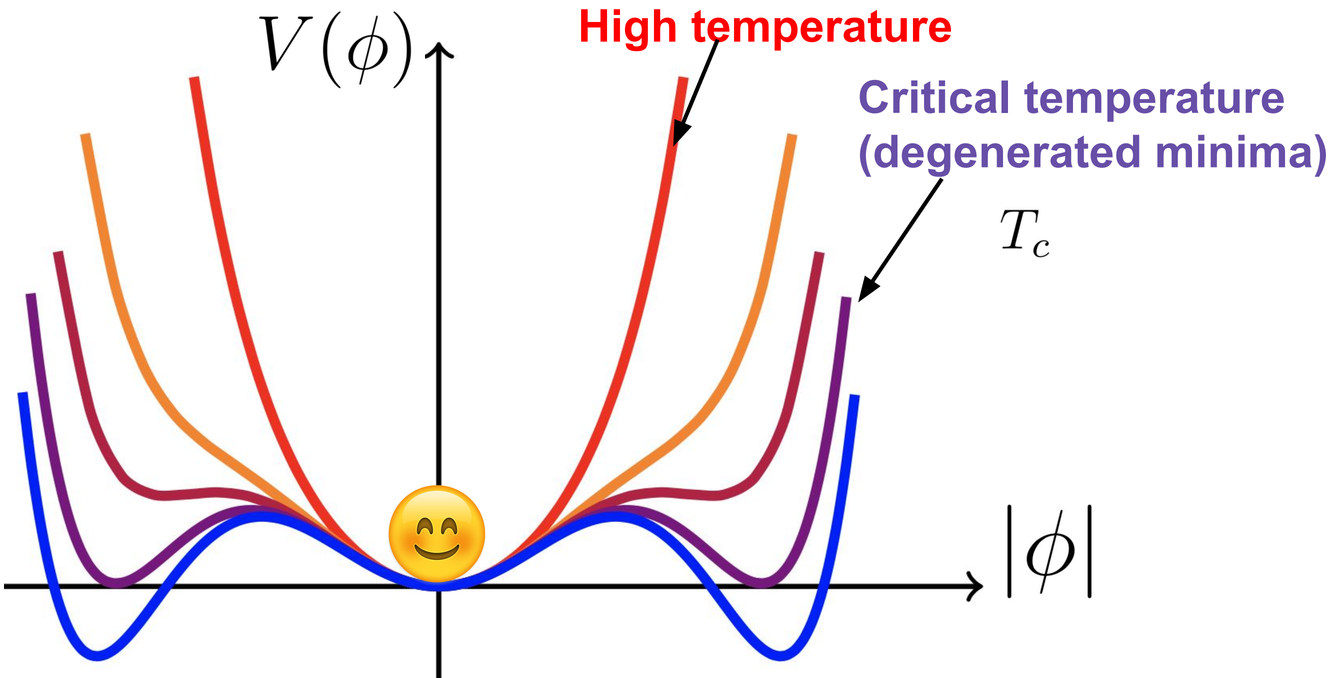
$$V_{\text{eff}}^{T>0}(\rho_1,\rho_2,\rho_3) = V_{\text{tree}} + V_{\text{CW}}(\rho_1,\rho_2,\rho_3) + V_{\text{T}}(\rho_1,\rho_2,\rho_3,T) + V_{\text{Daisy}}$$

$$\boxed{V_{\text{Daisy}} = -\sum_k \frac{T}{12\pi}\left(\left(\bar{m_k}^2(\phi,T)\right)^{\frac{3}{2}} - \left(m_k^2(\phi)\right)^{\frac{3}{2}}\right)}$$

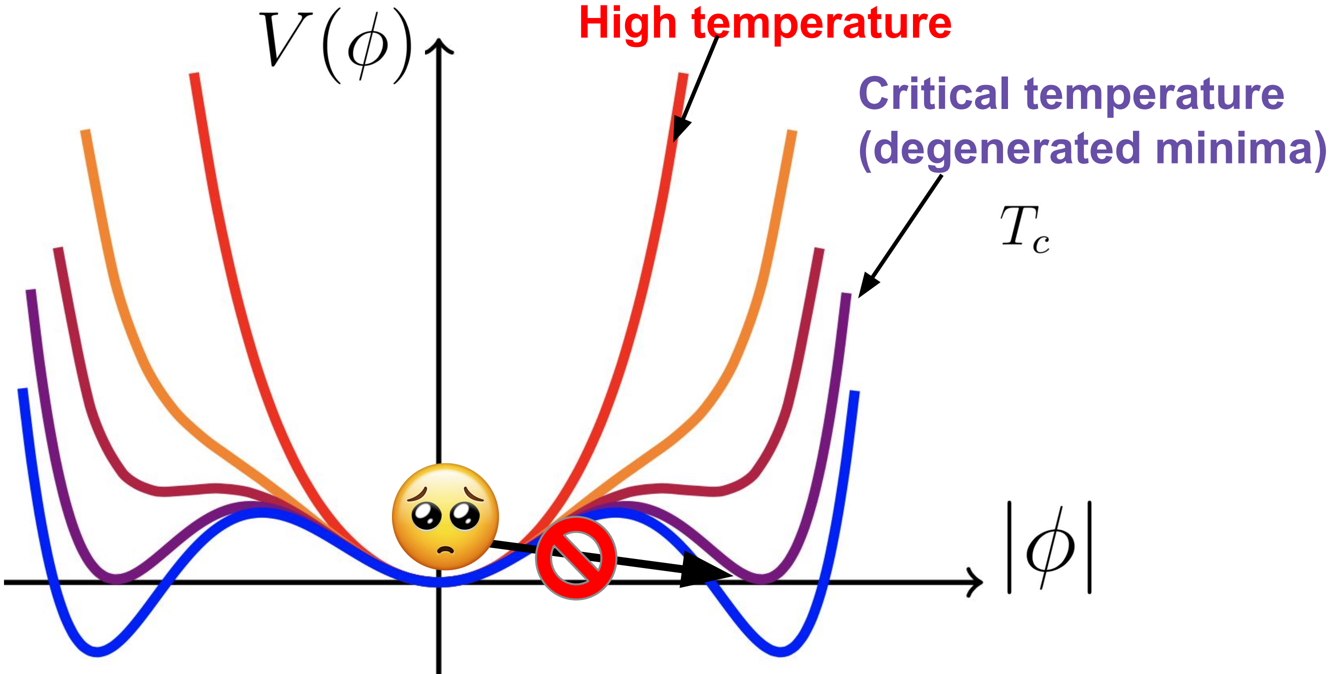
Vacuum trapping

- What is “vacuum trapping” and how does it change the picture of a usual FOEWPT?

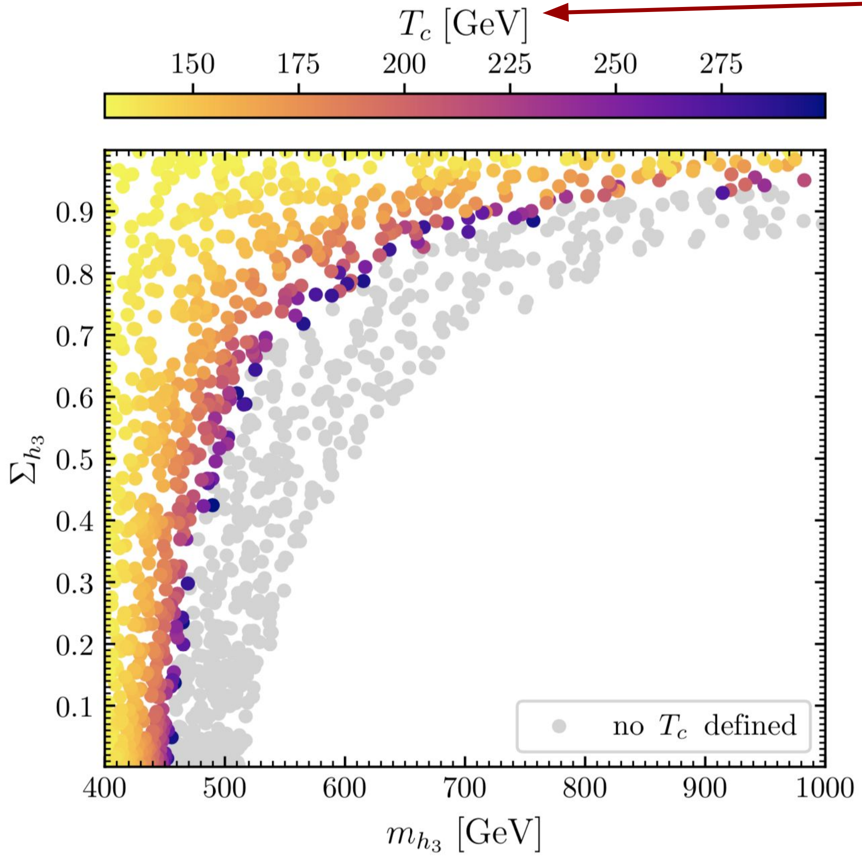


Vacuum trapping

- **Vacuum trapping**: The transition probability is not big enough for the transition to take place. The Universe can not reach the usual electroweak vacuum configuration at T=0.



Vacuum trapping

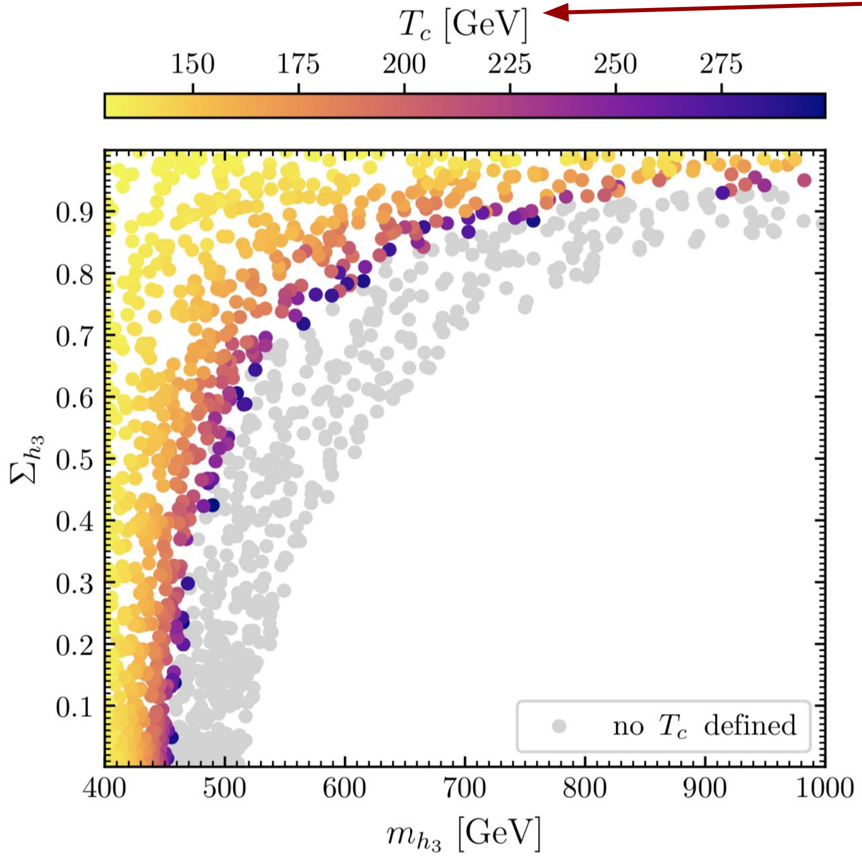


Critical temperature: degenerate minima

1. We perform a scan where we vary the **mass of one of the CP-even Higgs** bosons, its **singlet component** and the **singlet vev**.
   a. In this model there are 3 CP-even Higgs bosons and they mix.

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

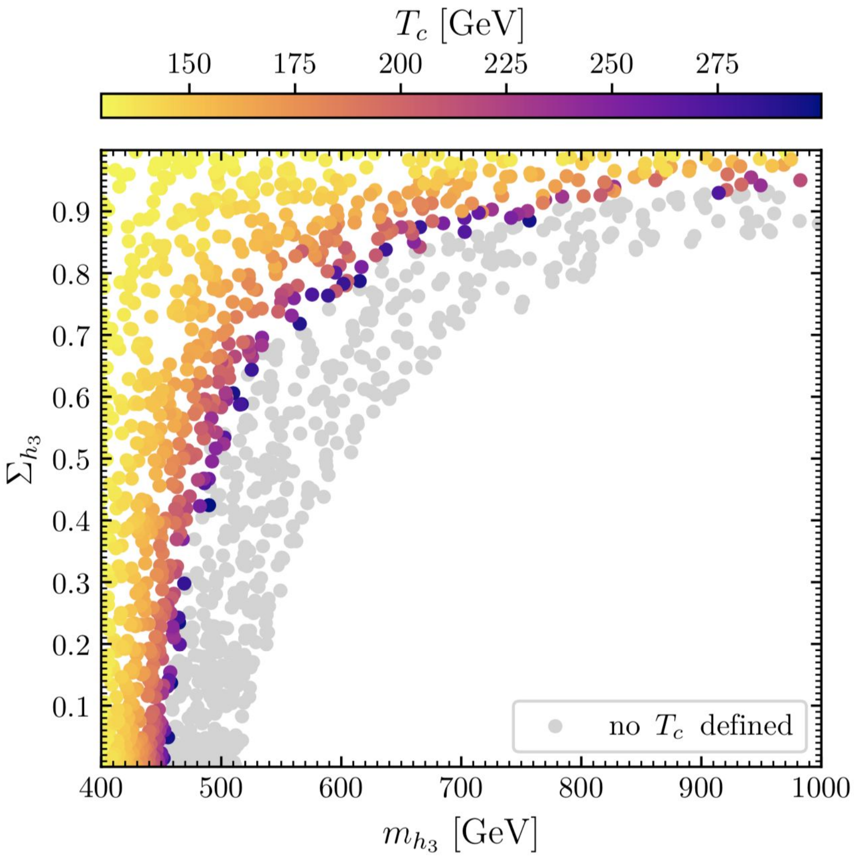
Vacuum trapping

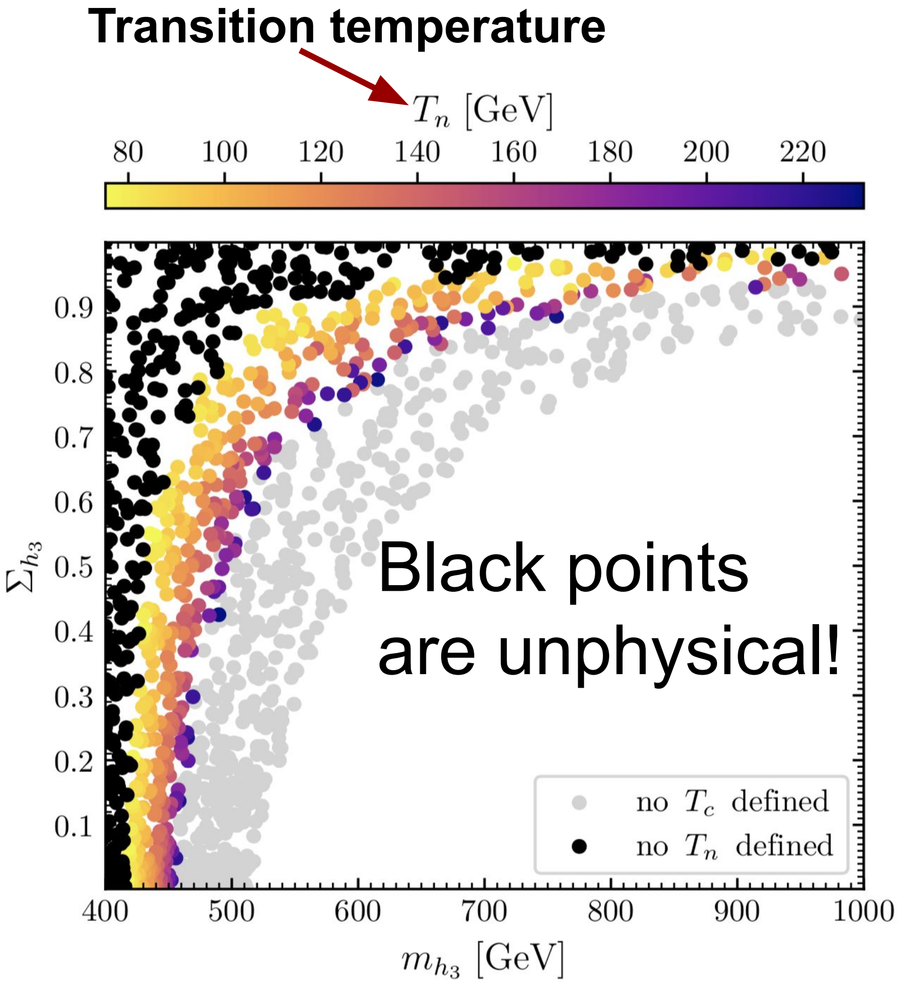


Critical temperature: degenerate minima

1. We perform a scan where we vary the **mass of one of the CP-even Higgs** bosons, its **singlet component** and the **singlet vev**.
2. There are numerous studies that regard the existence of a critical temperature as a **sufficient condition** for the FOEWPT to occur.
3. **According to this plot**, a big part of the studied parameter space features a FOEWPT.

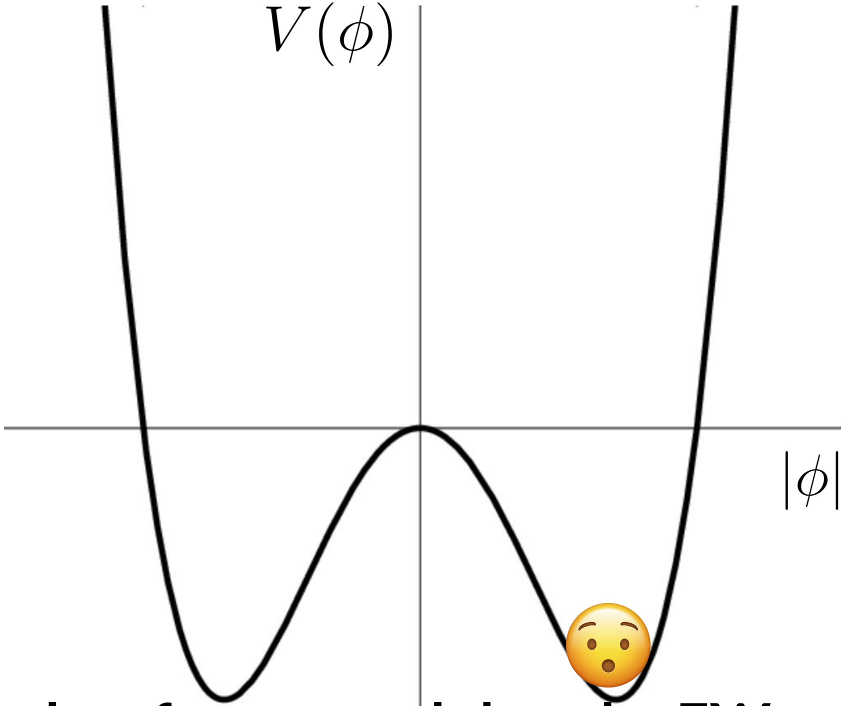
Vacuum trapping





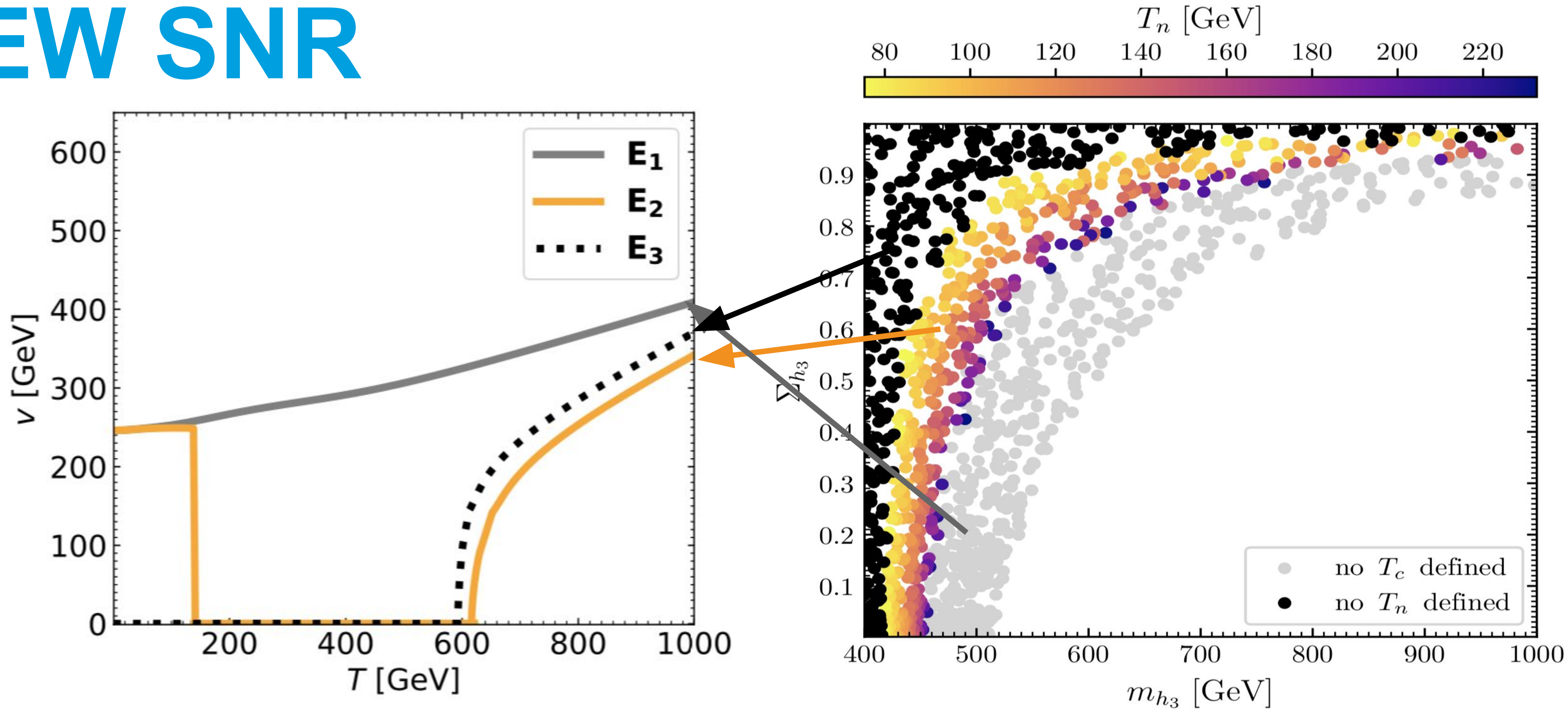
EW SNR

At large temperature values (in comparison to the electroweak scale):



It is commonly **taken for granted that the EW symmetry gets restored** at high temperature (in the very early Universe). This is **not always true**

EW SNR



- **E1**: The electroweak symmetry is **never restored**.
- **E2**: There is a **FOEWPT**. The EW symmetry gets broken again at high temperatures.
- **E3** is **trapped in a false minimum** at T=0. This point also shows EWSNR at high temperatures.

EW SNR

- The 1-loop effective potential can be approximated to a expression that can be handled **analytically** **in the high temperature limit**.

- We can compute the **curvature at the origin of field space** in this approximation: $H_{ij}^0 = \partial^2 V / \partial\rho_i \partial\rho_j |_{(0,0,0)}$

The conditions for the origin to be a minimum are:

$$H_{11}^0 > 0$$

$$H_{11}^0 H_{22}^0 - \left(H_{12}^0\right)^2 > 0$$

$$H_{33}^0 > 0$$

In the high temperature limit these conditions can be simply cast in three coefficients

$$\boxed{c_{ii} \equiv \lim_{T\to\infty} H_{ii}^0 / T^2 > 0}$$

EW SNR

Conditions for the stability of the origin of field space at high temperature:

$$\boxed{c_{ii} \equiv \lim_{T\to\infty} H^0_{ii}/T^2 > 0}$$

$$\boxed{\begin{aligned}
c_{11} &\simeq -0.025 + c_1 - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_1\sqrt{c_1} + \lambda_3\sqrt{c_2} + \frac{1}{2}\lambda_4\sqrt{c_2} + \frac{1}{4}\lambda_7\sqrt{c_3}\right) \\
c_{22} &\simeq -0.025 + c_2 - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_2\sqrt{c_2} + \lambda_3\sqrt{c_1} + \frac{1}{2}\lambda_4\sqrt{c_1} + \frac{1}{4}\lambda_8\sqrt{c_3}\right) \\
c_{33} &= c_3 - \frac{1}{2\pi}\left(\lambda_7\sqrt{c_1} + \lambda_8\sqrt{c_2} + \frac{3}{4}\lambda_6\sqrt{c_3}\right) ,
\end{aligned}}$$

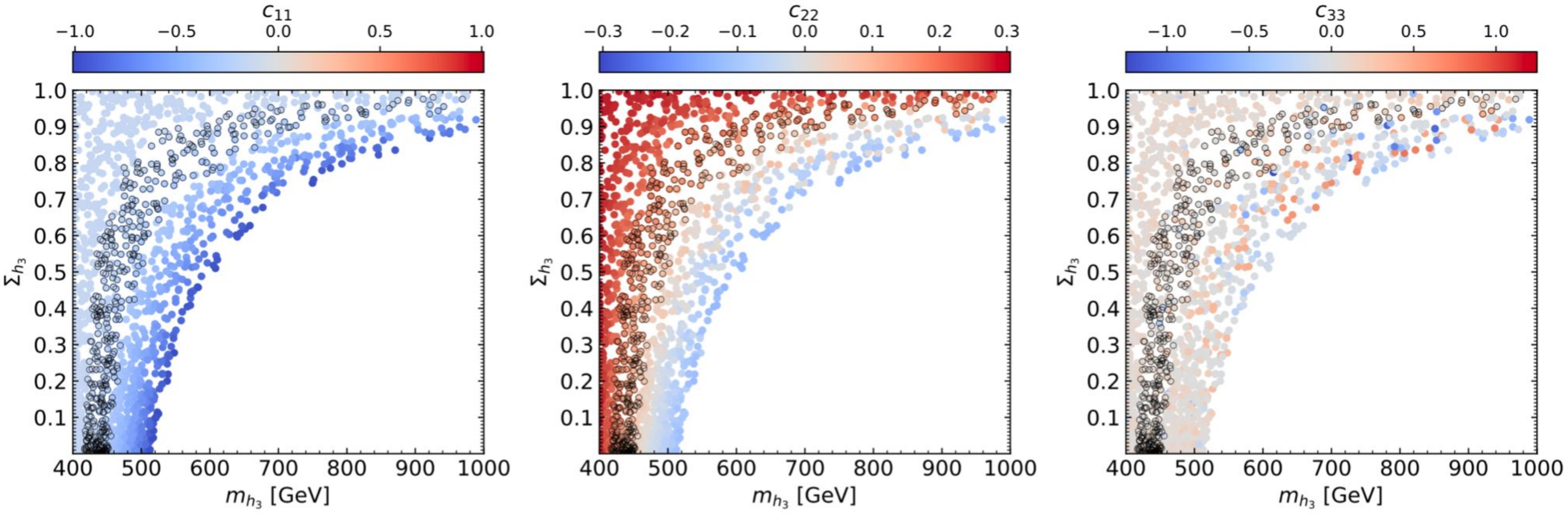
Linear combinations of gauge and quartic couplings

- **A negative coefficient cii** indicates that the origin of potential is unstable in the **direction of ρi** at high temperature.

EW SNR

$$c_{ii} \equiv \lim_{T\to\infty} H^0_{ii}/T^2 > 0$$

- Due to the **large positive contribution to c22** from the Yukawa coupling of the top quark, EW symmetry restoration will occur at the origin of field space when c11 >0 and c33 >0.
- Under certain conditions, the coefficients c11 and c33 **also control the restoration behavior** outside the origin of field space.



Conclusions

- The quick assessment of the **coefficients cii** can identify points in the N2HDM parameter space where the EW symmetry is broken at high temperature. If we are interested in a **particular thermal history** where the EW is not restored we can **easily impose this condition** to our model.

- **SNR** can be present at high temperature for points that at a lower temperature feature a **FOEWPT**.

- A finite temperature analysis and the **calculation of the transition temperature are needed** in order to correctly specify the physical parameter space of our model.

Thank you for your attention!
Any questions?

Appendix

$$
\begin{aligned}
c_{11}^S = \lim_{T\to\infty} \Bigg\{ & -0.025 + c_1 + \frac{\lambda_7}{2}\frac{v_S^2(T)}{T^2} - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_1\sqrt{c_1 + \frac{\lambda_7}{2}\frac{v_S^2(T)}{T^2}}\right. \\
& \left. + \lambda_3\sqrt{c_2 + \frac{\lambda_8}{2}\frac{v_S^2(T)}{T^2}} + \frac{\lambda_4}{2}\sqrt{c_2 + \frac{\lambda_8}{2}\frac{v_S^2(T)}{T^2}} + \frac{\lambda_7}{4}\sqrt{c_3 + \frac{\lambda_3}{2}\lambda_6\frac{v_S^2(T)}{T^2}}\right)\Bigg\} \\
= c_{11} + \mathcal{O}\left(\frac{v_S(T)^2}{T^2}\right) .
\end{aligned}
$$