

# Electroweak Baryogenesis in extended Higgs sectors

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# Electroweak Baryogenesis

Observation of a **non-zero baryon asymmetry** of the universe (**BAU**)

$$\eta \equiv \frac{n_b - \bar{n}_b}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10} \quad [\text{Planck, 2018}]$$

*What happened to the antimatter in our universe?*

*How can we generate a non-zero baryon asymmetry of the universe?*

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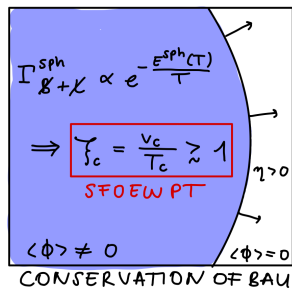
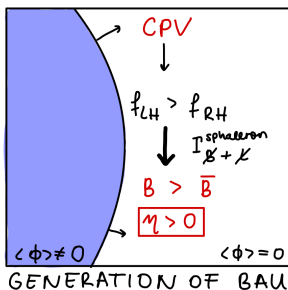
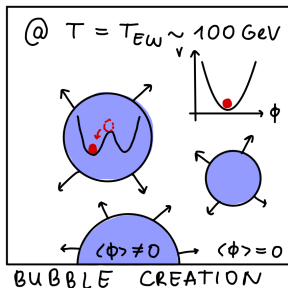
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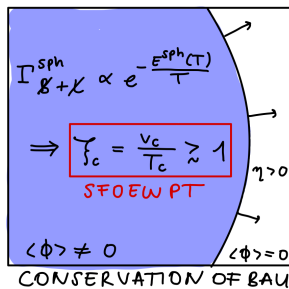
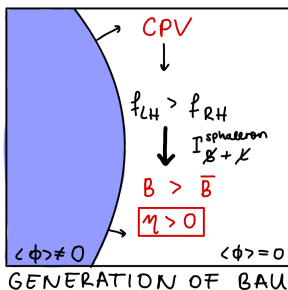
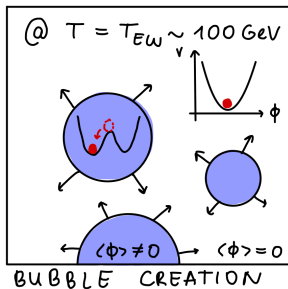
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**Electroweak Baryogenesis (EWBG)** [A. D. Sakharov, 1967], [D. Morrissey, M. Ramsey-Musolf, 2012]



⇒ **BSM physics** required for **additional CP violation** and **strong first-order electroweak phase transition (SFOEWPT)**

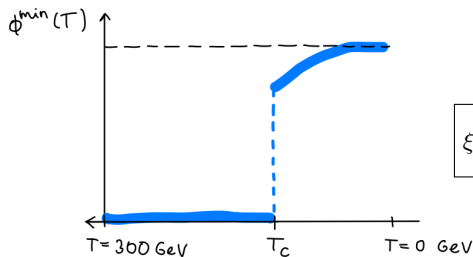
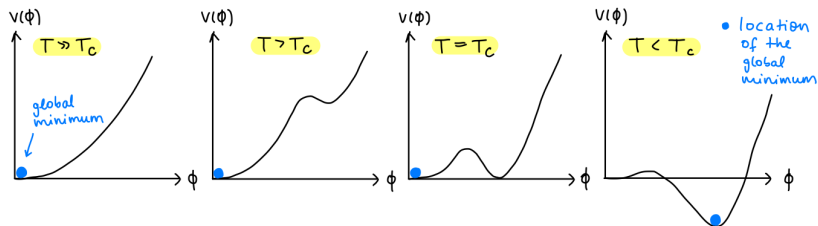
→ **Extended Higgs sector models** as promising road to BSM

# Investigating SFOEWPTs with BSMPT

**How** do we look for *strong first-order electroweak phase transitions* (SFOEWPTs)?

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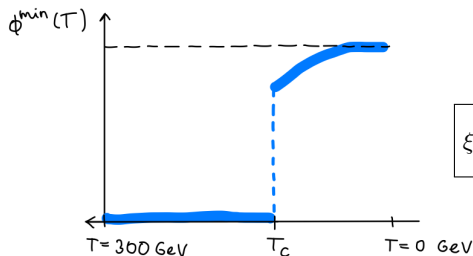
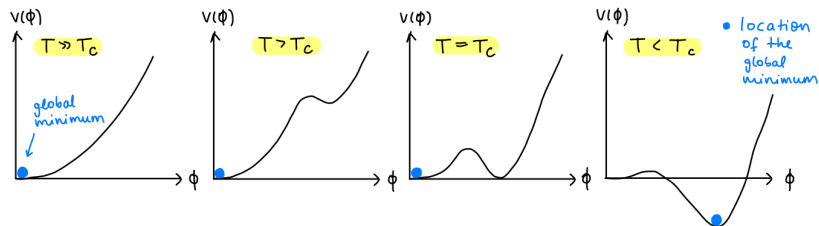


$$\xi_c \equiv \frac{\phi^{\min}(T = T_c)}{T_c} \gtrsim 1$$

**SFOEWPT**

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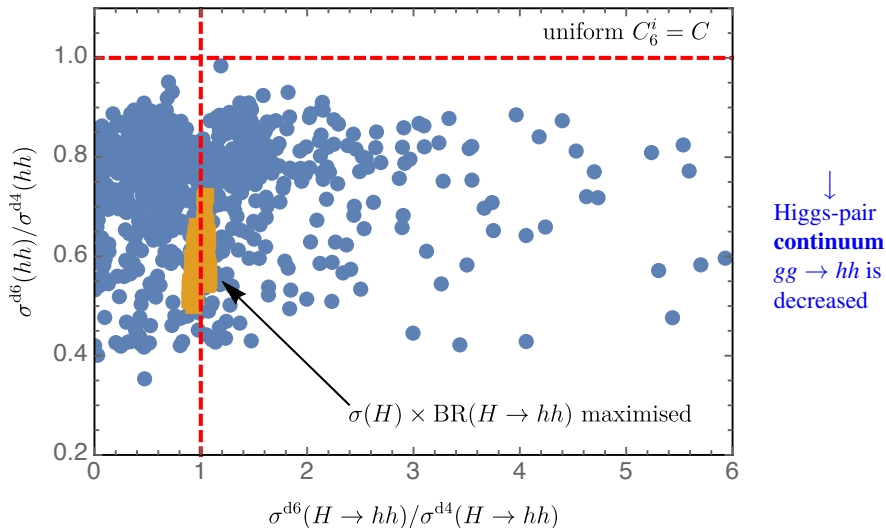
**SFOEWPT**

⇒ global minimization of the one-loop corrected effective potential @  $T \neq 0$  with **BSMPT**

[P. Basler, M. Mühlleitner, J. Müller, 2018/20] <https://github.com/phbasler/BSMPT>

# Interplay between an SFOEWPT and HPP in a 2HDM-T2-EFT

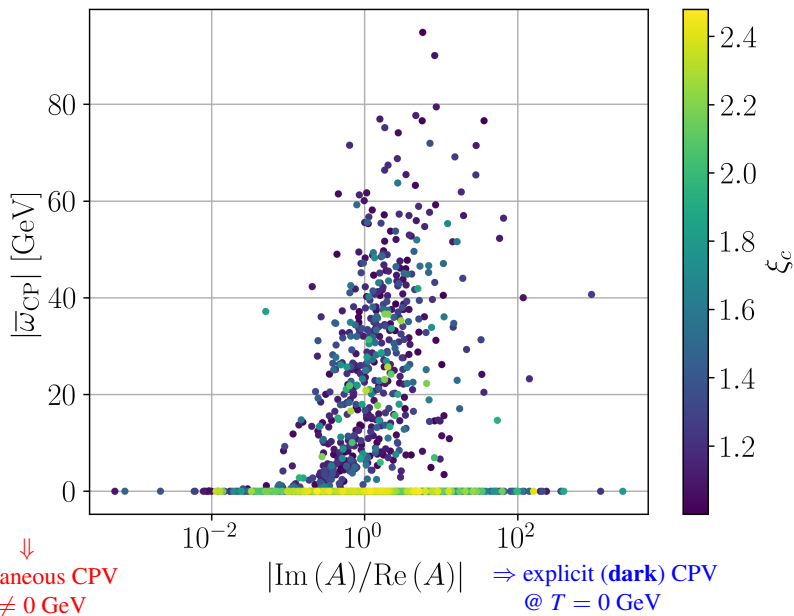
[Anisha, LB, C. Englert,  
M. Mühlleitner, 2022]



→ (exotic) Higgs **resonance** increased (within (future) LHC-sensitivity!)

→ see also talk by **J. Braathen**  
21.10.2022 4/6

# SFOEWPT in an N2HDM-like model (CP in the Dark) [LB, M. Mühlleitner, J. Müller, 2022]



# Conclusion

- Dynamical generation of the baryon asymmetry of the universe (BAU) possible if *Sakharov conditions* fulfilled
  - *Electroweak Baryogenesis*: fulfill Sakharov conditions with
    - **BSM models**
    - **Non-standard *CP*-violation (CPV)**
    - *Strong first-order electroweak phase transition (SFOEWPT)*
  - **Extended Higgs sector models** as promising framework for EWBG:
    - **CP in the Dark**: viable **SFOEWPT** points that additionally show *spontaneous CPV* at finite temperature
- *Can these points successfully generate the BAU?*
- **Type-II R2HDM-EFT**:  $|1 - \xi_c^{d4}|$  **minimised** by scalar dim-6 contributions
- Get *indirect* constraints on  $\xi_c \sim 1$  from Higgs pair production measurements @ LHC

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**Thanks for Your attention!**

# Baryon Asymmetry of the Universe and Sakharov Conditions

initial: *Big Bang* (symmetric universe)  $\Leftrightarrow$  today: **BAU** (asymmetric universe)

$$\eta \equiv \frac{n_b - \bar{n}_b}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10} \quad [\text{Planck, 2018}]$$

How can we generate a non-zero *baryon asymmetry of the universe*?

[Sakharov, 1967]: Dynamical generation of a BAU with an initially symmetric state possible if

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## Condition

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Existence of  $B$  violating processes  $\Rightarrow$  Sphaleron-mediated @  $T > T_{\text{EW}} = 100 \text{ GeV}$   
[N. Manton, 1983], [F. Klinkhammer, N. Manton, 1984]

$\mathcal{C}$  and  $\mathcal{CP}$  violation (CPV)  $\Rightarrow$  *Cabibbo-Kobayashi-Maskawa* mechanism  
[N. Cabibbo, 1963], [M. Kobayashi, T. Maskawa, 1973]

Departure from thermal equilibrium  $\Rightarrow$  Electroweak phase transition (EWPT)  
[D. Kirznits, 1972], [L. Dolan, R. Jackiw, 1974]

# EWBG and an SFOEWPT

- EWBG takes place around  $T \sim T_{EW}$
- EWPT happens and bubbles with non-zero vacuum expectation value (VEV) are created and expand
- Necessary departure from thermal equilibrium achieved through **strong first-order** EWPT (SFOEWPT)

→ ‘**first-order**’: discontinuity in VEV  $v$  at  $T_c$ :

$$V(v = 0, T_c) = V(v \neq 0, T_c)$$

- How do we see this in the potential?

→ global minimum jumps from symmetric to broken minimum @  $T_c$

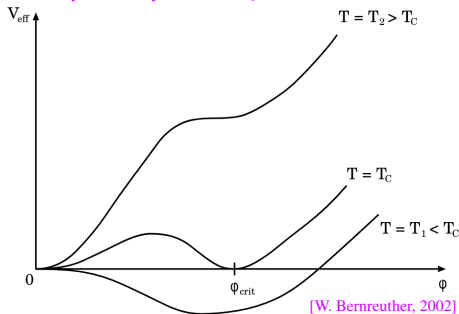
→ ‘**strong**’: conservation of BAU through sufficient suppression of the sphaleron rate inside the bubbles

$$\Gamma_{\cancel{B}+L}^{\text{sph}} \propto \exp - \frac{E_{\text{sph}}(T)}{T} \quad \Rightarrow \quad \xi_c \equiv \frac{v_c}{T_c} \gtrsim 1 \quad \text{baryon-wash-out condition}^* \quad [\text{M. Quiros, 1994}]$$

⇒ EWPT in SM only *smooth cross-over* [K. Kajantie et al., 1996]

⇒ Need BSM models that enable an **SFOEWPT\*** + *non-standard CPV*

[D. Morrissey, M. Ramsey-Musolf, 2012]



# Minimizing the One-Loop Corrected Effective Potential @ $T \neq 0$

- true vacuum state @ finite temperature (FT) including radiative corrections = global minimum of the **effective potential @ FT**
- general one-loop effective potential @ FT splits into temperature-dependent and independent part [L. Dolan, R. Jackiw, 1974]

↖ optional finite shift

$$V^{(1)}(\omega, T) = \underbrace{V^{(0)}(\omega)}_{\text{tree-level}} + \underbrace{V^{\text{CW}}(\omega)}_{\substack{T\text{-indep.} \\ \text{Coleman-Weinberg} \\ \text{potential} \\ \text{renormalized in } \overline{MS}\text{-scheme}}} + \underbrace{V^T(\omega, T)}_{\substack{T\text{-dep.} \\ \text{UV finite} \\ \text{IR finite after resummation} \\ m^2 \rightarrow m^2 + \Pi^{(1)}(0)}} + \underbrace{V^{\text{CT}}(\omega)}_{\substack{\text{finite shift of} \\ \text{scalar masses} \\ \text{and mixing angles}}}$$

[S. Coleman, E. Weinberg, 1973]      [M. Carrington, 1992],  
[R. Parwani, 1992],  
[P. Arnold, O. Espinosa, 1993]

[P. Basler et al., 2017]

- $V^{\text{CT}}$  absorbs NLO scalar mass and angle shift [P. Basler et al., 2017]

$$0 = \partial_{\phi_i} (V^{\text{CW}} + V^{\text{CT}}|_{\vec{\omega}=\vec{\omega}_{\text{tree}}})$$

$$0 = \partial_{\phi_i} \partial_{\phi_j} (V^{\text{CW}} + V^{\text{CT}}|_{\vec{\omega}=\vec{\omega}_{\text{tree}}})$$

## R2HDM-Type-II EFT in Detail

- CP-conserving 2HDM, **softly broken** discrete  $\mathbb{Z}_2$  symmetry:  $\Phi_1 \rightarrow -\Phi_1, \Phi_2 \rightarrow \Phi_2$   
[T. D. Lee, 1973], [G. C. Branco et al., 2012]

$$V_{\text{tree}}(\Phi_1, \Phi_2) = m_{11}^2(\Phi_1^\dagger \Phi_1) + m_{22}^2(\Phi_2^\dagger \Phi_2) - m_{12}^2(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \lambda_1(\Phi_1^\dagger \Phi_1)^2 + \lambda_2(\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2]$$

- inclusion of (purely scalar) dim-6 EFT contributions to the Higgs potential [Anisha et al., 2019]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{2HDM}} + \sum_i \frac{C_6^i}{\Lambda^2} O_6^i \quad \Rightarrow \quad V_{\text{dim-6}} = - \sum_i \frac{C_6^i}{\Lambda^2} O_6^i$$

|                |                                                                         |                |                                                                         |
|----------------|-------------------------------------------------------------------------|----------------|-------------------------------------------------------------------------|
| $O_6^{111111}$ | $(\Phi_1^\dagger \Phi_1)^3$                                             | $O_6^{222222}$ | $(\Phi_2^\dagger \Phi_2)^3$                                             |
| $O_6^{111122}$ | $(\Phi_1^\dagger \Phi_1)^2(\Phi_2^\dagger \Phi_2)$                      | $O_6^{112222}$ | $(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)^2$                      |
| $O_6^{122111}$ | $(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_1)$ | $O_6^{122122}$ | $(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$ |
| $O_6^{121211}$ | $(\Phi_1^\dagger \Phi_2)^2(\Phi_1^\dagger \Phi_1) + \text{h.c.}$        | $O_6^{121222}$ | $(\Phi_1^\dagger \Phi_2)^2(\Phi_2^\dagger \Phi_2) + \text{h.c.}$        |

- absorb dim-6 contributions (to scalar masses) in shifts  $\lambda_i \rightarrow \lambda_i + \delta\lambda_i, m_{12}^2 \rightarrow m_{12}^2 + \delta m_{12}^2$
- ⇒ scalar mass spectrum same as for dim-4 @ LO  
 ⇒ shift EFT effects into **Higgs self-couplings & multi-Higgs final states**

- N2HDM-like extended scalar sector, *one* discrete  $\mathbb{Z}_2$  symmetry

$$\Phi_1 \rightarrow +\Phi_1, \quad \Phi_2 \rightarrow -\Phi_2, \quad \Phi_S \rightarrow -\Phi_S$$

- $SU(2)_L \times U(1)_Y$  and  $\mathbb{Z}_2$ -invariant tree-level potential:

$$V^{(0)} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + \frac{m_S^2}{2} \Phi_S^2 + \left( A \Phi_1^\dagger \Phi_2 \Phi_S + h.c. \right) + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 \\ + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} \left[ \left( \Phi_1^\dagger \Phi_2 \right)^2 + h.c. \right] + \frac{\lambda_6}{4} \Phi_S^4 + \frac{\lambda_7}{2} |\Phi_1|^2 \Phi_S^2 + \frac{\lambda_8}{2} |\Phi_2|^2 \Phi_S^2$$

- general vacuum structure @  $T \neq 0$ :

$$\Phi_1 = \frac{1}{\sqrt{2}} \left( \begin{matrix} \rho_1 + i\eta_1 \\ \zeta_1 + \omega_1 + i\Psi_1 \end{matrix} \right), \quad \Phi_2 = \frac{1}{\sqrt{2}} \left( \begin{matrix} \rho_2 + \omega_{\text{CB}} + i\eta_2 \\ \zeta_2 + \omega_2 + i(\Psi_2 + \omega_{\text{CP}}) \end{matrix} \right), \quad \Phi_S = \zeta_S + \omega_S$$

↖ charge-breaking VEV,  $\omega_{\text{CB}} = 0$

↗ CP-violating VEV

# ‘CP in the Dark’ in Detail

- general vacuum structure @  $T = 0$ :

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + v_1 + i\Psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + i\eta_2 \\ \zeta_2 + i\Psi_2 \end{pmatrix}, \quad \Phi_S = \zeta_S$$
$$\langle \Phi_1 \rangle|_{T=0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle|_{T=0} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad \langle \Phi_S \rangle|_{T=0} = 0$$

→  $\omega_1|_{T=0 \text{ GeV}} = v_1 \equiv v = 246.22 \text{ GeV}$ , SM-Yukawa sector and tree-level FCNCs prohibited

→  $\mathbb{Z}_2$  symmetry *unbroken*  $\Rightarrow$  conserved quantum number: *dark charge*

\*  $\Phi_1$  (*SM-like particles* with  $+1$ ):  $G^\pm, G^0, h$

\*  $\Phi_2, \Phi_S$  (*dark particles* with  $-1$ ):  $H^\pm, h_1, h_2, h_3$  ( $m_{h_1} < m_{h_2} < m_{h_3}$ )

$\Rightarrow$  **DM**: *stable* particle dark matter candidate  $h_1$

$\Rightarrow$  **explicit CPV**: introduced through  $\text{Im}(A) \neq 0$

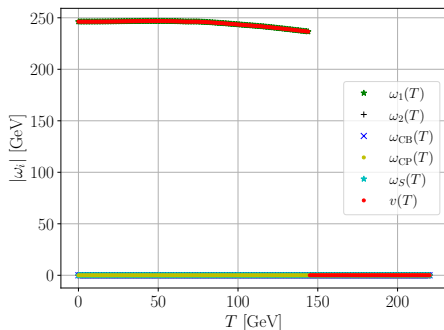
→ CPV after SSB, but vacuum is CP-symmetric  $\Rightarrow$  CPV is *explicit*

→ solely in the dark sector -  $h_1, h_2, h_3$ : states with mixed CP quantum number

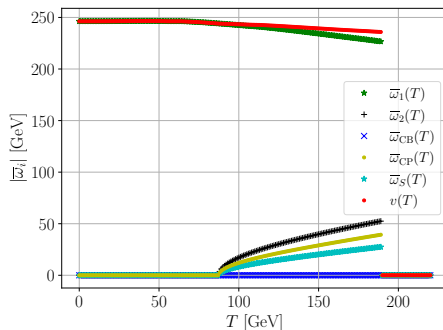
$\Rightarrow$  *not* constrained by EDM constraints

# Spontaneous CPV in ‘CP in the Dark’ at Finite Temperature

- Two different VEV patterns in detail:



**only  $\omega_1$  develops non-zero values**



**dark VEVs (except  $\omega_{CB}$ ) participate in EWPT  
spontaneous CPV!**

- @ FT:  $\mathbb{Z}_2$  symmetry is broken → dark charge no longer conserved → dark sector **mixes** with SM-like particles
- ⇒ **additional non-standard CPV transferred to the SM-like couplings to fermions @ FT!**