Cosmological Phase Transitions in a Two-Higgs-Doublet Model with Classical Scale Invariance

PhD seminar presentation December 2025

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December 11, 2025

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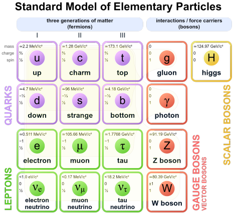
Shortcomings of the Standard Model (SM):

- The SM explains the electroweak (EW) and strong interactions, but does *not* explain gravity.

  Possible to achieve a unified description?



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- "Aesthetic" issues:
  - Large number of parameters (25[1]).

    Are they free?
  - Fine-tuning/hierarchy problem:
    - Why is the Higgs boson so light?
    - Why is the EW interaction so much stronger than gravity?
- What is the nature of neutrino masses (as evidenced by neutrino oscillations)?

[T. W. Kibble, 2015, J. M. Butterworth, 2016, S. Weinberg, 2018]

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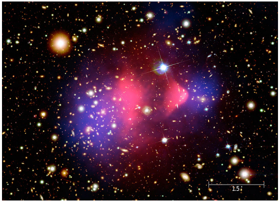
[1] If we include neutrino masses and neutrino oscillations.

Further shortcomings of the SM:

- The SM cannot explain why there is so much more matter than antimatter (baryon asymmetry).
- The SM cannot explain dark energy (severe mismatch between SM vacuum energy and dark energy density).
- The SM cannot explain the nature of dark matter.



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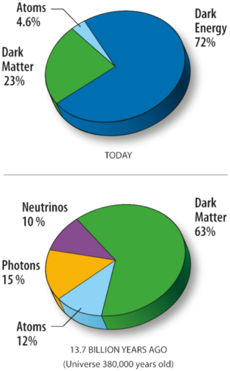

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[G. Bertone et al., 2005, A. Ahriche, 2007]

Baryon asymmetry continued:

- Why is there so much more matter than antimatter?
- Conditions for baryogenesis: [A. Sakharov, 1967]
  - Baryon number violation
  - Breaking of C- and CP-symmetry
  - Processes (strongly) out of thermal equilibiurm → phase transition (PT)

Credit: Wikipedia

- The SM cannot account for measured baryon asymmetry:
  - Too little CP-violation
  - Electroweak PT (EWPT) not strong enough

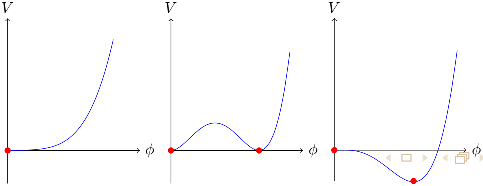
[G. Bertone et al., 2005, A. Ahriche, 2007]

Going beyond the SM

- Our focus: extensions of the scalar sector:
  - Example: Two-Higgs doublet model (2HDM)

    [I. P. Ivanov, 2017, G. Branco et al., 2012, A. Ahriche, 2007]
- How to detect new physics?:
  - New particles: $h, H, A, H^{\pm}$ (2HDM), . . .
  - Changes to EWPT → affects baryon asymmetry
  - Gravitational waves (GW) from cosmological PT:
    - * Planned detectors: LISA (decided), DECIGO, BBO, . . .

  [C. Caprini et al., 2019, P. Amaro-Seoane *et al.* (LISA Collaboration), 2017, Kawamura Seiji *et al.*, 2011, Vincent Corbin and Neil J Cornish , 2006]



Two-Higgs-doublet model

- Two $SU(2)$ Higgs doublets Φ_1, Φ_2
- Generic 2HDM potential:

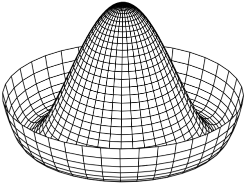
$$V_{\mathrm{2HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{ h.c.}] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4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

- Parameters:
  - Generic: $m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4 \in \mathbb{R}, \;\; m_{12}^2, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C}$
  - $\mathcal{CP}$-conserving: $m_{11}^2, m_{22}^2, m_{12}^2, \lambda_1, \ldots, \lambda_7 \in \mathbb{R}$
  - Classical scale invariance: $m_{11}^2, m_{22}^2, m_{12}^2 = 0$
- Higgs spectrum:
  - Five scalars: three neutral, two charged
  - $\mathcal{CP}$-conserving scenario: $h, H, A, H^\pm$

[I. P. Ivanov, 2017, G. Branco et al., 2012]

Spontaneous symmetry breaking in the SM

- Recall the SM Higgs potential:
  $$V_{\text{Higgs}}(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$
  $$\mu^2 < 0,\ \ \lambda > 0$$
- Degenerate minimum given by
  $$\Phi^\dagger\Phi = -\mu^2/(2\lambda)$$
- Global minimum away from $\Phi = 0 \Rightarrow$ spontaneous symmetry breaking (SSB)



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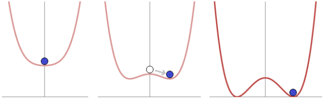

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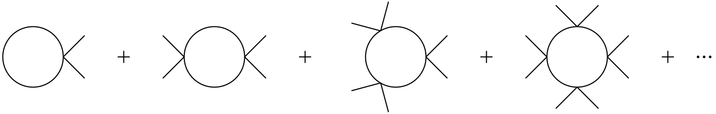
SSB from radiative corrections: Coleman-Weinberg

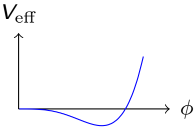
- No mass term ⇒ no broken minimum at tree-level.
- Loop effects can change this! [S. Coleman et al., 1973]
- Adding upp all one-loop diagrams



gives the Coleman-Weinberg one-loop contribution (generic):

$$V_{\mathrm{CW}}(\phi) = \sum_i \frac{s_i n_i}{64\pi^2} m_i^4(\phi) \left(\ln \left[m_i^2(\phi)/Q^2 \right] - c_i \right)$$

- For the Abelian Higgs: $V_{\mathrm{eff}}(\phi) \propto \phi^4 \left(\ln(\phi^2/v^2) - 1/2 \right)$



SSB from radiative corrections: Gildener-Weinberg

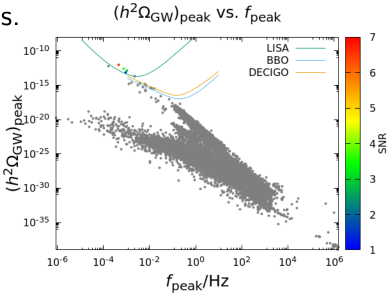
- Consider more generic model with no mass term:
  $V = f_{ijkl}\Phi_i\Phi_j\Phi_k\Phi_l$ [E. Gildener et al., 1976]
- Existence of non-trivial local minimum ⇒ flat direction **n** (by Euler's theorem)
- Along **n** the model is similar to the CW-model and we have
  $V_{\rm eff}(\varphi\mathbf{n}) = A\varphi^4 + B\varphi^4 \ln\left(\varphi^2/\Lambda_{\rm W}^2\right)$
- The excitation along **n** is called the *scalon*.
- The scalon mass is naturally light and is generated by radiative corrections.
- The one-loop scalon mass is (approximately) determined by the vev, the heavy scalars, the fermions and the gauge bosons:
  $m_s^2 = \frac{1}{8\pi^2 v^2}\left(6m_W^4 + 3m_Z^4 + \sum_H m_H^4 - 4\sum_F m_F^4\right)$
- No need for inversion procedure!

Setup and parameter space scan

- Make a random scan over the C2HDM parameter space.
- Get (approximately) correct m_h and vev v from the start due to the GW-setup!
- Check loop-corrections to vev and other masses to ensure small deviations.
- Impose theoretical constraints:
  - Boundedness from below
  - Perturbative unitarity
- Impose phenomenological constraints:
  - Oblique parameters S, T and U
  - HiggsBounds [P. Bechtle et al., 2010],...,[P. Bechtle et al., 2020]
  - HiggsSignals [P. Bechtle et al., 2014],...,[P. Bechtle et al., 2014]

Next step

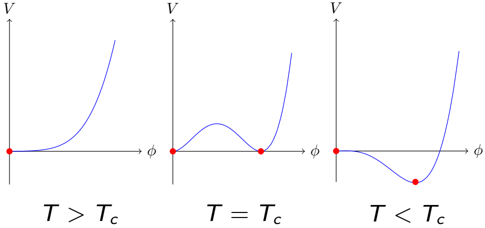
- Study the thermal history and phase transitions for all viable parameter space points.
- Calculate the gravitational wave signal due to first-order transitions.
- Compare with the sensitivity curves of planned gravitational wave detectors.



- Try to identify possible correlations between gravitational wave signals and collider signals.
- We will be using `Dratopi` (own research) for the PT calculations.

Overview

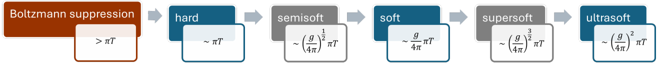
- Thermal effects modify the potential → Thermal effective potential $V_{\mathrm{eff}}(\phi, T)$.
- Basic idea: The thermal effective potential evolves with T. If and when a lower minimum develops, a phase transition (PT) takes place.



- A potential barrier at $T = T_c$ corresponds to a first-order PT (FOPT). A strong FOPT is needed for baryogenesis.

The 3D/EFT approach and Dratopi

- Imaginary time formalism: $t \to -i\tau$, where τ is periodic (antiperiodic) for bosons (fermions) with period $\beta = 1/T$.
- The time dimension disappears and is replaced by a sum over discrete frequencies $\omega_n = n\pi T, n \in \mathbb{Z}$ (Matsubara modes) $\Rightarrow$ Tower of particle masses: $m^2 \to m^2 + (n\pi T)^2, n \in \mathbb{Z}$
- Fermionic modes have n odd $\Rightarrow n \neq 0$, so they are *heavy*. Bosonic modes have n even. Those with $n \neq 0$ are also *heavy*.
- Integrating out the heavy modes leaves us with a 3D effective field theory (EFT) matched to the 4D theory.
- DRalgo [A. Ekstedt et al., 2023] for calculation of the 3D EFT.
- Own research: Dratopi: DRalgo to Python Interfacer

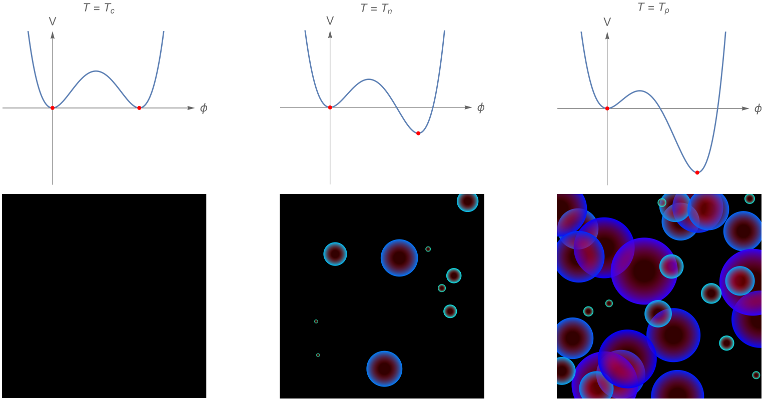

Boltzmann suppression $> \pi T$
hard $\sim \pi T$
semisoft $\sim \left(\frac{g}{4\pi}\right)^{\frac{1}{2}} \pi T$
soft $\sim \frac{g}{4\pi} \pi T$
supersoft $\sim \left(\frac{g}{4\pi}\right)^{\frac{3}{2}} \pi T$
ultrasoft $\sim \left(\frac{g}{4\pi}\right)^{2} \pi T$

Credit: Marco Finetti

Dynamics of cosmological FOPT

- Thermal jumps and tunnelling across barrier drive transition.

  [S. Coleman, 1977, A. Linde, 1983, M. E. Carrington et al., 1993]
- Transition is not homogeneous in space → bubble nucleation



Credit: Marco Finetti

Dynamics of cosmological FOPT, continued

- Extremize the Euclidean action at finite temperature:

$$S_3[\phi] = 4\pi \int r^2 dr \left[(1/2)(d\phi/dr)^2 + V_{\mathrm{eff}}(\phi, T)\right]$$

- Key parameters to extract: [C. Caprini et al., 2016]
  - Nucleation rate: $\Gamma/V = Ae^{-S_3/T}$
  - Nucleation and percolation temperature: $T_n, \ T_p$
  - Energy release/radiation energy in plasma: α
  - Inverse duration: β/H
- Gravitational waves (GW) generated by bubble dynamics:
  - Collisions of bubble walls.
  - Sound waves in the plasma.
  - Turbulence due to magnetohydrodynamic effects.
- Power spectrum of GWs can be calculated from PT params:

$$h^2\Omega_{\mathrm{GW}}(f) = h^2 \frac{d(\rho_{\mathrm{GW}}/\rho_c)}{d \ln f}$$

Conclusion:

- There are several reasons to go beyond the SM:
  - Dark matter, dark energy, baryogenesis, . . .
  - Unification, hierarchy problem, . . .
- Signals from BSM models can show up in many places:
  - Collider experiments
  - Dark matter properties
  - Gravitational waves due to phase transition

    $\vdots$
- Finding viable BSM scenarios takes some care.
- The Gildener-Weinberg approach allows us to (approximately) nail down the Higgs mass.
- Phase transition and gravitational wave analysis offer (future) new phenomenological signatures.
- Accurately calculating PT parameters is challenging.

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