Exploring Phase Transitions and Gravitational Waves in the Conformal Two-Higgs-Doublet Model (C2HDM)

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Why go beyond the Standard Model?

- The nature of dark energy
- The nature of dark matter
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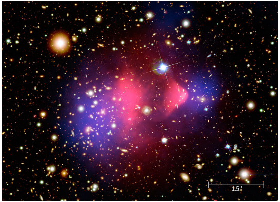

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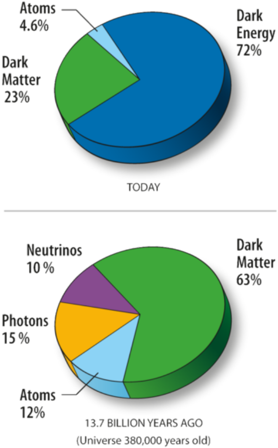
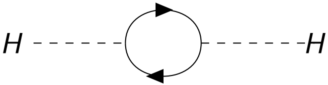


Source: Wikipedia

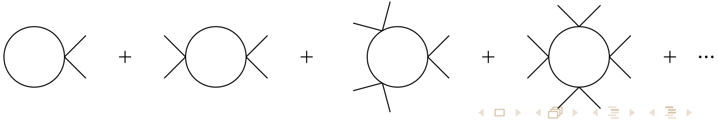
The hierarchy problem

- Why is the Higgs boson so light?
- How to fix? [P. Saake, 2024]
  - SUSY
  - Composite Higgs
  - Conformal symmetry!



- Zero tree-level mass and radiative generation of the mass of the SM Higgs boson keeps it naturally light $\rightarrow$ Conformal BSM models
- Radiative mass generation and spontaneous symmetry breaking from the Coleman-Weinberg mechanism

  [S. Coleman et al., 1973, E. Gildener et al., 1976]



The baryon asymmetry problem

- Why is there so much more matter than antimatter?
- Sakharov conditions for baryogenesis: [A. Sakharov, 1967]
  - Baryon number violation
  - Breaking of C- and CP-symmetry
  - Processes (strongly) out of thermal equilibiurm $\rightarrow$ phase transition (PT)
- The SM cannot account for measured baryon asymmetry: [L. Canetti et al., 2012]
  - Too little CP-violation
  - Electroweak PT (EWPT) not strong enough
- How to fix? Modify the scalar potential! $\rightarrow$ BSM models

Source: Wikipedia

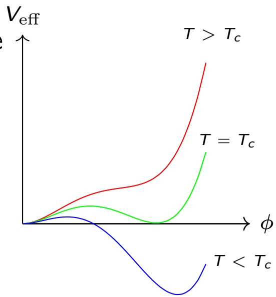
Phase transitions

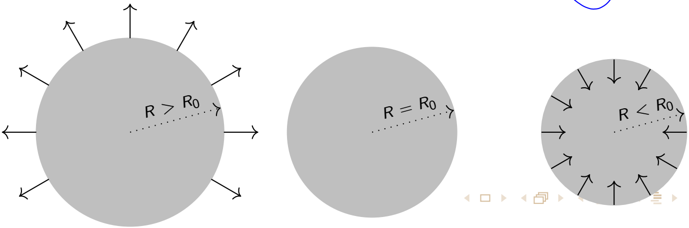
- Phase: local minimum of thermal effective potential $V_{\text{eff}}(\phi, T)$
- Phase transition: transition from one local minimum to a lower one
- First-order PT: PT with a barrier
- Nucleation rate: [S. Coleman, 1977]

  $$\Gamma / V = A e^{-S_3/T}$$

- Bounce action: [A. Linde, 1983]

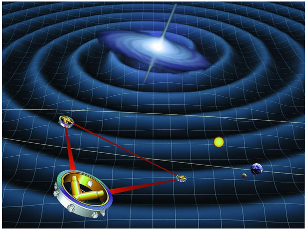
  $$S_3 = 4\pi \int r^2 dr \left[\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V_{\text{eff}}(\phi, T) \right]$$





Gravitational waves

- Bubbles create GWs: [C. Caprini et al., 2024]
  - Bubble wall collisions
  - Sound waves in the plasma
  - MHD turbulence
- GW signal can be estimated semi-analytically from PT parameters: [C. Caprini et al., 2024]
  - Percolation temperature: T_p
  - Strength: α
  - Inverse duration: β/H



Source: NASA (public domain)

- SGW spectrum to be studied by future space-based detectors:
  - LISA [M. Colpi et al., 2024]
  - DECIGO [Kawamura Seiji *et al.*, 2011]
  - BBO [Vincent Corbin and Neil J Cornish , 2006]

  ⋮

Conformal Two-Higgs-doublet model (C2HDM)

- Higgs basis: $$\langle\mathcal{H}_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \ \langle\mathcal{H}_2\rangle = \begin{pmatrix}0\\ 0\end{pmatrix}$$
- Potential in the Higgs basis:
$$V_{\text{C2HDM}}^{\text{Higgs}} = \frac{1}{2}Z_1(\mathcal{H}_1^\dagger\mathcal{H}_1)^2 + \frac{1}{2}Z_2(\mathcal{H}_2^\dagger\mathcal{H}_2)^2 + Z_3(\mathcal{H}_1^\dagger\mathcal{H}_1)(\mathcal{H}_2^\dagger\mathcal{H}_2) + Z_4(\mathcal{H}_1^\dagger\mathcal{H}_2)(\mathcal{H}_2^\dagger\mathcal{H}_1) + \left[\frac{1}{2}Z_5(\mathcal{H}_1^\dagger\mathcal{H}_2)^2 + [Z_6(\mathcal{H}_1^\dagger\Phi_1) + Z_7(\mathcal{H}_2^\dagger\mathcal{H}_2)](\mathcal{H}_1^\dagger\mathcal{H}_2) + \text{ h.c.}\right]$$
- Parameters: $Z_1, Z_2, Z_3, Z_4 \in \mathbb{R}, \ Z_5, Z_6, Z_7 \in \mathbb{C}$
- Stationary point: $Z_1 = Z_6 = 0$
- CP-violating angle γ: $\tan(2\gamma) = -\mathrm{Im}(Z_5)/\mathrm{Re}(Z_5)$
- Tree-level scalar masses:
$$m_{H_1}^2 = 0, \ m_{H_2}^2 = \frac{v^2}{2}(Z_3 + Z_4 - |Z_5|), \ m_{H_3}^2 = \frac{v^2}{2}(Z_3 + Z_4 + |Z_5|), m_{H\pm}^2 = \frac{v^2}{2}Z_3$$
- Parameter set for scan:
$$Z_2, \mathrm{Im}(Z_5), \mathrm{Re}(Z_7), \mathrm{Im}(Z_7), m_{H_2}, m_{H_3} \ (\beta, \delta)$$
- NOTE: We eliminate $m_{H\pm}$ for m_h using the GW-approach.

The Gildener-Weinberg approach

- Generic model with no mass term: [E. Gildener et al., 1976]

  $$V = f_{ijkl}\Phi_i\Phi_j\Phi_k\Phi_l$$

- Existence of non-trivial local minimum $\Rightarrow$ flat direction $\mathbf{n}$
- One-loop potential along the flat direction:

  $$V_{\text{eff}}(\varphi\mathbf{n}) = A\varphi^4 + B\varphi^4 \ln\left(\varphi^2/\Lambda_{\text{W}}^2\right)$$

- The excitation along $\mathbf{n}$ is called the *scalon* $\rightarrow h$
- One-loop scalon mass (approximate):

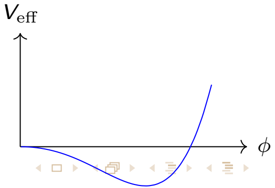
  $$m_h^2 = 8Bv^2 = \frac{1}{8\pi^2 v^2}\left(6m_W^4 + 3m_Z^4 + \sum_H m_H^4 - 4\sum_F m_F^4\right)$$

- NOTE: True vev may differ:

  $$|v^{\text{true}} - v| \leq 5 \text{ GeV}$$

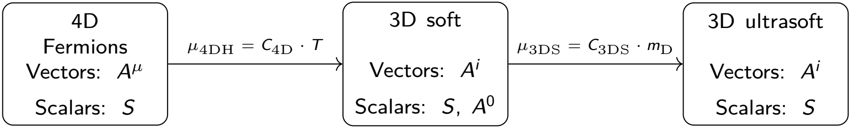
- NOTE: True m_h may differ:

  $$|m_h^{\text{true}} - m_h| \leq 2 \text{ GeV}$$



Effective potential and phase transitions

- We use dimensional reduction to construct $V_{\text{eff}}(\phi, T)$.
- Basic idea: Match the 4D theory to a 3D EFT by integrating out the non-zero Matsubara modes: $m^2 + (n\pi T)^2, n \neq 0$.
- Advantage over 4D: reduction of theoretical uncertainty
- Dratopi: Constructs the 3D EFT using DRalgo [A. Ekstedt et al., 2023]
- PhatCat: Phase tracing, bounce action and PT parameters (currently using CosmoTransitions [C. L. Wainwright, 2012])



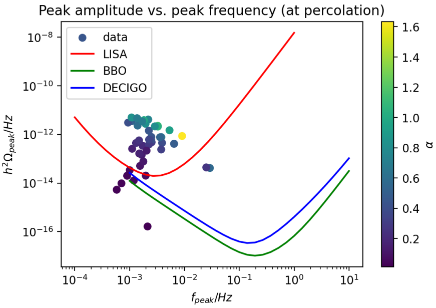
Analysis pipeline

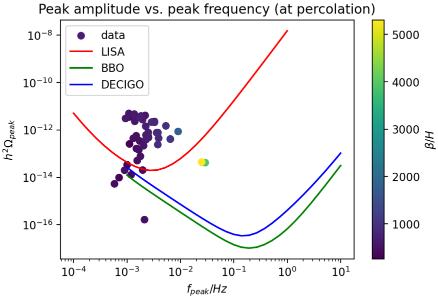
- Scan the parameter space:

  $Z_2, \mathrm{Im}(Z_5), \mathrm{Re}(Z_7), \mathrm{Im}(Z_7), m_{H_2}, m_{H_3}\ (\beta, \delta)$
- Apply theoretical constraints:
  - Perturbative unitarity
  - Boundedness from below (be careful for conformal models!)
- Apply phenomenological constraints:
  - Oblique parameters S, T, U [Peskin, M. and Takeuchi, T., 1990]
  - Collider constraints: HiggsTools [H. Bahl et al., 2023]
- Construct the effective potential
- Study the thermal history and identify the PTs
- Calculate the PT parameters: α, β/H, T_p
- Calculate the contribution to the SGW background

Preliminary results

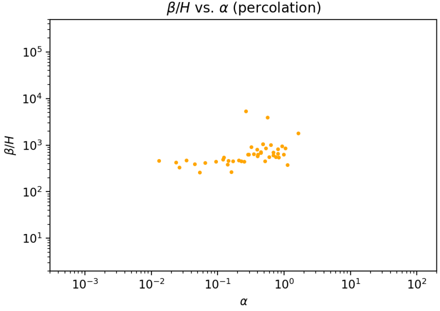
- GW spectrum characterized by peak amplitude $h^2\Omega_{\text{peak}}$ and peak frequency f_{peak}
- Point above sensitivity curve for detector $\Rightarrow$ SNR > 1
- $\alpha \uparrow \Rightarrow h^2\Omega_{\text{peak}} \uparrow$
- $\beta/H \uparrow \Rightarrow f_{\text{peak}} \uparrow$



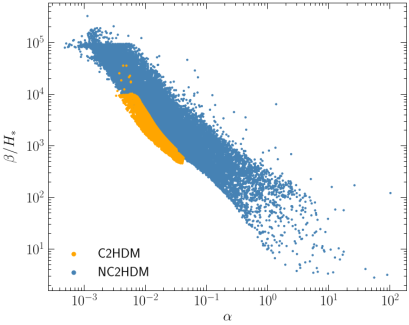


Comparison to previous work

- Comparison to previous work on C2HDM and NC2HDM
  [N. Benincasa et al., 2026]
- We find PTs with much larger α!



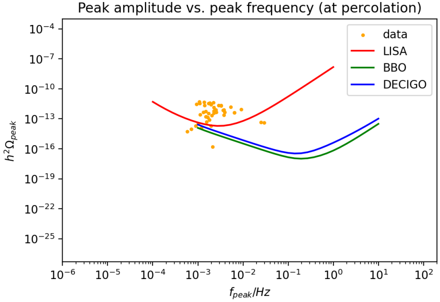
(a) Our results



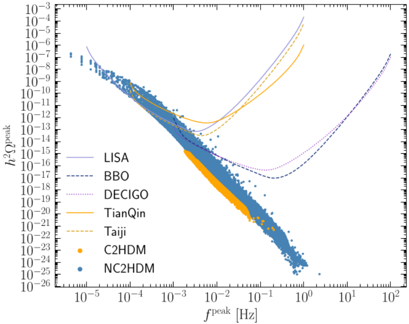
(b) [N. Benincasa et al., 2026]

Comparison to previous work

- Comparison to previous work on C2HDM and NC2HDM
  [N. Benincasa et al., 2026]
- We find PTs with much larger $h^2\Omega_{\rm peak}$!



(a) Our results



(b) [N. Benincasa et al., 2026]

Conclusion

- BSM models with extended scalar sectors are well-motivated e.g. by the baryon asymmetry problem.
- Conformal models are motivated e.g. by the hierarchy problem.
- The C2HDM is a conformal model with additional CP-violation (on top of the SM).
- The results are preliminary but clearly feature first-order phase transitions.
- These phase transitions are stronger than expected from previous work.
- Possible explanations for differences?
  - Construction of effective potential: 4D vs. 3D approach
  - Gildener-Weinberg vs. on-shell scheme
  - CP-violation?
- Further investigations are needed to understand this!

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