Low temperature electroweak phase transition in the Standard Model with hidden scale invariance [1]

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[1] SA, A. Kobakhidze, C. Lagger, S. Liang, A. Zhou, PLB 776 (2018) 48-53

Outline

1. The model
2. The electroweak phase transition
3. Implications

Outline

Motivation

- Scale invariance is an attractive framework for addressing the problem of the origin of mass and hierarchies of mass scales.
- Quantum fluctuations result in a mass scale via dimensional transmutation
- Dimensionless couplings are responsible for generating mass hierarchies.
- Scale (conformal) invariance is an essential symmetry in string theory
- What is the nature of the EWPT in this framework?

The model

- Consider the SM as a low energy Wilsonian effective theory with cutoff Λ:

$$V(\Phi^\dagger\Phi) = V_0(\Lambda) + \lambda(\Lambda)\left[\Phi^\dagger\Phi - v_{ew}^2(\Lambda)\right]^2$$

- Assume the fundamental theory exhibits conformal invariance which is spontaneously broken down to Poincare invariance
- Promote dimensionful parameters to the dilaton field, the scalar Goldstone boson.

$$\Lambda \to \alpha\chi, \quad v_{ew}^2(\Lambda) \to \frac{\xi(\alpha\chi)}{2}\chi^2, \quad V_0(\Lambda) \to \frac{\rho(\alpha\chi)}{4}\chi^4 \;, \qquad (1)$$

The model

- Impose the following conditions:
  - $\frac{dV}{d\phi}\Big|_{\Phi=v_{ew},\chi=v_\chi} = \frac{dV}{d\chi}\Big|_{\Phi=v_{ew},\chi=v_\chi} = 0$ (Existence of the electroweak vev)
  - $V(v_{ew}, v_\chi) \approx 0$ (Cosmological constant)
- Implications:
  - $\rho(\alpha v_\chi) = \beta_\rho(\alpha v_\chi) = 0$
  - $\xi(\alpha v_\chi) = \frac{v_{ew}^2}{v_\chi^2}$
  - $m_\chi^2 \simeq \frac{\beta'_\rho(\Lambda)}{4\xi(\Lambda)} v_{ew}^2 \simeq (10^{-8}\text{eV})^2$ for $\alpha\chi \sim M_P$

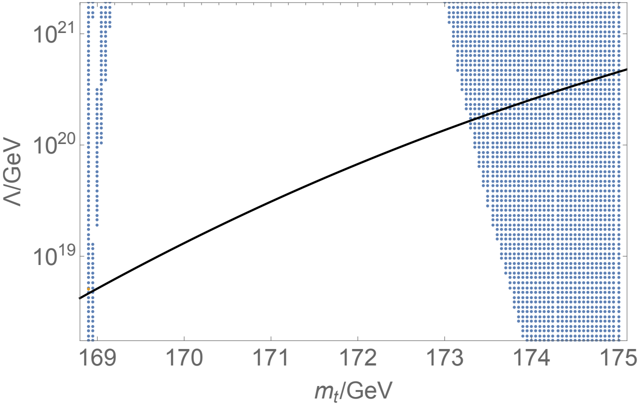


Figure: Plot of the allowed range of parameters (shaded region) with $m^2_\chi(v_{ew}) > 0$, i.e., the electroweak vacuum being a minimum. The solid line displays the cut-off scale Λ as function of the top-quark mass m_t for which the conditions are satisfied.

The thermal effective potential

- At high temperatures:

$$V_T(h,\chi) = \frac{\lambda(\Lambda)}{4}\left[h^2 - \frac{v_{ew}^2}{v_\chi^2}\chi^2\right]^2 + c(h)\pi^2 T^4 - \frac{\lambda(\Lambda)}{24}\frac{v_{ew}^2}{v_\chi^2}\chi^2 T^2 + \frac{1}{48}\left[6\lambda(\Lambda) + 6y_t^2(\Lambda) + \frac{9}{2}g^2(\Lambda) + \frac{3}{2}g'^2(\Lambda)\right] h^2 T^2$$

- Minimising this potential w.r.t. χ :

$$\chi^2 \approx \frac{v_\chi^2}{v_{ew}^2}\left(h^2 + \frac{T^2}{12}\right)$$

Thermal effective potential

The effective potential in this direction is given by:

$$V_T(h,\chi(h)) = \left[c(h)\pi^2 - \frac{\lambda(\Lambda)}{576}\right] T^4 + \frac{1}{48}\left[4\lambda(\Lambda) + 6y_t^2(\Lambda) + \frac{9}{2}g^2(\Lambda) + \frac{3}{2}g'^2(\Lambda)\right] h^2 T^2$$

Outline

Standard model

- SM high temperature 1-loop effective potential:

$$V(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 - \frac{1}{4}\lambda_T\phi^4$$

- curvature at the origin changes at $T = T_0$
- the nature of the transition depends on the values of the SM parameters.

First order phase transition

- The minima become degenerate before T_0
- Bubbles of the broken phase form
- collisions lead to gravitational waves, baryogenesis etc.

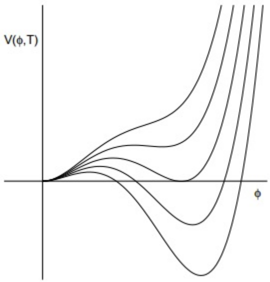


Figure: First order phase transition (Petropoulos,2003)

Second order phase transition

- the universe rolls homogeneously into the broken phase
- predicted by SM parameters
- Not necessarily the case in SM extensions.

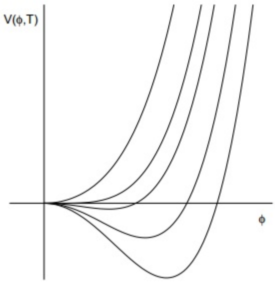


Figure: Second order phase transition (Petropoulos,2003)

The scale-invariant model

- Along the flat direction, $T_0 = 0$
- Furthermore, the minima are degenerate only at $T = 0$
- No phase transition???

Chiral phase transition

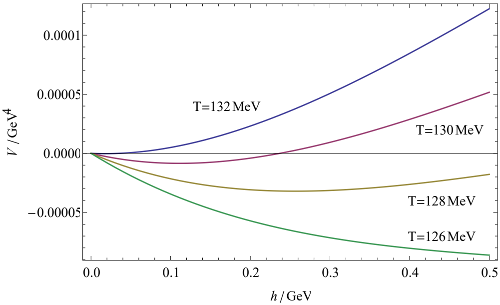
- Consider the Yukawa term:

$$y \langle \bar{q}q \rangle_T \phi$$

- At $T \sim 132\text{MeV}$, chiral condensates form.
- This term is given by (Gasser & Leutwyler, 1987):

$$\langle \bar{q}q \rangle_T = \langle \bar{q}q \rangle \left[1 - (N^2 - 1)\frac{T^2}{12Nf_\pi^2} + \mathcal{O}\left(T^4\right)\right]$$

The electroweak phase transition



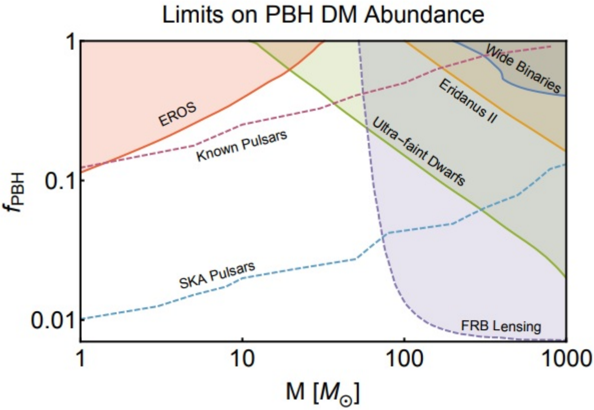
- The linear term shifts the minimum from the origin
- at $T \sim 127$MeV, the minimum disappears and the EWPT is triggered
- The EWPT is 2nd order.

Outline

Implications

- 6 relativistic quarks at the critical temperature indicates a 1st order chiral PT. (Pisarski& Wilczek, 1983)
- Gravitational waves with peak frequency $\sim 10^{-7}$ Hz, potentially detectable by means of pulsar timing (EPTA, SKA...)

- Production of primordial black holes with mass $M_{BH} \sim M_{\odot}$



(Schutz & Liu, 2016)

Summary

- Scale invariant theories predict a light feebly coupled dilaton.
- Electroweak phase transition driven by the QCD chiral phase transition and occurs at $T \sim 130$ MeV.
- QCD phase transition could be strongly first order $\Longrightarrow$ gravitational waves, black holes, QCD baryogenesis.
- Detection of a light scalar particle + the above astrophysical signatures will provide strong evidence for the fundamental role of scale invariance in particle physics and cosmology.

Backup slides

Gravitational wave production

- Peak frequency is given by the radius of the bubble at collision: $f_p \sim R_c^{-1}$
- Observed frequency is

$$f_0 = \frac{a(t_c)}{a(t_0)} f_p \approx 1.65 \cdot 10^{-8} \frac{1}{R_c H_c} \frac{T_c}{100\text{MeV}} \text{Hz} \approx 10^{-7} \text{Hz}$$