Low temperature electroweak phase transition with hidden scale invariance

Cyril Lagger

THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

S. Arunasalam, A. Kobakhidze, CL, S. Liang, A. Zhou, PLB 776 (2018) 48-53

Les Rencontres de Physique - La Thuile - February 26, 2018

Motivation and overview

- Approach: exploring particle physics from cosmological considerations

Motivation and overview

- Approach: exploring particle physics from cosmological considerations
- Cosmology provides
  - evidences for the incompleteness of the Standard Model
  - potential new signatures of BSM (phase transitions, gravitational waves,...)

Motivation and overview

- Approach: exploring particle physics from cosmological considerations
- Cosmology provides
  - evidences for the incompleteness of the Standard Model
  - potential new signatures of BSM (phase transitions, gravitational waves,...)

This talk: a study of the electroweak phase transition in an extension of the Standard Model with classical scale invariance.

Standard Model with hidden scale invariance

- Scale invariant models are attractive to address the hierarchy problem

Standard Model with hidden scale invariance

- Scale invariant models are attractive to address the hierarchy problem
- Assume existence of UV complete scale invariant model (string theory,...)

Standard Model with hidden scale invariance

- Scale invariant models are attractive to address the hierarchy problem
- Assume existence of UV complete scale invariant model (string theory,...)
- Focus on low-energy effective field theory:
  - Standard Model Higgs potential at UV scale Λ

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

  - spontaneously broken scale invariance manifests through dilaton field χ

$$\begin{aligned}
\Lambda &\to \Lambda\frac{\chi}{f_\chi} \equiv \alpha\chi \\
v_{ew}^2(\Lambda) &\to \frac{v_{ew}^2(\alpha\chi)}{f_\chi^2}\chi^2 \equiv \frac{\xi(\alpha\chi)}{2}\chi^2 \\
V_0(\Lambda) &\to \frac{V_0(\alpha\chi)}{f_\chi^4}\chi^4 \equiv \frac{\rho(\alpha\chi)}{4}\chi^4
\end{aligned}$$

Standard Model with hidden scale invariance

- Scale invariant models are attractive to address the hierarchy problem
- Assume existence of UV complete scale invariant model (string theory,...)
- Focus on low-energy effective field theory:
  - Standard Model Higgs potential at UV scale Λ

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

  - spontaneously broken scale invariance manifests through dilaton field χ

$$\begin{aligned}
&\Lambda \to \Lambda\frac{\chi}{f_\chi} \equiv \alpha\chi \\
&v_{ew}^2(\Lambda) \to \frac{v_{ew}^2(\alpha\chi)}{f_\chi^2}\chi^2 \equiv \frac{\xi(\alpha\chi)}{2}\chi^2 \\
&V_0(\Lambda) \to \frac{V_0(\alpha\chi)}{f_\chi^4}\chi^4 \equiv \frac{\rho(\alpha\chi)}{4}\chi^4
\end{aligned}$$

We get an effective scale invariant potential:

$$V(\Phi^\dagger\Phi,\chi) = \lambda(\alpha\chi)\left[\Phi^\dagger\Phi - \frac{\xi(\alpha\chi)}{2}\chi^2\right]^2 + \frac{\rho(\alpha\chi)}{4}\chi^4$$

Hierarchy and light dilaton

- Scale invariance is broken by quantum effects:

$$\lambda^{(i)}(\alpha\chi) = \lambda^{(i)}(\mu) + \beta_{\lambda^{(i)}}(\mu)\ln(\alpha\chi/\mu) + \beta'_{\lambda^{(i)}}(\mu)\ln^2(\alpha\chi/\mu) + \ldots$$

Hierarchy and light dilaton

- Scale invariance is broken by quantum effects:

$$\lambda^{(i)}(\alpha\chi) = \lambda^{(i)}(\mu) + \beta_{\lambda^{(i)}}(\mu)\ln(\alpha\chi/\mu) + \beta'_{\lambda^{(i)}}(\mu)\ln^2(\alpha\chi/\mu) + \ldots$$

- Minimisation conditions and small vacuum energy density:

$$\left.\frac{\partial V}{\partial \chi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad \left.\frac{\partial V}{\partial \Phi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad V(v_{ew}, v_\chi) = 0$$

Hierarchy and light dilaton

- Scale invariance is broken by quantum effects:

$$\lambda^{(i)}(\alpha\chi) = \lambda^{(i)}(\mu) + \beta_{\lambda^{(i)}}(\mu)\ln(\alpha\chi/\mu) + \beta'_{\lambda^{(i)}}(\mu)\ln^2(\alpha\chi/\mu) + \dots$$

- Minimisation conditions and small vacuum energy density:

$$\left.\frac{\partial V}{\partial \chi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad \left.\frac{\partial V}{\partial \Phi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad V(v_{ew}, v_\chi) = 0$$

- We obtain dimensional transmutation and hierarchy of VEVs ($\Lambda \sim v_\chi$):

$$\rho(v_\chi) = 0, \quad \beta_\rho(v_\chi) = 0, \quad \xi(v_\chi) = \frac{v_{ew}^2}{v_\chi^2}$$

Hierarchy and light dilaton

- Scale invariance is broken by quantum effects:

$$\lambda^{(i)}(\alpha\chi) = \lambda^{(i)}(\mu) + \beta_{\lambda^{(i)}}(\mu)\ln(\alpha\chi/\mu) + \beta'_{\lambda^{(i)}}(\mu)\ln^2(\alpha\chi/\mu) + \ldots$$

- Minimisation conditions and small vacuum energy density:

$$\left.\frac{\partial V}{\partial \chi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad \left.\frac{\partial V}{\partial \Phi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad V(v_{ew}, v_\chi) = 0$$

- We obtain dimensional transmutation and hierarchy of VEVs ($\Lambda \sim v_\chi$):

$$\rho(v_\chi) = 0, \quad \beta_\rho(v_\chi) = 0, \quad \xi(v_\chi) = \frac{v_{ew}^2}{v_\chi^2}$$

- $\xi(v_\chi)$ can be hierarchically small (technical naturalness)

Hierarchy and light dilaton

- Scale invariance is broken by quantum effects:

$$\lambda^{(i)}(\alpha\chi) = \lambda^{(i)}(\mu) + \beta_{\lambda^{(i)}}(\mu)\ln(\alpha\chi/\mu) + \beta'_{\lambda^{(i)}}(\mu)\ln^2(\alpha\chi/\mu) + \ldots$$

- Minimisation conditions and small vacuum energy density:

$$\left.\frac{\partial V}{\partial \chi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad \left.\frac{\partial V}{\partial \Phi}\right|_{\Phi=v_{ew},\chi=v_\chi} = 0, \quad V(v_{ew}, v_\chi) = 0$$

- We obtain dimensional transmutation and hierarchy of VEVs ($\Lambda \sim v_\chi$):

$$\rho(v_\chi) = 0, \quad \beta_\rho(v_\chi) = 0, \quad \xi(v_\chi) = \frac{v_{ew}^2}{v_\chi^2}$$

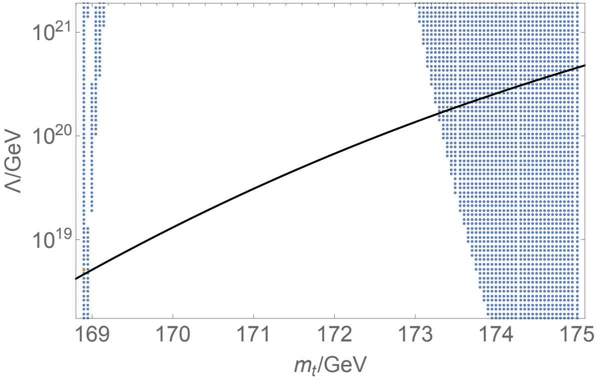
- $\xi(v_\chi)$ can be hierarchically small (technical naturalness)
- Prediction of a light dilaton: $m_\chi^2 \simeq \frac{\beta'_\rho(v_\chi)}{4\xi(v_\chi)} v_{ew}^2 \qquad \frac{m_\chi}{m_h} \sim \sqrt{\xi}$

Recovering the Standard Model at $\mu = v_{ew}$

- Consider the running of parameters between v_{ew} and $v_\chi \sim \Lambda$

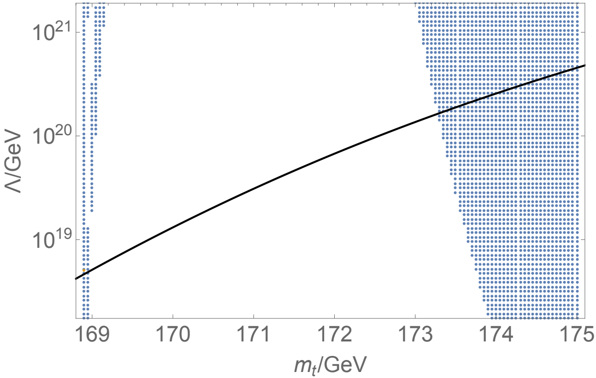
Recovering the Standard Model at $\mu = v_{ew}$

- Consider the running of parameters between v_{ew} and $v_\chi \sim \Lambda$
- Require that $m_\chi^2(v_{ew}) > 0$



Recovering the Standard Model at $\mu = v_{ew}$

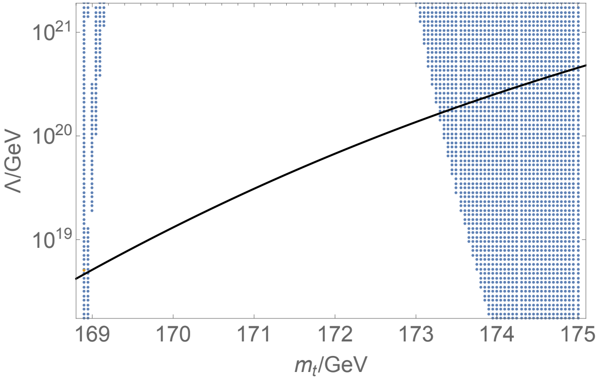
- Consider the running of parameters between v_{ew} and $v_\chi \sim \Lambda$
- Require that $m_\chi^2(v_{ew}) > 0$



- Dilaton mass at $v_\chi \sim \Lambda \sim M_P$: $m_\chi \sim 10^{-8}$ eV

Recovering the Standard Model at $\mu = v_{ew}$

- Consider the running of parameters between v_{ew} and $v_\chi \sim \Lambda$
- Require that $m_\chi^2(v_{ew}) > 0$



- Dilaton mass at $v_\chi \sim \Lambda \sim M_P$: $m_\chi \sim 10^{-8}$ eV
- Indicative only and requires higher-loop corrections

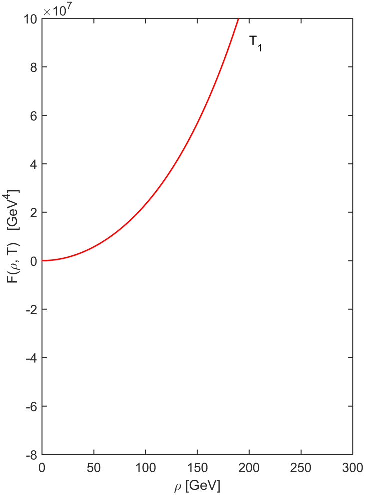
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

2nd-order transition / crossover:

- smooth dynamics
- no particular signatures



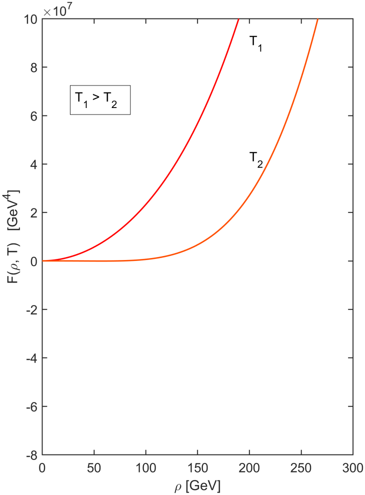
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

2nd-order transition / crossover:

- smooth dynamics
- no particular signatures



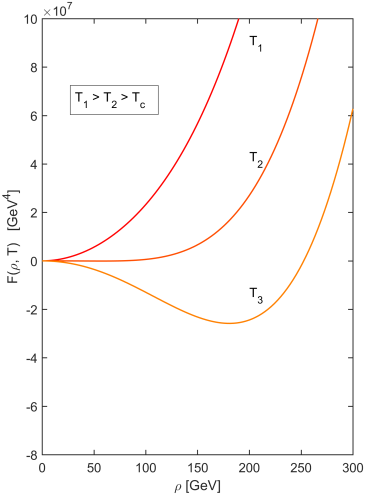
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

2nd-order transition / crossover:

- smooth dynamics
- no particular signatures



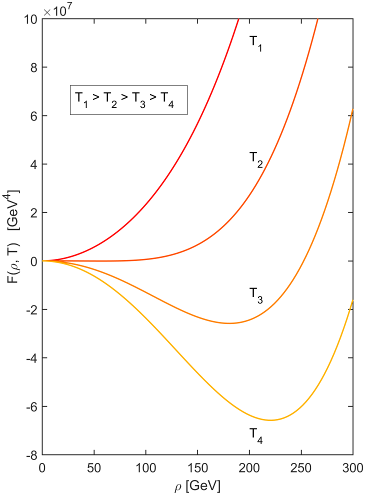
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

2nd-order transition / crossover:

- smooth dynamics
- no particular signatures



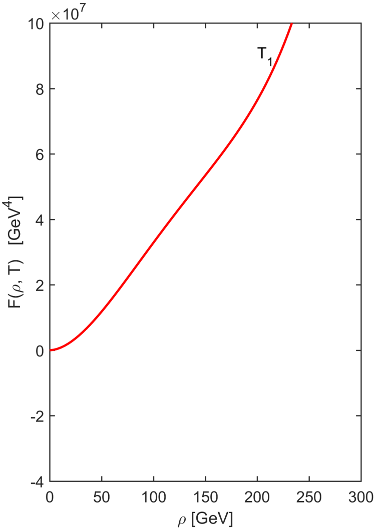
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

1st-order transition:

- bubble nucleation/collision
- stochastic GW background



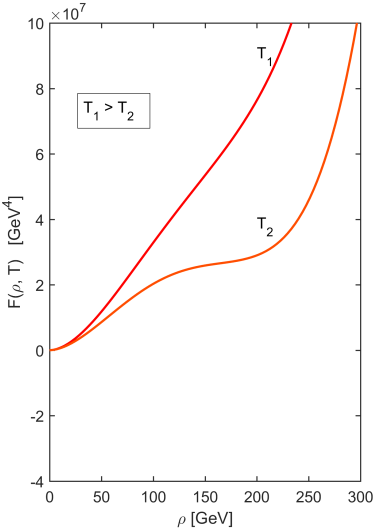
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

1st-order transition:

- bubble nucleation/collision
- stochastic GW background



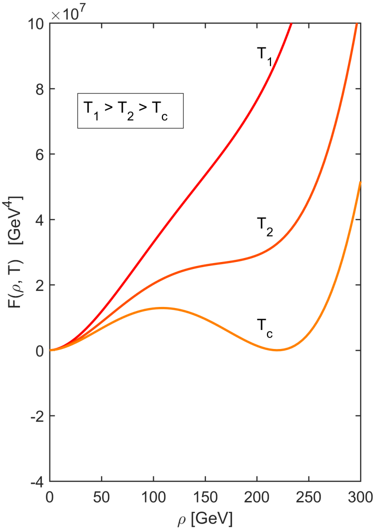
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

1st-order transition:

- bubble nucleation/collision
- stochastic GW background



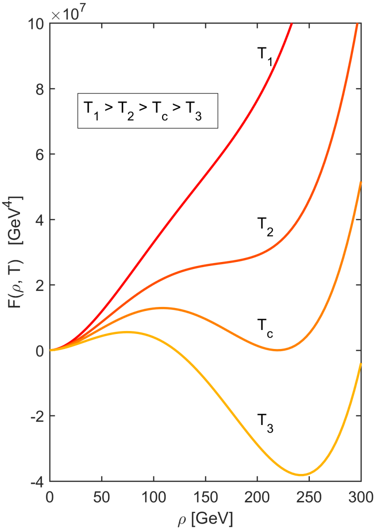
Early universe phase transitions

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

1st-order transition:

- bubble nucleation/collision
- stochastic GW background



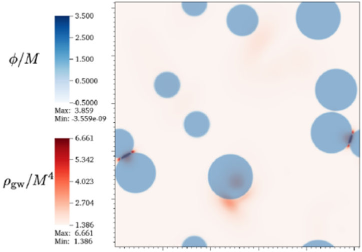
Early universe phase transitions

Hot Big Bang scenario:

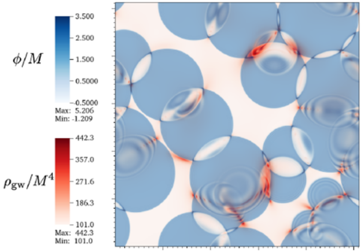
- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- dynamics depend on the underlying particle physics model

1st-order transition:

- bubble nucleation/collision
- stochastic GW background



(a) $t/R_* = 0.35$



(b) $t/R_* = 0.66$

[D. Cutting, M. Hindmarsh, D. Weir, arXiv:1802.05712]

Electroweak and QCD phase transitions

In the Standard Model, both electroweak and QCD PTs are crossover

[K. Kajantie et al., Phys. Rev. Lett. 77 (1996) 2887] [Y. Aoki et al, Nature 443 (2006) 675]

$\Rightarrow$ no stochastic GW background predicted in the SM

Electroweak and QCD phase transitions

In the Standard Model, both electroweak and QCD PTs are crossover

[K. Kajantie et al., Phys. Rev. Lett. 77 (1996) 2887] [Y. Aoki et al, Nature 443 (2006) 675]

$\Rightarrow$ no stochastic GW background predicted in the SM

In the model with hidden scale invariance:

- flat direction in the Higgs-dilaton potential at tree level
- vacua are almost degenerate $\Rightarrow$ no EWPT until $T \ll T_{EW}$

Electroweak and QCD phase transitions

In the Standard Model, both electroweak and QCD PTs are crossover

[K. Kajantie et al., Phys. Rev. Lett. 77 (1996) 2887] [Y. Aoki et al, Nature 443 (2006) 675]

$\Rightarrow$ no stochastic GW background predicted in the SM

In the model with hidden scale invariance:

- flat direction in the Higgs-dilaton potential at tree level
- vacua are almost degenerate $\Rightarrow$ no EWPT until $T \ll T_{EW}$

QCD-induced electroweak phase transition:

- supercooling until $T \sim T_{QCD}$
- at T_{QCD}: chiral phase transition with 6 massless quarks
- quark condensates reduce the barrier in the Higgs potential $\Rightarrow$ EWPT

Electroweak and QCD phase transitions

In the Standard Model, both electroweak and QCD PTs are crossover

[K. Kajantie et al., Phys. Rev. Lett. 77 (1996) 2887] [Y. Aoki et al, Nature 443 (2006) 675]

$\Rightarrow$ no stochastic GW background predicted in the SM

In the model with hidden scale invariance:

- flat direction in the Higgs-dilaton potential at tree level
- vacua are almost degenerate $\Rightarrow$ no EWPT until $T \ll T_{EW}$

QCD-induced electroweak phase transition:

- supercooling until $T \sim T_{QCD}$
- at T_{QCD}: chiral phase transition with 6 massless quarks
- quark condensates reduce the barrier in the Higgs potential $\Rightarrow$ EWPT

See also: [E. Witten Nucl.Pys.B177 (1981) 477] [W. Buchmuller, D. Wyler, PLB 249 (1990) 281] [S. Iso et al., PRL 119 (2017) 141301] [B. von Harling, G. Servant, JHEP 1801 (2018) 159]

Thermal Higgs-dilaton potential + quark condensates

- Thermal contributions to the Higgs-dilaton potential $\Rightarrow$ barrier along the flat direction:

$$V_T(h, \chi(h)) \approx AT^4 + \frac{1}{48}\left[4\lambda(\Lambda) + 6y_t^2(\Lambda) + \frac{9}{2}g^2(\Lambda) + \frac{3}{2}g'^2(\Lambda)\right] h^2 T^2 + \ldots$$

Thermal Higgs-dilaton potential + quark condensates

- Thermal contributions to the Higgs-dilaton potential $\Rightarrow$ barrier along the flat direction:

$$V_T(h, \chi(h)) \approx AT^4 + \frac{1}{48}\left[4\lambda(\Lambda) + 6y_t^2(\Lambda) + \frac{9}{2}g^2(\Lambda) + \frac{3}{2}g'^2(\Lambda)\right] h^2 T^2 + \dots$$

- Quark-antiquark condensate with N massless quarks:

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

Thermal Higgs-dilaton potential + quark condensates

- Thermal contributions to the Higgs-dilaton potential $\Rightarrow$ barrier along the flat direction:

$$V_T(h,\chi(h)) \approx AT^4 + \frac{1}{48}\left[4\lambda(\Lambda) + 6y_t^2(\Lambda) + \frac{9}{2}g^2(\Lambda) + \frac{3}{2}g'^2(\Lambda)\right]h^2T^2 + \dots$$

- Quark-antiquark condensate with N massless quarks:

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

- Quark-Higgs Yukawa interactions induce a linear term in the potential:

$$V_T(h) \to V_T(h) + \frac{y_q}{\sqrt{2}}\langle\bar{q}q\rangle_T h$$

Thermal Higgs-dilaton potential + quark condensates

- Thermal contributions to the Higgs-dilaton potential $\Rightarrow$ barrier along the flat direction:

$$V_T(h,\chi(h)) \approx AT^4 + \frac{1}{48}\left[4\lambda(\Lambda) + 6y_t^2(\Lambda) + \frac{9}{2}g^2(\Lambda) + \frac{3}{2}g'^2(\Lambda)\right] h^2T^2 + \ldots$$

- Quark-antiquark condensate with N massless quarks:

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

- Quark-Higgs Yukawa interactions induce a linear term in the potential:

$$V_T(h) \to V_T(h) + \frac{y_q}{\sqrt{2}}\langle\bar{q}q\rangle_T h$$

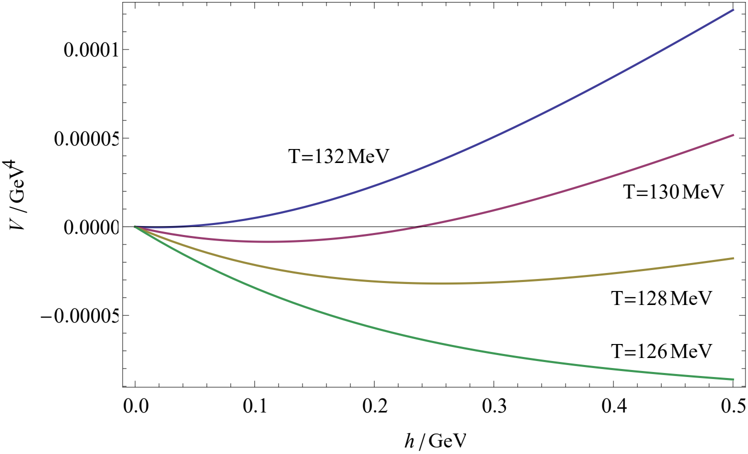
- This linear term dominates over the barrier for small enough T

Results and dynamics of the transitions

- For $N = 6$ and $f_\pi \approx 93$ MeV, $\langle \bar{q}q \rangle_{T_c} = 0$ at $T_c \approx 132$ MeV

Results and dynamics of the transitions

- For $N = 6$ and $f_\pi \approx 93$ MeV, $\langle \bar{q} q \rangle_{T_c} = 0$ at $T_c \approx 132$ MeV
- For $T \approx 127$ MeV the barrier disappears and the EWPT completes



Results and dynamics of the transitions

- For $N = 6$ and $f_\pi \approx 93$ MeV, $\langle \bar{q} q \rangle_{T_c} = 0$ at $T_c \approx 132$ MeV
- For $T \approx 127$ MeV the barrier disappears and the EWPT completes
- The Higgs-dilaton rolls down the potential (smooth transition)

Results and dynamics of the transitions

- For $N = 6$ and $f_\pi \approx 93$ MeV, $\langle \bar{q} q \rangle_{T_c} = 0$ at $T_c \approx 132$ MeV
- For $T \approx 127$ MeV the barrier disappears and the EWPT completes
- The Higgs-dilaton rolls down the potential (smooth transition)
- However, $SU(6)_R \times SU(6)_L$ chiral symmetry breaking is 1st-order for massless quarks [D. Pisarski, F. Wilczek, PRD 29 (1984) 338]

Results and dynamics of the transitions

- For $N = 6$ and $f_\pi \approx 93$ MeV, $\langle \bar{q}q \rangle_{T_c} = 0$ at $T_c \approx 132$ MeV
- For $T \approx 127$ MeV the barrier disappears and the EWPT completes
- The Higgs-dilaton rolls down the potential (smooth transition)
- However, $SU(6)_R \times SU(6)_L$ chiral symmetry breaking is 1st-order for massless quarks [D. Pisarski, F. Wilczek, PRD 29 (1984) 338]
- Implicit assumption: chiral transition completes quickly

Results and dynamics of the transitions

- For $N = 6$ and $f_\pi \approx 93$ MeV, $\langle \bar{q}q \rangle_{T_c} = 0$ at $T_c \approx 132$ MeV
- For $T \approx 127$ MeV the barrier disappears and the EWPT completes
- The Higgs-dilaton rolls down the potential (smooth transition)
- However, $SU(6)_R \times SU(6)_L$ chiral symmetry breaking is 1st-order for massless quarks [D. Pisarski, F. Wilczek, PRD 29 (1984) 338]
- Implicit assumption: chiral transition completes quickly
- More refined analysis currently under investigation:
  - effective field theory for the Higgs, dilaton and pions
  - $U(6) \times U(6)$ linear sigma model for the pions

$$\mathcal{L} = \mathrm{Tr}\left(\partial_\mu \varphi^\dagger \partial^\mu \varphi - m^2 \varphi^\dagger \varphi\right) - \lambda_1 \left[\mathrm{Tr}\left(\varphi^\dagger \varphi\right)\right]^2 - \lambda_2 \mathrm{Tr}\left(\varphi^\dagger \varphi\right)^2 + \mathcal{L}(\varphi, \phi, \chi)$$

Gravitational Waves

- 1st order chiral transition $\Rightarrow$ stochastic background of GWs

Gravitational Waves

- 1st order chiral transition $\Rightarrow$ stochastic background of GWs
- Peak frequency roughly given by size of bubbles at collision: $f_p \approx R_c^{-1}$

Gravitational Waves

- 1st order chiral transition $\Rightarrow$ stochastic background of GWs
- Peak frequency roughly given by size of bubbles at collision: $f_p \approx R_c^{-1}$
- observed frequency today:

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

Gravitational Waves

- 1st order chiral transition $\Rightarrow$ stochastic background of GWs
- Peak frequency roughly given by size of bubbles at collision: $f_p \approx R_c^{-1}$
- observed frequency today:

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

- possible detection with Pulsar Timing Arrays (EPTA, NANOGrav, SKA)

[C. Caprini et al., PRD 82 (2010) 063511] [A. Kobakhidze et al., EPJ C77 (2017) 570]

Gravitational Waves

- 1st order chiral transition $\Rightarrow$ stochastic background of GWs
- Peak frequency roughly given by size of bubbles at collision: $f_p \approx R_c^{-1}$
- observed frequency today:

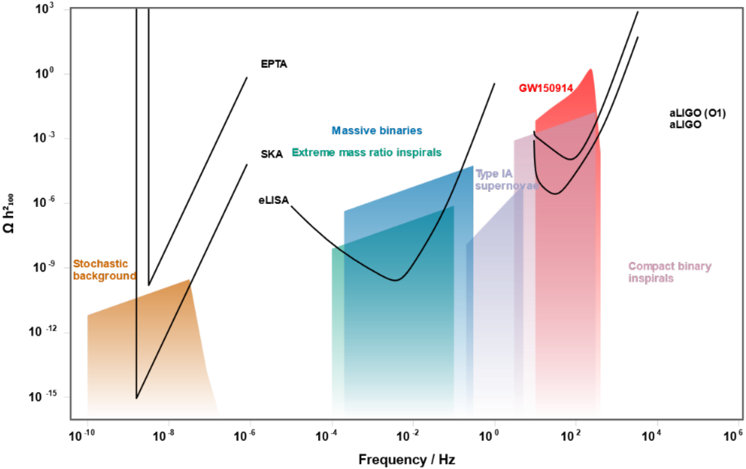
$$f_0 = f_p \frac{a(t_c)}{a(t_0)} \approx 1.65 \cdot 10^{-8} \frac{1}{R_c\, H_c} \frac{T_c}{100 \text{ MeV}} \text{ Hz} \approx 10^{-7} \text{ Hz}$$

- possible detection with Pulsar Timing Arrays (EPTA, NANOGrav, SKA)

  [C. Caprini et al., PRD 82 (2010) 063511] [A. Kobakhidze et al., EPJ C77 (2017) 570]

- precise spectrum and amplitude of the background currently under computation

Gravitational Waves



[From rhcole.com/apps/GWplotter/]

Conclusion

- Scale invariant extensions of the SM motivated by the hierarchy problem

Conclusion

- Scale invariant extensions of the SM motivated by the hierarchy problem
- Low energy effective formulation with a dilaton field

Conclusion

- Scale invariant extensions of the SM motivated by the hierarchy problem
- Low energy effective formulation with a dilaton field
- Interesting predictions:
  - small dilaton mass: $m_\chi \approx 10^{-8}$ eV
  - low temperature QCD-induced electroweak transition
  - GW signal in the range of Pulsar Timing Arrays