Cosmological phase transition in the Standard Model with hidden scale invariance

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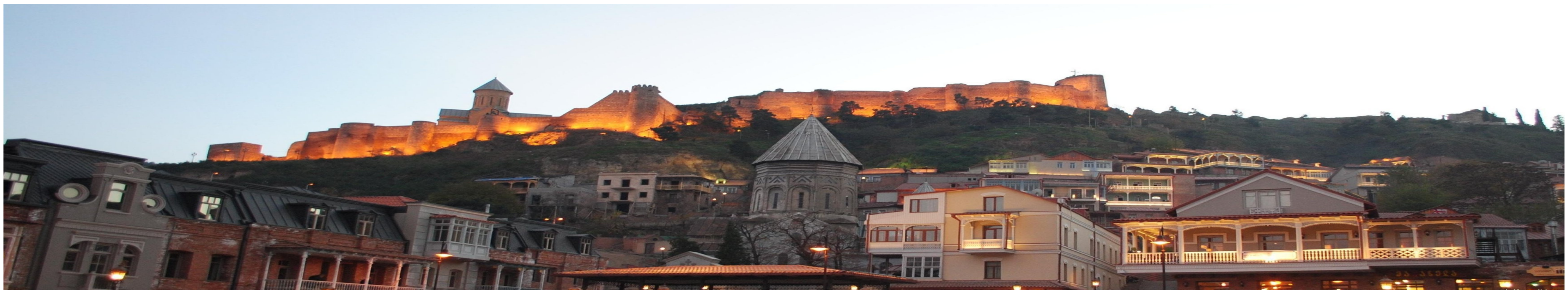

Outline

- Higgs and naturalness (again)
- Scale invariant Standard Model with light dilaton
- Electroweak phase transition in the Standard Model with light dilaton and its implications
- Conclusion

Higgs 2017

ATLAS+CMS,
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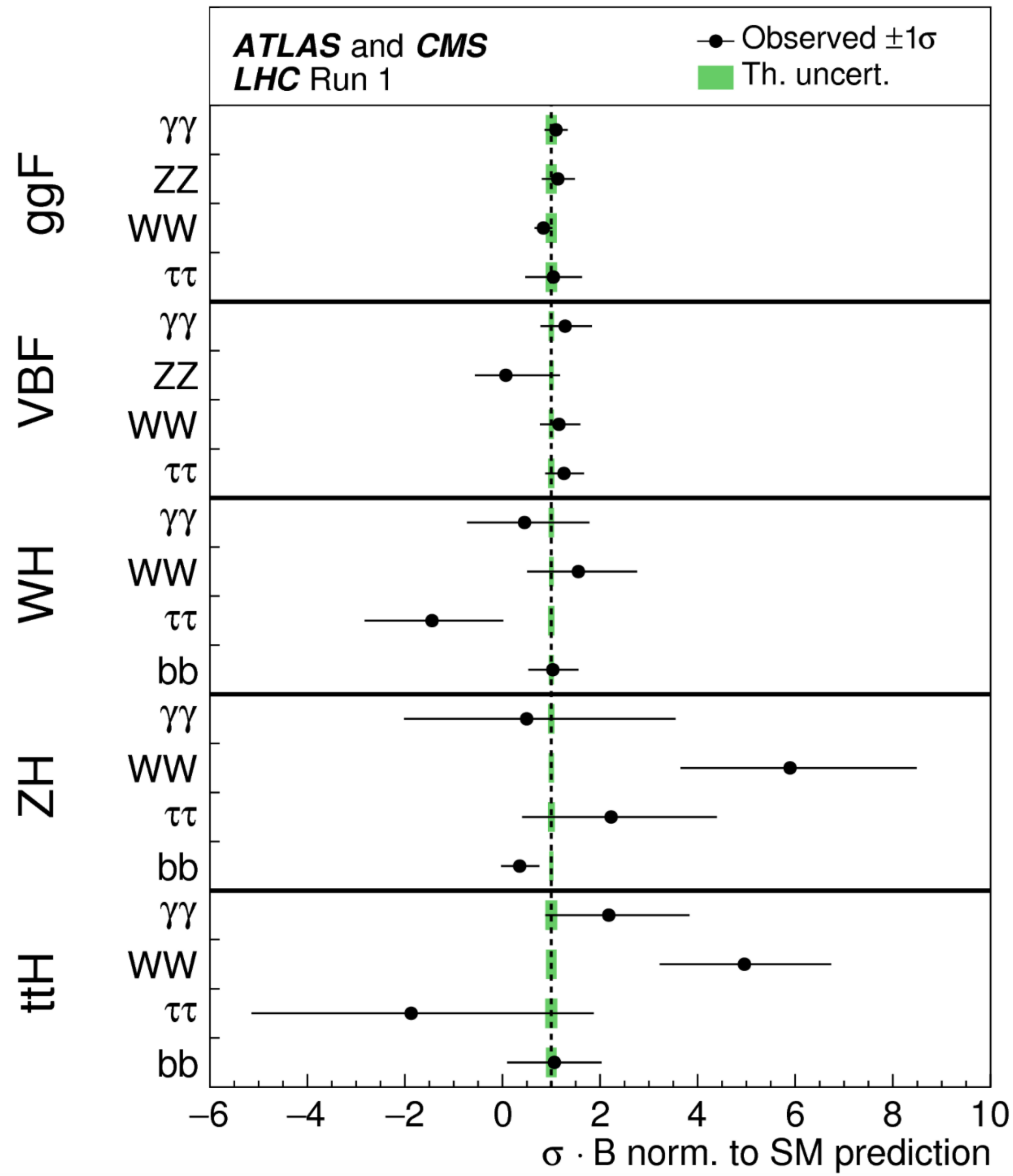

Higgs and naturalness

- Higgs with mh=125 GeV is somewhat heavy than in typical supersymmetric models and somewhat light than typical prediction of technicolour models.

- People started to question the validity of the naturalness principle.

- My personal point of view: The naturalness principle reflects our current understanding of basics of QFT. A failure of naturalness would mean that these basics must be fundamentally reviewed.

Higgs and naturalness

- P. Dirac was the first who recognised importance of naturalness in quantum physics. He asserted that all the dimensionless parameters of a theory must be of the same order of magnitude (strong naturalness principle) – why? – because in quantum theory all the parameters are related to each other via quantum corrections!

- Dirac's Large (Small) Number Hypothesis:

Gravity/EM $\alpha \left(\frac{m_e}{M_P}\right)\left(\frac{m_p}{M_P}\right) \approx 10^{-40}$ is = $\left(\frac{m_p}{M_U}\right)^{1/2} \approx 10^{-40}$

Predicts time variation of Newton's constant, which turned out to be at odds with observations.

- Lesson: The principle applies to microscopic parameters. Macroscopic parameters, such as mass of the universe M_U can be random (maybe CC is the same?).

Higgs and naturalness

- G. 't Hooft: Dimensionless parameter can be small if it is supported by a symmetry (technical naturalness):

$$\left(\frac{m_e}{M_P}\right) << 1-$$ chiral symmetry

$$\left(\frac{m_p}{M_P}\right) << 1-$$ dimensional transmutation in QCD, a.k.a. scale invariance

- Higgs mass naturalness:

$$\left(\frac{m_h}{M_P}\right) << 1-$$???

Higgs and naturalness

- Consider an effective theory with a 'physical' cut-off Λ, which contains scalars, S, fermions, F, and vector fields, V.
- 1-loop scalar mass term:

$$m_S^2(\mu) = m_S^2(\Lambda) + \frac{1}{32\pi^2}\mathrm{STr}\; g_A\left[\Lambda^2 - M_A^2 \ln\left(\Lambda^2/\mu^2\right)\right]$$

$$\mathrm{STr} \equiv (-1)^{2J_A}(2J_A+1)$$

- $m_S^2 << \Lambda^2$ requires fine-tuning and thus is unnatural (hierarchy problem)

- According to 't Hooft we need a symmetry to remove quadratic dependence on UV scale

Higgs and naturalness

- Supersymmetry
  Non-renormalisation theorem:

$$\mathrm{STr}\; g_A = 0 \quad \text{(holds in for softly broken supersymmetry)}$$

$$\mathrm{STr}\; g_A M_A^2 = 0$$

Quadratic divergences are absent in softly broken supersymmetry!

- Scale invariance

$$m_S^2(\mu = \Lambda) = 0 \rightarrow \bar{m}_S^2(\Lambda) + \mathrm{STr} g_A \Lambda^2 = 0$$

Classical scale invariance is broken spontaneously and explicitly by logarithmic quantum corrections,

$$T_\mu^\mu = \sum_i \beta_i \mathcal{O}_i \quad \text{- dimensional transmutation}$$

Scale invariant SM with light dilaton

- Consider SM as an effective Wilsonian theory with 'physical' cut-off Λ.

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

- Assume, the 'fundamental' theory exhibits conformal invariance, which is spontaneously broken down to the Poincare invariance,

$$SO(2,4) \to ISO(1,3)$$

Only one scalar (pseudo)Goldstone is relevant in the low energy theory, the dilaton, $\chi(x)$

- Promote all dimensionfull parameters in the low energy action to $\chi(x)$ [Coleman, '85]:

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

Scale invariant SM with light dilaton

- Theory becomes manifestly scale invariant (up to quantum anomaly):

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

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

$$\beta_{\lambda^{(i)}}(\mu)=\left.\frac{\partial\lambda^{(i)}}{\partial\ln\chi}\right|_{\alpha\chi=\mu}\sim\mathcal{O}(\hbar)\ ,\quad \beta'_{\lambda^{(i)}}(\mu)=\left.\frac{\partial^2\lambda^{(i)}}{\partial(\ln\chi)^2}\right|_{\alpha\chi=\mu}\sim\mathcal{O}(\hbar^2)\ ,...$$

- At leading order dilaton-SM interactions are given by:

$$\mathcal{L}_{\chi-SM}\propto\frac{\chi}{f_\chi}\,T^\mu_\mu\ \text{(SM anomaly)}$$

Scale invariant SM with light dilaton

- Find vacuum configuration + impose cancelation condition on vacuum energy:

$$\left.\frac{dV}{d\chi}\right|_{\Phi=\langle\Phi\rangle,\chi=\langle\chi\rangle}=0 \qquad \rho(\Lambda)=0\ ,$$

$$\left.\frac{dV}{d\Phi}\right|_{\Phi=\langle\Phi\rangle,\chi=\langle\chi\rangle}=0 \quad \Longrightarrow \quad \beta_\rho(\Lambda)=0\ ,$$

$$V(v_{ew},v_\chi)=0 \qquad \xi(\Lambda)=\frac{v_{ew}^2}{v_\chi^2}\ .$$

- Scalar mass spectrum:

$$m_h^2\simeq 2\lambda(\Lambda)v_{ew}^2\ ,$$

$$m_\chi^2\simeq\frac{\beta'_\rho(\Lambda)}{4\xi(\Lambda)}v_{ew}^2\propto m_h^2\xi\ ,$$

$$\sin\alpha\sim\sqrt{\xi}$$

Scale invariant SM with light dilaton

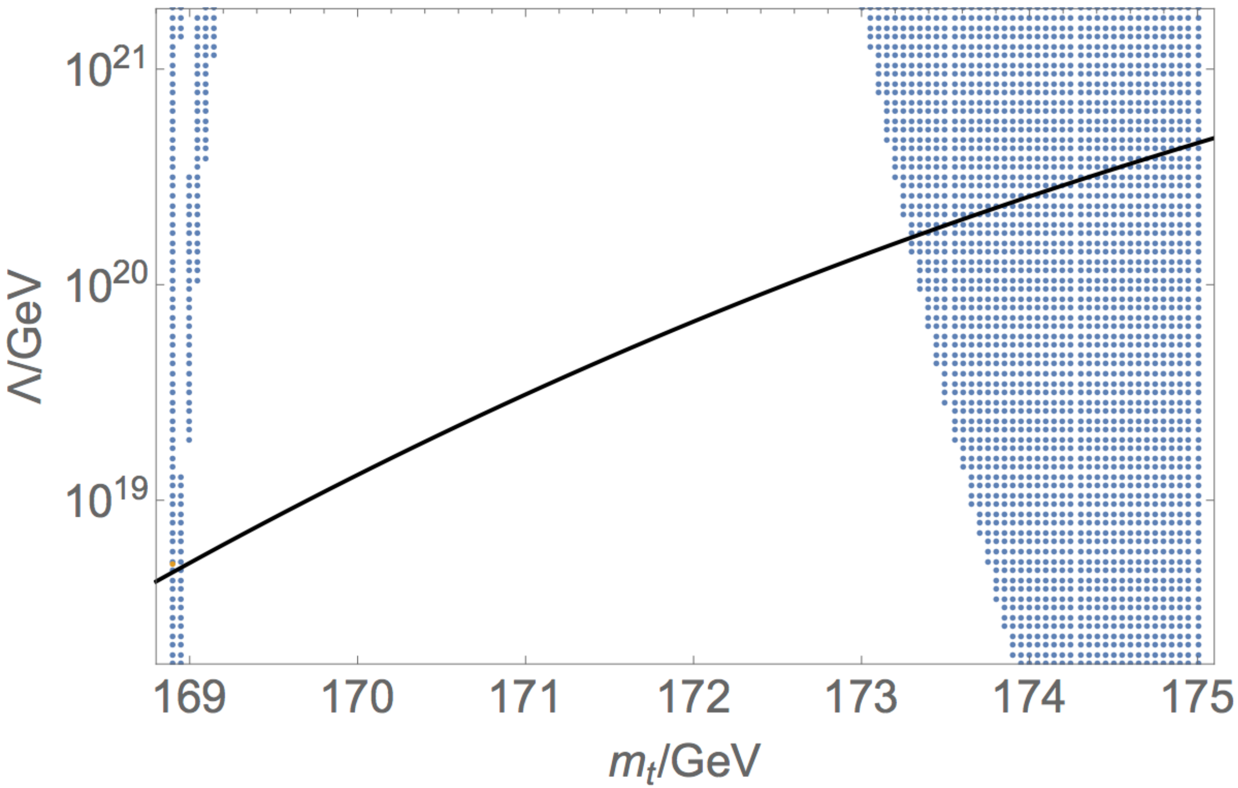

Figure 1: Plot of the allowed range of parameters (shaded region) with $m_\chi^2(v_{ew}) > 0$, i.e., the electroweak vacuum being a minimum. The solid line displays the cut-off scale Λ as function of the top-quark mass m_t for which the conditions in Eq. (6) are satisfied.

- If $\Lambda \sim 10^{19}$ GeV, $m_\chi \sim 10^{-8}$ eV!

Scale invariant SM with light dilaton

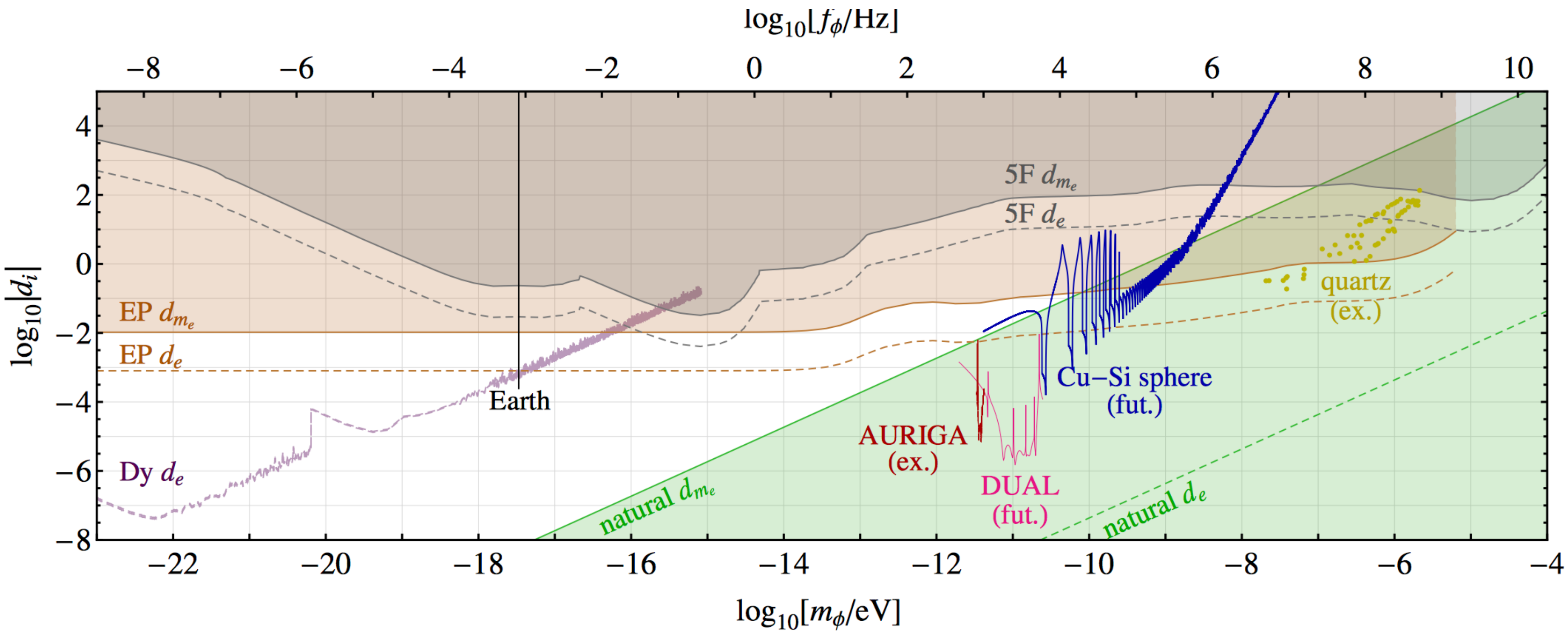

FIG. 1. Scalar field parameter space, with mass m_ϕ and corresponding DM oscillation frequency $f_\phi = m_\phi/2\pi$ on the bottom and top horizontal axes, and couplings of both an electron mass modulus ($d_i = d_{m_e}$) and electromagnetic gauge modulus ($d_i = d_e$) on the vertical axis. Natural parameter space for a 10 TeV cutoff is depicted in green, while the other regions and dashed curves represent 95% CL limits from fifth-force tests ("5F", gray), equivalence-principle tests ("EP", orange), atomic spectroscopy in dysprosium ("Dy", purple), and low-frequency terrestrial seismology ("Earth", black). The blue curve shows the projected SNR = 1 reach of a proposed resonant-mass detector—a copper-silicon (Cu-Si) sphere 30 cm in radius—after 1.6 y of integration time, while the red curve shows the reach for the current AURIGA detector with 8 y of recasted data. Rough estimates of the 1-y reach of a proposed DUAL detector (pink) and several harmonics of two piezoelectric quartz resonators (gold points) are also shown.

taken from arXiv:1508.01798

Cosmological electroweak phase transition

- Higgs-dilaton potential: the energy densities at the origin and at the electroweak vev are degenerate and are separated by a very small barrier (flat direction lifted by 2-loop quantum corrections).

- Thermal barrier is also generated which implies that the critical temperature of the transition is $T_c=0$.

- QCD condensates drive the electroweak phase transition! (Witten 81')

Cosmological electroweak phase transition

$$V_T(h,\chi) = \frac{\lambda(\Lambda)}{4}\left[h^2 - \frac{v_{ew}^2}{v_\chi^2}\chi^2\right]^2 + \sum_i n_i(-1)^{2s_i+1}\left[\frac{m_i^4}{32\pi^2}\log\frac{\alpha\chi}{m_i} - \frac{1}{2\pi^2}T^4 J_i(m_i^2/T^2)\right]$$

- High temperature/small field expansion:

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

- Solve for the dilaton field:

$$\chi^2 = \frac{v_\chi^2}{v_{ew}^2}h^2 + \frac{T^2}{12}$$

Cosmological electroweak phase transition

- The Higgs potential becomes:

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

- $4\lambda(\Lambda)+6y_t^2(\Lambda)+\frac{9}{2}g^2(\Lambda)+\frac{3}{2}g'^2(\Lambda)>0 \implies$ *h=0* is a local minimum for any T.

- If so, the universe would be trapped in symmetric vacuum *h=0*.

Cosmological electroweak phase transition

- In *h=0* vacuum all quarks are massless. *SU(6)xSU(6)* chiral symmetry is broken at T_c~132 MeV. The quark condensate break the electroweak symmetry as well.

$$\langle \bar{q}q \rangle_T = \langle \bar{q}q \rangle \left[1 - (N^2-1)\frac{T^2}{12Nf_\pi^2} - \frac{1}{2}(N^2-1)\left(\frac{T^2}{12Nf_\pi^2}\right)^2 + \mathcal{O}\left((T^2/12Nf_\pi^2)^3\right) \right]$$

$$\langle \bar{q}q \rangle \approx -(250\ \mathrm{MeV})^3$$

(Gasser & Leutwyler, 86')

- Higgs-quark Yukawa interactions: $y_q \langle \bar{q}q \rangle_T h/\sqrt{2}$

- $y_q \langle \bar{q}q \rangle_T/\sqrt{2} + \frac{\partial V_T}{\partial h} = 0 \rightarrow$ *h=0* is no more an extremum

Cosmological electroweak phase transition

- Quark condensate tips the Higgs field from the origin, which ‘runs down’ classically towards the electroweak minimum, smoothly and quickly completing the transition

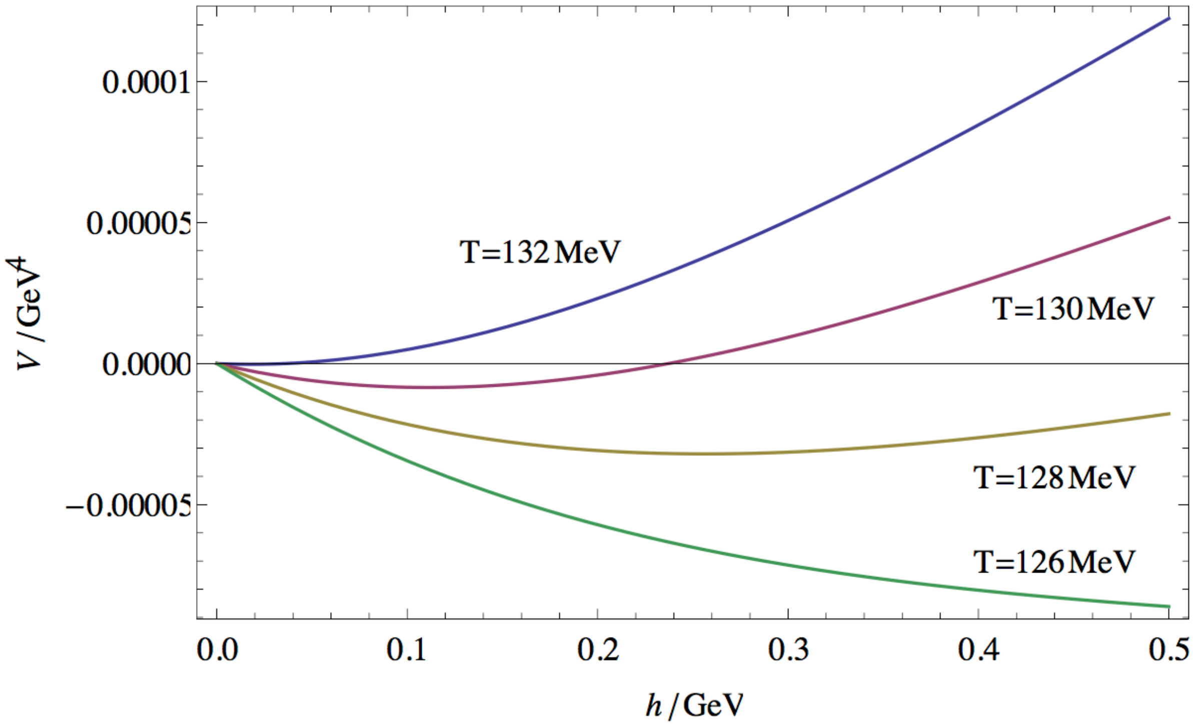

Figure 2: $V_T(h) - V_T(0)$ for different temperatures below the chiral phase transition.

Cosmological electroweak phase transition

- QCD with $N=6$ quarks undergoes first-order phase transition, unlike the standard case with $N=3$.
- Gravitational waves with peak frequency ~10^{-8} Hz, potentially detectable by means of pulsar timing (EPTA, SKA…)
- Production of primordial black holes with mass $M_{bh} \sim M_{\odot}$
- Cold electroweak baryogenesis(?)

Conclusion

- Scale invariant theories predict a light feebly copupled dilaton.
- Electroweak phase transition driven by the QCD chiral phase transition and occurs at T~130 MeV.
- QCD phase transiotion could be strongly first order => gravitational waves, black holes, cold 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.