Cosmological Signatures of a UV-Conformal Standard Model

Gláuber Carvalho Dorsch
with S. J. Huber and J. M. No

University of Sussex

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Introduction

Hierarchy problem: $m_h \approx 125$ GeV but $\delta m_h^2 \sim \Lambda^2 \sim M_{\rm Pl}^2$.

Arises because the mass of a scalar is not protected by any symmetry.

Possible solutions:

- Admit fine-tuning;
- Composite Higgs (not a fundamental scalar);
- Extra-dimensions;
- Supersymmetry;
- Conformal invariance.

Outline

- Conformal invariance and GMESB mechanism
- Effective Higgs potential
- Electroweak phase transition
- Gravitational wave spectrum
- Collider constraints
- Conclusions

Conformal invariance

$$\mathcal{L}_{\text{SM}} \supset \mu^2 H^\dagger H - \lambda (H^\dagger H)^2$$

- In SM Lagrangian, μ is the only dimensionful parameter.
  Introduced *ad hoc* to account for EWSB.
  Unprotected.
- Setting $\mu = 0$ makes SM conformal only at classical level.
  But there is an anomaly (couplings still run).

Proposal

SM is the IR manifestation of a UV-conformal theory.

- More particles must be added to make conformal symmetry exact $\Rightarrow$ "Hidden" sector.
- Nature is not conformal $\Rightarrow$ symmetry must be broken.
- EWSB is a by-product of Conformal Symmetry Breaking.

Conformal invariance: GMESB mechanism

- But it's hard to embed SM in a conformal model.
- In general, need to know the details of the hidden sector.
- m_h is sensitive to scale of conformal breaking f_c, so $f_c \sim \Lambda_{EW}$.
- Working hypothesis:

Gauge Mediation of Exact Scale Breaking (GMESB)

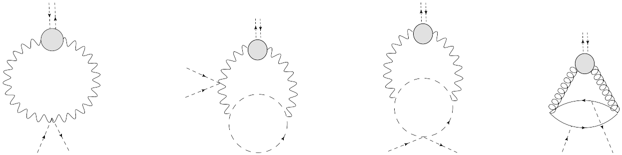
Scale symmetry is spontaneously broken in hidden sector at some scale f_c and communicated to the visible sector (SM) via gauge interactions only.

Abel & Mariotti, arXiv:1312.5335

$$\mathcal{L} \supset g A_\mu^a \left(J^{\mu a}_{\text{vis}} + J^{\mu a}_{\text{hid}} \right)$$

- Effectively, scale anomalies introduce corrections to gauge boson's propagators, parametrized as C_{vis} and C_{hid}.

Effective Higgs Potential



$$V_{\text{eff}} = \text{Tr} \int \frac{d^4p}{(2\pi)^4} \log\left(p^2 + m_V^2 + g^2 C_{\text{vis}} + g^2 C_{\text{hid}}\right)$$

- 2- to 3-loop suppression $\Rightarrow m_h \ll f_c \sim 10 - 100$ TeV.
- Terms contributing to m_h must involve f_c, so define

$$\delta V_{\text{eff}} \equiv V_{\text{eff}} - V_{\text{eff}}\big|_{f_c=0}.$$

- Expanding in g up to $\mathcal{O}(g^4)$, considering only the dominant $p^2 \gg v^2$ contributions, and imposing the correct value of VEV v and Higgs mass m_h, we arrive at

$$\delta V_{\text{eff}} \equiv V_0 = -\frac{m_h^2}{4} h^2 \left(1 + X \log\left[\frac{h^2}{v^2}\right]\right) + \frac{\lambda}{4} h^4$$

with $X = \frac{2v^2\lambda}{m_h^2} - 1$ (m_h, X depend on f_c and C_{hid}).

Effective Higgs Potential

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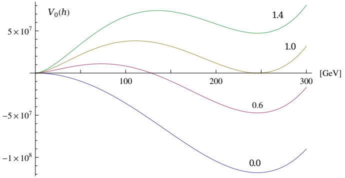
$$X = \frac{2v^2\lambda}{m_h^2} - 1$$

- SM is recovered for $X = 0$.
- $X > 1$: no SSB!
- $0 < X < 1$: barrier at zero-temperature!
  EWPT stronger than in SM.



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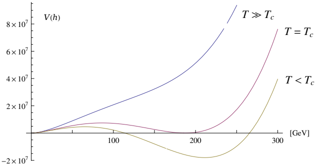


- 1-loop thermal potential (High-T expansion):

$$V \approx V_0 + \frac{T^2}{24} m^2(h) - \frac{T}{12\pi} m^3(h) - \frac{m^4(h)}{64\pi^2} \log\left(\frac{m^2(h)}{16\pi^2 c T^2}\right)$$

- EW Symmetry restored at high temperatures ($T \gg v$).
- As T decreases, a second minimum appears.
- If there is a barrier separating both minima, PT is first order. Tunneling, bubble nucleation.

Electroweak Phase Transition

- Nucleation rate per unit volume:

$$\Gamma/V \sim T^4 \, e^{-F_c/T}.$$

F_c: free-energy of critical bubble.
$T_{\mathrm{n(ucleation)}}$: $F_c/T_n \approx 140$.

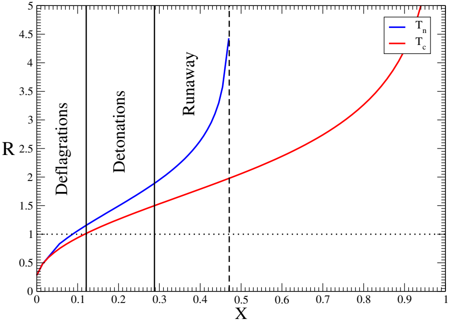
- Symmetric vacuum metastable for $X \gtrsim 0.47 \Rightarrow$ Excluded!
- Phase transition strength:

$$R(T) \equiv v(T)/T$$

$$R_n \geq 1 \Leftrightarrow X \gtrsim 0.08.$$

- Hydrodynamic equations give wall velocity v_w.
  - $v_w < v_s$: deflagration;
  - $v_w > v_s$: detonation;
  - $v_w \approx 1$: runaway.

v_s: speed of sound in plasma.



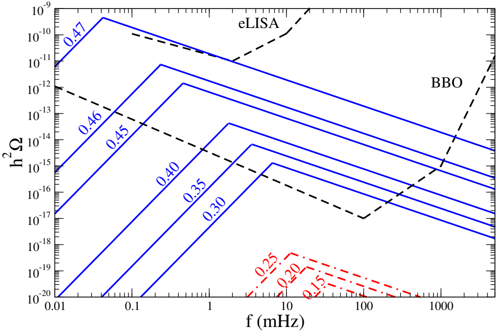
Gravitational Wave Spectrum

- GW spectrum depends mainly on 2 parameters:
  - Latent heat to radiation energy density: $\alpha \sim 10^{-2} - 10^{-1}$;
  - mean bubble size as they collide $\sim \beta^{-1}$.

After red-shift:

$$h^2\Omega_{\text{peak}} \simeq 10^{-6} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\kappa\,\alpha}{1+\alpha}\right)^2 \frac{1.84\,v_w^3}{0.42+v_w^2}$$
$$f_{\text{peak}} \simeq 10^{-2}\text{mHz} \left(\frac{T}{100\,\text{GeV}}\right)^2 \frac{\beta}{H_*} \frac{1.02}{1.8+v_w^2}$$

Small frequencies: $\sim f^3$.
Large frequencies: $\sim f^{-1}$.

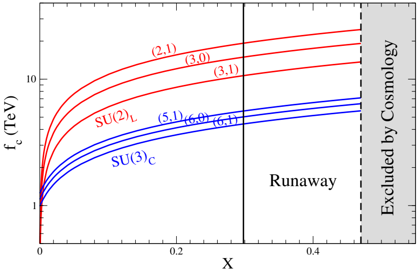


Collider Constraints

- $(\lambda^{hhh}/\lambda^{hhh}_{\rm SM}) - 1 = 2X/3$.
- LHC with 3 ab^{-1} sensitive to $X > 0.45$ only ($\sim 30\%$ accuracy on λ_{hhh}). Runaway region could be probed at ILC @ 1 TeV ($\sim 21\%$ accuracy). Better prospects at CLIC @ 3 TeV ($\sim 15\%$ accuracy).
- A toy model:
  - Two hidden sectors coupling to $SU(2)$ and $SU(3)$ separately;
  - $f_{c(2)}$ and $f_{c(3)}$;
  - N_B^n bosons (N_F^n fermions), all with anomalous dimension $\gamma_B^{(n)}$ ($\gamma_F^{(n)}$);
  - $\gamma_B^{(n)}, \gamma_F^{(n)} < 0$ for consistency:

    $$X > 0$$

  - Perturbativity bounds ($|\gamma^{(n)}_{B,F}| < 1$) + vanishing of 1-loop beta functions $\Rightarrow$ upper bounds on $f_{c(n)}$.



Conclusions

- Conformal symmetry with GMESB can solve hierarchy problem.
- The only imprint in the SM would be in the scalar sector.
- Difficult, but possible to probe in near-future colliders (λ_{hhh}).
- Exotic logarithmic term implies interesting cosmology:
  - Strong EWPT for $0.08 < X < 0.47$;
  - GW production (BBO and possibly eLISA for $X > 0.3$).
- Baryogenesis may be challenging: large wall velocity; $\not{C}\not{P}$?

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Thank you!

Appendix

Appendix

- Definition of $C_{\rm vis}$ (similar for $C_{\rm hid}$):

$$\langle J^\mu_{\rm vis} J^\nu_{\rm vis}\rangle = -\left(p^2\eta^{\mu\nu} - p^\mu p^\nu\right)\frac{C_{\rm vis}}{p^2}.$$

- Effective potential:

$$\delta V^{(2)}_{\rm eff} = \frac{9g_2^4\mathcal{A}_2}{16\pi^2} f^2_{c(2)} H^\dagger H \left[4\pi^2 - 6\lambda_t^2 + \lambda\left(1+\frac{\mathcal{B}_2}{\mathcal{A}_2}\right) + \frac{51}{8}g_2^2\left(1-\frac{13}{51}\frac{\mathcal{B}_2}{\mathcal{A}_2}\right)\right.$$
$$\left. +\lambda\log\frac{4\lambda H^\dagger H}{f^2_{c(2)}} - \frac{13}{8}g_2^2\log\frac{g_2^2 H^\dagger H}{2f^2_{c(2)}}\right],$$

$$\delta V^{(3)}_{\rm eff} = -\tfrac{72 g_3^4\lambda_t^2\mathcal{A}_3}{8\pi^2} f^2_{c(3)} H^\dagger H,$$

with

$$\mathcal{A}_2 = -\frac{1}{f^2_{c(2)}}\int\frac{d^4p}{(2\pi)^4}\frac{\delta C^{(2)}_{\rm hid}}{p^2}, \qquad \mathcal{B}_2 = -\frac{1}{f^2_{c(2)}}\int\frac{d^4p}{(2\pi)^4}\frac{\delta C^{(2)}_{\rm hid}}{p^2}\log\frac{f^2_{c(2)}}{p^2}.$$

Appendix

- After requiring V_0 to yield correct VEV v and mass m_h:

$$\mathcal{A}_2 = \frac{64\pi^2}{9g_2^4}\frac{X}{Y}\frac{m_h^2}{f_{c(2)}^2}\ , \qquad X = \frac{2v^2\lambda}{m_h^2} - 1\ , \qquad Y = 13g_2^2 - 8\lambda\ ,$$

$$\mathcal{A}_3 = \frac{\pi^2}{18g_3^4\lambda_t^2}\left(1 + 16\frac{X}{Y}(2\pi^2 - 3\lambda_t^2) - \frac{X}{\pi^2}\log\frac{v^2}{2f_{c(2)}^2}\right)\frac{m_h^2}{f_{c(3)}^2}$$

so that we arrive as

$$\delta V_{\text{eff}} \equiv V_0 = -\frac{m_h^2}{4}\,h^2\left(1 + X\log\left[\frac{h^2}{v^2}\right]\right) + \frac{\lambda}{4}\,h^4\,.$$

Appendix

GW spectrum with BICEP2 result: