# Gravitational Wave signal prospects for Classically Conformal Coleman Weinberg SM extension

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# Classically conformal extended SM

## Radiative $U(1)_H$ Symmetry breaking as origin of EWSB

- Classically Conformal SM Extension: $G_{SM} \times U(1)_H$ with hidden sector $U(1)_H$ containing only a $+2$ gauge charged scalar $\Phi$.
- CW mechanism (Coleman & Weinberg, 1973) for radiative symmetry breaking in $U(1)_H$ sector:

$$
\begin{aligned}
V_\phi &= \lambda_\phi \left(\Phi^\dagger \Phi\right)^2 + V_{1loop} \\
&= \frac{1}{4}\lambda_\phi \phi^4 + \frac{\beta_\phi}{8}\phi^4 \left( ln\left[\frac{\phi^2}{v_\phi^2}\right] - \frac{25}{6}\right), \text{ where } \phi = \sqrt{2}\mathrm{Re}\left[\Phi\right]
\end{aligned}
$$

- Full scalar potential reads:

$$
V = \lambda_h \left(H^\dagger H\right)^2 - \boxed{\lambda_{mix}\left(H^\dagger H\right)\left(\Phi^\dagger \Phi\right)} + \lambda_\phi \left(\Phi^\dagger \Phi\right)^2 + V_{1loop}
$$

# Coleman-Weinberg Mechanism

## Radiative $U(1)_H$ Symmetry breaking as origin of EWSB

- **Radiative symmetry breaking in $U(1)_H$ sector at $\langle\phi\rangle = v_\phi$ generates negative SM Higgs mass squared term, driving EW symmetry breaking.**
- Obtain and diagonalize $M_{sq}$ to find eigenstate mixing:

$$h = h_1\cos(\theta) + h_2\sin(\theta)$$
$$\phi = -h_1\sin(\theta) + h_2\cos(\theta)$$

We set $M_{h_1} > 2M_{h_2}, \theta \ll 1 \Rightarrow \boxed{h \sim h_1,\ \phi \sim h_2}$

- **Coupling analysis reveals strongly suppressed $g_{h_1 h_2 h_2}$ in conformal system vs. conventional system.**

# Coupling Analysis

- Express potentials in terms of observables and extract couplings.

For $M_{h_1} > 2M_{h_2}, \theta \ll 1$, conventional system coupling goes as

$$g_{h_1 h_2 h_2} \simeq -\frac{M_{h_1}^2}{2v_\phi}\left(1 + 2\frac{M_{h_2}^2}{M_{h_1}^2}\right)\theta \quad \text{for} \quad \theta \ll \frac{v_h}{v_\phi},$$

$$g_{h_1 h_2 h_2} \simeq \frac{M_{h_1}^2}{2v_h}\left(1 + 2\frac{M_{h_2}^2}{M_{h_1}^2}\right)\theta^2 \quad \text{for} \quad \frac{v_h}{v_\phi} \lesssim \theta,$$

while conformal system coupling goes as

$$g_{h_1 h_2 h_2} \simeq -\frac{M_{h_2}^2}{2v_h}\left(1 - 4\frac{M_{h_2}^2}{M_{h_1}^2}\right)\theta^2.$$

- Cancellation of lower order $\theta$ terms and unique CW structure leads to coupling suppression.

# Higgs Phenomenology at ILC

- Gray regions excluded by LHC (ATLAS, 2020) and LEP-II (for $M_{h_2} = 25$ GeV) (LEP-II, 2003)
- Prospective ILC search reach in blue for anomalous Higgs decay (Liu, Wang, Zhang, 2017) and red for anomalous coupling (Barklow et. al., 2018).

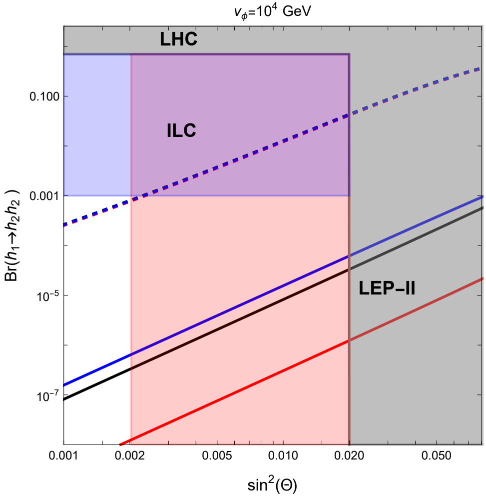


Figure: Conventional (dashed) and Conformal (solid) branching ratios. $M_{h_2}$ = 10 (red), 25 (black), and 50 (blue) GeV.

# $U(1)_H$ vector boson Dark Matter

- Consider $Z'$, the gauge boson of $U(1)_H$, as DM candidate
- Reproduce observed $\Omega_{DM}h^2 = 0.12$ (Planck 2018) with $\langle \sigma v_{rel} \rangle \sim 1$ pb

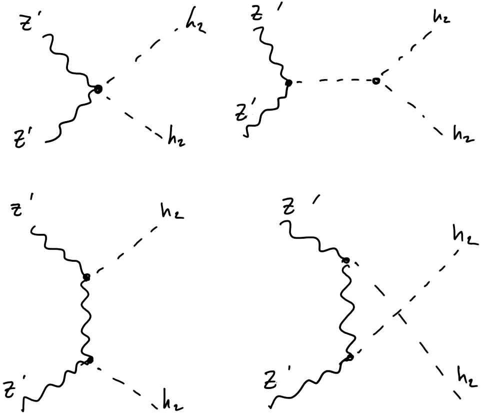


Figure: $Z'Z' \to h_2 h_2$ DM annihilation process diagrams

# Complementarity between $U(1)_H$ vector boson Dark Matter and ILC Higgs Phenomenology

- Red, Black, Blue lines correspond to non-excluded parameter space for $\theta$ below LEP-II bounds for $M_{h_2} = 10$ (red), 25 (black), and 50 (blue) GeV, respectively.
- $\langle \sigma v_{rel} \rangle \sim 1$pb satisfied along purple curve. Conformal model reproduces $\Omega_{DM} h^2 = 0.12$ at intersection points.

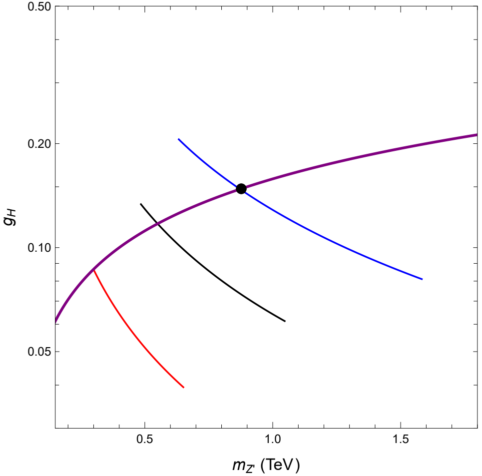


Figure: Gauge coupling $g_H$ vs. $Z'$ (DM) mass, for select values of $m_{h_2}$.

# $U(1)_H$ Higgs sector First Order Phase Transition (FOPT)

- $Z'$ DM benchmark case $M_{h_2} = 50$ GeV exhibits FOPT
- FOPT at finite T may source Gravitational Waves (GW) from bubble collisions, depending on model parameters

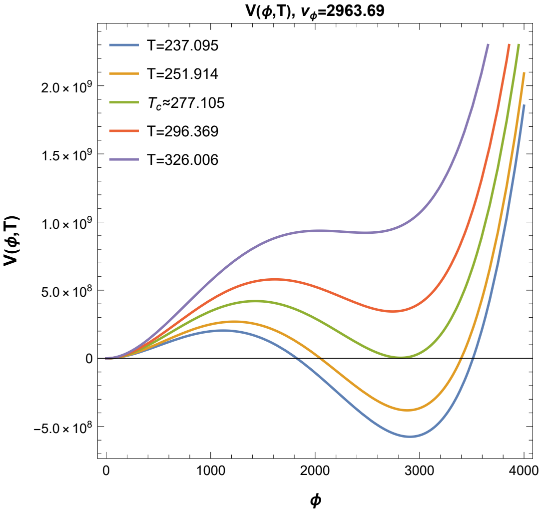


Figure: $V(\phi, T)$ for $M_{h_2} = 50$ GeV case

# GW signals

- Peak amplitude of $h^2\Omega \sim 10^{-11}$ at frequency $f \sim 10^{-4}$ Hz
- Signals fall within range of future U-DECIGO AND $\mu$-ARES search reach

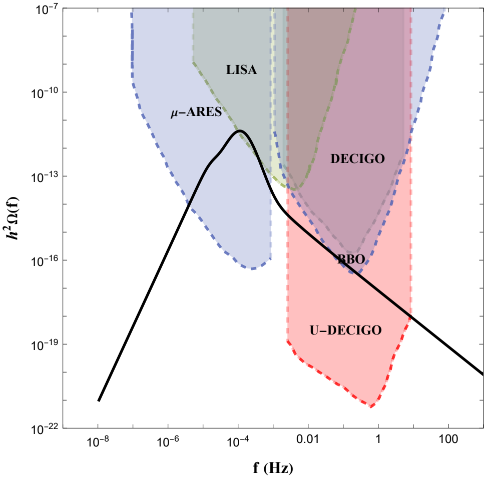


Figure: $h^2\Omega(f)$ for the $M_{h_2} = 50$ GeV case

# Summary

- Classical conformal structure & Coleman-Weinberg mechanism as origin of EW Symmetry breaking.
  - **Radiative symmetry breaking in $U(1)_H$ sector induces negative SM Higgs mass term, driving EW symmetry breaking**
- Higgs Phenomenology greatly affected by unique conformal potential
  - **Models distinguishable by precision measurement of anomalous Higgs coupling alongside (non-)observation of anomalous Higgs decay $h_1 \to h_2 h_2 \to b\bar{b}b\bar{b}$ at future $e^+e^-$ or $\mu^+\mu^-$ colliders.**
- With $Z'$ as DM candidate, $\Omega_{DM} h^2 = 0.12$ can be satisfied for appropriate choice of $M_{h_2}$.
- GW signal from Vector DM Model with $M_{h_1} = 50$ GeV from FOPT with signal within U-DECIGO and $\mu$-ARES search regions
- **Complementarity among Higgs Pheno., Z' DM, and GW signals** good for future detection prospects of conformal models