Gravitational waves at aLIGO and vacuum stability from a gauge singlet scalar field

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A long-long time ago in a Universe far-far away …

- Electroweak phase transition happened at $10^3$ GeV
- But vacuum stability needed new physics below $10^9$ GeV
- A gauge singlet stabilized the vacuum and
- Had a phase transition at $10^8$ GeV leading to
- Gravitational waves from bubble collisions
- Potentially in the reach of aLIGO
Electroweak phase transition

- Higgs potential
  \[ V = \mu^2 |H|^2 + \lambda |H|^4 + \cdots \]
evolves with \( T \)
- \( \mu^2 \) changes sign \( \sim 300 \) GeV
- the famous Mexican hat forms
- Higgs develops a vev.

in early Universe \( E = T \)
Electroweak vacuum stability

- $\lambda$ changes sign $
\sim 10^9$ GeV
- unstable vacuum
- unless new physics before $
\sim 10^9$ GeV
  Universe falls into bottomless pit
2014 God Particle Project: Opening A Bottomless Pit to Hell Now! (Disturbing Video)

Friday, January 3, 2014 21:35

(Before It’s News)

The Key to the Bottomless Pit, Top World Researchers are attempting to open other dimensions. http://www.BpearthWatch.com
Gauge singlet scalar

- a gauge singlet scalar can stabilize the Higgs potential

- Standard particles

- Standard forces
  - SU(3) x U(1) x SU(2) strong electroweak
  - a singlet doesn’t couple to g, photon, Z, W

Gauge singlet scalar model

- scalar potential: masses and interactions at zero temperature

\[ V_0(H, S) = \mu^2 |H|^2 + \frac{1}{2} \lambda |H|^4 \]

\[ + \frac{1}{2} M_S^2 S^2 + \frac{1}{3} \kappa S^3 + \frac{1}{2} \lambda_S S^4 \]

\[ + \kappa_1 S |H|^2 + \frac{1}{2} \kappa_2 S^2 |H|^2, \]

- thermal contributions to the potential

\[ V = V_0 + \Delta V_D + \Delta V_T + \Delta V_{CW} \]

- free parameters: \( M_S, \lambda_S, \kappa_{1,2} \)
Phase transition at $\sim 10^8$ GeV

- $S$ can develop a vev.
- its mass & vev. are set by vacuum stability to $\sim 10^8$ GeV
- accompanying phase transition can be 1st order
Phase transition at $\sim 10^8$ GeV

- regions in the para space
  $10^{-8}$ GeV $\leq |\kappa_1| \leq 10^8$ GeV
  $10^{-8} \leq \kappa_2 \leq 2$
  $10^{12}$ GeV$^2 \leq M_S^2 \leq 10^{18}$ GeV$^2$
  $10^7$ GeV $\leq T_C \leq 10^8$ GeV
  $2.3 \leq \gamma \leq 3$

- exist with

- stable vacuum

- acceptable pheno.

- strong 1st OPT at $\sim 10^8$ GeV
Bubble nucleation
Gravitational wave production during a 1\textsuperscript{st} order phase transition gravitational waves are produced by

- collisions of bubble walls
- sound waves in the plasma
- magneto-hydrodynamics turbulence following bubble collisions
for bubble collisions the amplitude and frequency of GWs is determined by the

- length of the PT \(1/\beta\)
- latent heat \(\alpha\)
- wall velocity \(v_w\)

\(g_* = 107.75\)

\[
\Omega_{GW} \simeq 10^{-9} \cdot \left( \frac{31.6H_N}{\beta} \right)^2 \left( \frac{\alpha}{\alpha + 1} \right)^2 \\
\epsilon^2 \left( \frac{4v_w^3}{0.43 + v_w^2} \right) \left( \frac{100}{g_*} \right)^{\frac{1}{3}}
\]

\[
f_0 \simeq 16.5 \text{ Hz} \cdot \left( \frac{f_N}{H_N} \right) \left( \frac{T_N}{10^8 \text{ GeV}} \right) \left( \frac{g_*}{100} \right)^{1/6}
\]

\[
f_N = \frac{0.62\beta}{1.8 - 0.1v_w + v_w^2}
\]
Frequency and amplitude

- \( \beta \) is calculated by numerical differentiation of the action

\[
\beta \equiv - \frac{dS_4}{dt} \bigg|_{t_N} \approx H_N \left[ \frac{d \ln S_E/T}{d \ln T} \right] \frac{S_E}{T} \bigg|_{T_N}
\]

- A complete calculation of \( \beta(T) \) requires a lattice calculation.

- We reflect uncertainties in our calculation by using a range for \( \beta \).

- \( \alpha \) comes from the latent heat during the phase transition

\[
\Delta \rho = \left[ V - \frac{dV}{dT} T_N \right]_{\mathcal{F}} - \left[ V - \frac{dV}{dT} T_N \right]_{\mathcal{T}}
\]

- \( v_w \) is approximated to be \( O(1) \)
Benchmark points

three benchmark scenarios

<table>
<thead>
<tr>
<th>Point</th>
<th>$M_S^2$/GeV$^2$</th>
<th>$\lambda_S$</th>
<th>$\kappa$/GeV</th>
<th>$\kappa_1$/GeV</th>
<th>$\kappa_2$</th>
<th>$\lambda$</th>
<th>$m_S$/GeV</th>
<th>$\gamma$</th>
<th>$T_C$/GeV</th>
<th>$T_N/T_C$</th>
<th>$\beta/H_N$</th>
<th>$\Omega_{GW}$</th>
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<tbody>
<tr>
<td>SSM I</td>
<td>$4.2 \cdot 10^{14}$</td>
<td>0.064</td>
<td>$2.1 \cdot 10^7$</td>
<td>$-4.9 \cdot 10^5$</td>
<td>0.14</td>
<td>0.53</td>
<td>$4.5 \cdot 10^7$</td>
<td>2.8</td>
<td>$3.7 \cdot 10^7$</td>
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<td>$1.3 \cdot 10^{-9}$</td>
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<tr>
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<td>$2.8 \cdot 10^7$</td>
<td>$-7.3 \cdot 10^5$</td>
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<td>0.51</td>
<td>$5.5 \cdot 10^7$</td>
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<td>110</td>
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<tr>
<td>SSM III</td>
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<td>$7.4 \cdot 10^7$</td>
<td>$-1.4 \cdot 10^6$</td>
<td>0.09</td>
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<td>$1.3 \cdot 10^8$</td>
<td>2.3</td>
<td>$8.2 \cdot 10^7$</td>
<td>0.35</td>
<td>45</td>
<td>$6 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

- calculated all relevant thermal quantities: nucleation temperature, order parameter, characteristic timescale, and from those the peak amplitude and frequency
- checked vacuum stability
- checked TeV scale phenomenology (EWSB, Higgs properties, etc.)