Probing physics behind the electroweak symmetry breaking at future gravitational wave interferometers and future collider experiments

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References:
Motivation

Discovery of the 125 GeV Higgs boson $h$ at the CERN LHC

- The Standard Model (SM) has been established as a low-energy effective theory below $O(100)$ GeV

This is not the end of the story

The Higgs sector is still vague

- Guiding principle?
- Shape of the Higgs potential (multiplets, symmetries, ...)?
- Dynamics behind the electroweak symmetry breaking (EWSB)?

Phenomena beyond the SM (BSM) reported

- Baryon asymmetry of the Universe (BAU)
- Existence of dark matter
- Cosmic inflation
- Neutrino oscillations

Higgs sector = Window to New Physics

- The structure of the Higgs sector is related to BSM models

Information on new physics can be obtained by investigating the properties of the Higgs sector
Electroweak baryogenesis (EWBG) and Higgs boson couplings

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Strongly first order phase transition (1st OPT): $\varphi_c/T_c \gtrsim 1$

SM Higgs sector w/ one doublet:
- Electroweak phase transition (EWPT) is NOT of 1st order for $m_h = 125$ GeV
- e.g. Two Higgs doublet model (2HDM)
  - $\varphi_c/T_c \gtrsim 1$ \[ \Delta \lambda_{hhh}/\lambda_{hhh}^{SM} \gtrsim 10\% \]
  - [Kanemura, Okada, Senaha (2005)]

International Linear Collider (ILC) 1 TeV can measure $\lambda_{hhh}$ at 10% accuracy
  - [Fujii et al. (2015)]

EWBG can be tested at future colliders
Gravitational waves (GWs) as a probe of EWPT

Ground-based interferometers (aLIGO, KAGRA, aVirgo)
- Targets: GWs from binary systems, supernovae, ...
- aLIGO made the first direct observation of GWs
  \[\text{New era of GW astronomy} \quad \text{[LIGO and Virgo (2016)]}\]

Future space-based interferometers (eLISA, DECIGO, BBO)
- Sensitive to GWs from the early Universe
  \(\text{(Strongly 1}^{\text{st}}\text{ OPT, cosmic inflation, ...)}\)
  \[\text{New era for fundamental physics}\]

Goal of our work:
- To investigate testability of models of EWSB
  using the synergy between the measurements of the GWs,
  Higgs boson couplings \(\kappa_X\) and the \(hhh\) coupling

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Model 1: Models with additional singlet scalars (without CSI)

Idea:

- To generally handle strongly 1\textsuperscript{st} OPT via thermal loop, \( N \) isosinglet scalars \( S_i (i = 1, \cdots, N) \) are introduced
- For simplicity, \( O(N) \) symmetry is imposed

Tree-level scalar potential:

\[
V_0(\Phi, \vec{S}) = V_{\text{SM}}(\Phi) + \frac{\mu_S^2}{2} |\vec{S}|^2 + \frac{\lambda_S}{4} |\vec{S}|^4 + \frac{\lambda\Phi S}{2} |\Phi|^2 |\vec{S}|^2
\]

Singlet scalar boson mass:

\[
m_S^2 = \mu_S^2 + \frac{\lambda\Phi S}{2} v^2
\]

Triple Higgs boson coupling:

\[
\lambda_{hhh}^{O(N)} = \frac{3m_h^2}{v} \left\{ 1 - \frac{1}{\pi^2} \frac{m_t^4}{v^2 m_h^2} + \frac{N}{12\pi^2} \frac{m_S^4}{v^2 m_h^4} \left( 1 - \frac{\mu_S^2}{m_S^2} \right)^3 \right\}
\]

Finite temperature effective potential (high temperature expansion):

\[
V_{\text{eff}}(\varphi, T) \sim D(T^2 - T_0^2) \varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4} \varphi^4 + \cdots
\]

\[
\frac{\varphi_c}{T_c} \propto E = \frac{1}{12\pi^3} \left[ 6m_W^2 + 3m_Z^2 + Nm_S^2 \left( 1 - \frac{\mu_S^2}{m_S^2} \right)^{-1} \left( 1 + \frac{3\mu_S^2}{2m_S^2} \right) \right]^{1/4}
\]

Non decoupling loop effect from additional scalars
Model 2: CSI models with additional singlet scalars

Idea

[Hashino, Kanemura, Orikasa (2015)]

- Mass parameters are absent in the original Lagrangian due to Classical Scale Invariance (CSI) [Bardeen (1995)]
- EWSB is directly caused by thermal loop effects

Tree-level scalar potential

$$V_0(\Phi, \tilde{S}) = \frac{\lambda}{2} |\Phi|^4 + \frac{\lambda_S}{4} |\tilde{S}|^4 + \frac{\lambda_{\Phi S}}{2} |\Phi|^2 |\tilde{S}|^2$$

Singlet scalar boson mass

$$N m_S^4 = 8 \pi^2 v^2 m_h^2 - 6 m_W^4 - 3 m_Z^4 + 12 m_t^4$$

Triple Higgs boson coupling

$$\frac{\Delta \lambda_{hhh}}{\lambda_{hhh}^{SM(\text{tree})}} = \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM(\text{tree})}} - 1 = \frac{2}{3}$$

independent of $N$

[Hashino, Kanemura, Orikasa (2015)]
Model 3: Higgs singlet model

Idea

- To investigate EWPT caused by Higgs boson mixing by taking the extended model with a singlet Higgs boson $S$

Tree-level Higgs potential

$$V_0 = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \mu_S |\Phi|^2 S + \frac{\lambda_S}{2} |\Phi|^2 S^2 + \mu_S^3 S^3 + \frac{m_S^2}{2} S^2 + \frac{\mu'_S}{3} S^3 + \frac{\lambda_S}{4} S^4$$

Higgs boson couplings to SM particles

$$\kappa = \kappa_V = \kappa_F = \cos \theta$$

Triple Higgs boson couplings (effective potential approach)

$$\lambda_{h,h,h}^{\text{HSM}} = c_\theta^3 \left< \frac{\partial^3 V_{\text{eff},T=0}}{\partial \phi_\Phi^3} \right> + c_\theta^2 s_\theta \left< \frac{\partial^3 V_{\text{eff},T=0}}{\partial \phi_\Phi^2 \partial \phi_S} \right> + c_\theta s_\theta^2 \left< \frac{\partial^3 V_{\text{eff},T=0}}{\partial \phi_\Phi \partial \phi_S^2} \right> + s_\theta^3 \left< \frac{\partial^3 V_{\text{eff},T=0}}{\partial \phi_S^3} \right>$$

Finite temperature effective potential

(high temperature expansion; one field approximation)

$$V_{\text{eff}} = D(T^2 - T_0^2) \varphi^2 - (ET - e) \varphi^3 + \frac{\lambda(T)}{4} \varphi^4$$

$$\frac{\varphi_c}{T_c} = \frac{2E}{\lambda(1 - \frac{e \lambda}{ET})}$$

Effects from the Higgs boson mixing

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Important quantities for GW spectrum

Bubble nucleation

\[ \langle \phi \rangle \neq 0 \quad \langle \phi \rangle = 0 \]

Bubbles collision

Transition temperature \( T_t \):

\[ \frac{\Gamma}{H^4} \bigg|_{T=T_t} \simeq 1 \]

Released false vacuum energy (Latent heat)

\[ \epsilon(T) = -V_{\text{eff}}(\varphi_B(T), T) + T \frac{\partial V_{\text{eff}}(\varphi_B(T), T)}{\partial T} \]

Inverse of the duration of phase transition

\[ \beta = -\left. \frac{dS_E}{dt} \right|_{t=t_t} \approx \left. \frac{1}{\Gamma} \frac{d\Gamma}{dt} \right|_{t=t_t} \]

Sources of GWs

1. Collision of bubble walls
2. Compression wave of plasma
3. Plasma turbulence

- GW spectrum is derived from finite temperature effective potential \( V_{\text{eff}} \)

\[ \phi \neq 0 \]

Normalized parameter:

\[ \alpha = \frac{\epsilon(T_t)}{\rho_{\text{rad}}(T_t)} \]

Normalized parameter:

\[ \beta = \frac{\beta}{H_t} \]
GW spectrum

- Complicated numerical simulations are necessary
- Approximate fitting formula are available \[\text{[Caprini et al. (2015)]}\]

Collision of bubble walls (Envelope approximation):

\[
\tilde{\Omega}_{\text{env}} h^2 \simeq 1.67 \times 10^{-5} \times \left( \frac{0.11 v_b^3}{0.42 + v_b^2} \right) \tilde{\beta}^{-2} \left( \frac{\kappa_\phi \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*^t} \right)^{1/3} \\
\tilde{f}_{\text{env}} \simeq 1.65 \times 10^{-5} \text{ Hz} \times \left( \frac{0.62}{1.8 - 0.1 v_b + v_b^2} \right) \tilde{\beta} \left( \frac{T_i}{100 \text{ GeV}} \right)
\]

Sound waves (Compression waves of thermal plasma):

\[
\tilde{\Omega}_{\text{sw}} h^2 \simeq 2.65 \times 10^{-6} v_b \tilde{\beta}^{-1} \left( \frac{\kappa_\nu \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*^t} \right)^{1/3} \\
\tilde{f}_{\text{sw}} \simeq 1.9 \times 10^{-5} \text{ Hz} \frac{1}{v_b} \tilde{\beta} \left( \frac{T_i}{100 \text{ GeV}} \right)
\]

Magnetohydrodynamic (MHD) turbulence:

\[
\tilde{\Omega}_{\text{turb}} h^2 \simeq 3.35 \times 10^{-4} v_b \tilde{\beta}^{-1} \left( \frac{\epsilon \kappa_\nu \alpha}{1 + \alpha} \right)^{3/2} \left( \frac{100}{g_*^t} \right)^{1/3} \\
\tilde{f}_{\text{turb}} \simeq 2.7 \times 10^{-5} \text{ Hz} \frac{1}{v_b} \tilde{\beta} \left( \frac{T_i}{100 \text{ GeV}} \right)
\]

- $v_b$ : wall velocity
- $\kappa_\phi, \kappa_\nu$ and $\epsilon = 0.05$ : efficiency factors
Model A vs. Model B: Predicted values of $\alpha$ and $\tilde{\beta}$ in models with singlet scalars with and without CSI

- Condition for strongly 1\textsuperscript{st} OPT
  - Constraints on $\alpha$ and $\tilde{\beta}$ for each model

$O(N)$ models without CSI
- $\alpha$ and $\tilde{\beta}$ to be determined by GW observation are useful measures in determining $N$ and $m_S$

CSI $O(N)$ models
- Scale invariance is violated at finite temperatures
  - $\alpha$ and $\tilde{\beta}$ depend on $N$ though $\lambda_{hhh}$ is common

[Hashino, MK, Kanemura, Matsui (2016)]
What if the $hhh$ coupling is found to be

$$\frac{\Delta \lambda_{hhh}/\lambda_{hhh}^{SM}}{2/3(\sim 70\%)}$$

at future colliders?

- $O(N)$ models without CSI predicting

$$\frac{\Delta \lambda_{hhh}/\lambda_{hhh}^{SM}}{2/3(\sim 70\%)}$$

- CSI $O(N)$ models

[Hashino, MK, Kanemura, Matsui (2016)]

Models with and without CSI can be distinguished at future GW interferometers even if they share common $hhh$ coupling.
Testability of the Higgs singlet model

**Benchmark point**

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- Implemented into CosmoTransitions [Wainwright (2012)]

**Collider experiments**

- LHC Run I results
  \[ \kappa_Z = 1.03^{+0.11}_{-0.11}, \kappa_W = 0.91^{+0.10}_{-0.10} \] [ATLAS, CMS (2016)]
- High-Luminosity LHC
  \[ \kappa_V : 2\% \] [CMS (2013)]
  \[ \kappa_Z : 0.37\% \quad \kappa_W : 0.51\% \]
- ILC w/ \( \sqrt{s} = 500 \text{ GeV} \)
  \[ \kappa_Z : 0.37\% \quad \kappa_W : 0.51\% \]
- ILC w/ \( \sqrt{s} = 1 \text{ TeV} \)
  \[ \Delta \lambda_{hhh} : 10\% \] [Fujii et al. (2015)]

The synergy between the Higgs boson coupling measurements and GW observations is important for the HSM Higgs potential.
The strongly 1stOPT of the EWSB in extended Higgs sectors can be tested by the synergy of the measurements of Higgs boson couplings at the LHC, the $hhh$ coupling at the ILC and GWs at future space-based interferometers.
Electroweak baryogenesis (EWBG) and Higgs boson couplings

Sakharov’s conditions for BAU
1. Baryon number violation
   - Sphaleron process
2. Violation of C and CP
   - Extended Higgs sector
3. Departure from thermal equilibrium
   - Strongly first order phase transition (1\textsuperscript{st} OPT): \( \varphi_c / T_c \geq 1 \)

SM Higgs sector w/ one doublet:
- Electroweak phase transition (EWPT) is NOT of 1\textsuperscript{st} order for \( m_h = 125 \text{ GeV} \)

EWBG is an important physics case relating the Higgs sector to BSM phenomena

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Strongly 1\textsuperscript{st} OPT and Higgs boson couplings

Models with extended Higgs sector
- 1\textsuperscript{st} OPT is easily realized
- Signatures are testable at colliders

e.g. Two Higgs doublet model (2HDM)
- Condition for strongly 1\textsuperscript{st} OPT:
  \(\varphi_c/T_c \gtrsim 1\)

Large deviation in the triple Higgs boson coupling
  \((\Delta \lambda_{hhh}/\lambda_{hhh}^{SM} \gtrsim 10\%\))

ILC 1 TeV can measure \(\lambda_{hhh}\) at 10\% accuracy [Fujii et al. (2015)]

EWBG can be tested at future colliders

[Kanemura, Okada, Senaha (2005)]
Studies on the GWs from 1\textsuperscript{st} order EWPT

Model independent analysis

\cite{Grojean, Servant (2007); Kikuta, Kohri, So (2014), ...}

Higgs potential with higher order operators

\cite{Delaunay, Grojean, Wells (2008); Huang, Wan, Wang, Cai, Zhang (2016), ...}

Non-decoupling loop effects from hypothetical particles

- Light stop loop effects in the MSSM
  \cite{Apreda, Maggiore, Nicolis, Riotto (2002), ...}
- Additional scalar loop effects
  \cite{MK, Kanemura, Matsui (2015); Hashino, MK, Kanemura, Matsui (2016), ...}

Non-thermal effects even at the tree level

- Next-to-MSSM
  \cite{Apreda, Maggiore, Nicolis, Riotto (2002), Huber, Konstandin, Nardini, Rues (2015), ...}
- Real singlet extension
  \cite{Huang, Long, Wang (2016); Hashino, MK, Kanemura Ko, Matsui (2016), ...}

Large GW signals compatible with EWBG:

\cite{No (2011), ...}
Efficiency factor

[Image: Graph showing the relationship between $v_b$ and $\log_{10}[k_v]$.]

[Espinosa et al. (2010)]
Models with additional singlet scalars (without CSI) (contd.)

1. Effective potential:

\[
V_{\text{eff}}(\varphi) = -\frac{\mu^2}{2} \varphi^2 + \frac{\lambda}{4} \varphi^4 + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi) \left( \ln \frac{M_i^2(\varphi)}{Q^2} - \frac{3}{2} \right)
\]

\[
\lambda^{O(N)}_{h hh} = \frac{3m_h^2}{v} \left\{ 1 - \frac{1}{\pi^2} \frac{m_i^4}{v^2 m_h^2} + \frac{N}{12\pi^2} \frac{m_i^4}{v^2 m_h^2} \left( 1 - \frac{\mu_i^2}{m_i^2} \right)^3 \right\}
\]

Non decoupling loop effect from additional scalars

2. Finite temperature effective potential (high temperature expansion):

\[
V_{\text{eff}}(\varphi, T) \sim D(T^2 - T_0^2) \varphi^2 - ET \varphi^3 + \frac{\lambda T}{4} \varphi^4 + \cdots
\]

\[
\frac{\varphi_c}{T_c} \propto E = \frac{1}{12\pi v^3} \left[ 6m_W^3 + 3m_Z^3 + Nm_S^3 \left( 1 - \frac{\mu_S^2}{m_S^2} \right)^3 \left( 1 + \frac{3\mu_S^2}{2m_S^2} \right) \right]
\]

Typically $O(10)\%$ deviation in $\lambda_{h hh}$ for strongly 1st OPT

Non decoupling loop effect from additional scalars

\[\sqrt{\mu_S^2} = 0\]

Excluded by unitarity bound

$\Delta \lambda_{hh} \propto \lambda_{hh} \tilde{\lambda}_{hh} \tilde{\lambda}_{hh} \leq 200%$
Contribution to GWs:
- Collision: 
- Sound wave: 
- MHD Turbulence: 

Benchmark points:
\[ N = 1, 4, 12, 60 \]

from the bottom

[Hashino, MK, Kanemura, Matsui (2016)]

Experimental prospects:
- eLISA: [Caprini et al. (2015)]
- DECIGO: [Kawamura et al. (2011)]

Contribution from sound waves is dominant and detectable at future space-based interferometers, eLISA and DECIGO
Comparison of GW spectra

- **CSI $O(N)$ models**

- **$O(N)$ models without CSI**

  $\sqrt{\mu_S^2} = 0$

- **N.B.** Subsonic wall velocity is preferred for EWBG but not necessarily

[Hashino, MK, Kanemura, Matsui (2016)]

[No (2011)]
**GW spectrum for** \( v_b = 1 \)

- **Case of accelerating wall:**
  - For large \( \alpha \), the bubble wall can accelerate without reaching a terminal velocity

- **Contribution to GWs:**
  - Collision: 
  - Sound wave: 
  - MHD Turbulence: 

- **Benchmark points:**
  - \( N = 4, 12, 60 \) from the bottom

[Hashino, MK, Kanemura, Matsui (2016)]

- **\( O(N) \) models without CSI**
Transition temperature and wall velocity dependence of detectability of GWs

$T_t = 50$ GeV

$T_t = 100$ GeV

[Hashino, MK, Kanemura, Matsui (2016)]
Predicted values of $\alpha$ and $\tilde{\beta}$

Numerical results based on the two-field analysis

- Benchmark point

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<th>$v_S$ [GeV]</th>
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- Condition for strongly 1st OPT

  Constraints on $\alpha$ & $\tilde{\beta}$

  [Hashino, MK, Kanemura, Ko, Matsui (2016)]

Prospects of future interferometers

- eLISA (C1, C2, C3, C4):
  [Caprini et al. (2015)]

- DECIGO (Pre, 1 cluster, Correlation)
  [Kawamura et al. (2011)]

GWs from 1st OPT in the HSM are detectable at eLISA and DECIGO

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## eLISA design

[Caprini et al (2015)]

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