Probing symmetry breaking patterns of early universe and new physics by phase transition gravitational waves

Fa Peng Huang (IHEP, Beijing)


Rencontres de Moriond
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Outline

- Motivation
- Phase transition gravitational waves (GWs) in a nutshell
- GWs related to Higgs nature and baryogenesis
- GWs spectrum related to dark matter
- GWs spectra related to symmetry breaking of the early universe
- GWs in general new physics models
- Summary and outlook
The observation of GWs by aLIGO has initiated a new era of exploring the nature of gravity (See the nice talks in this Gravity session), cosmology as well as the fundamental particle physics by the GWs (My talk focuses on GWs probing of particle physics and cosmology).
Motivation

- Obvious shortcomings in our understanding of particle cosmology (such as the baryon asymmetry of the universe and the dark matter) and no evidence of new physics (NP) at LHC may just point us towards the novel universe with “hidden” NP, which might only be visible for GWs detectors.

- GWs may helps to probing the nature of Higgs boson, the baryogenesis, dark matter, new physics models, symmetry breaking patterns of the universe since they may be the triggers for a strong first order phase transition (FOPT).
First order phase transition can drive the plasma of the early universe out of thermal equilibrium, and bubble nucleate during it, which will produce GWs.

Pictures from Prof. Huber and Konstandin

C. J. Hogan, Phys. Lett. B 133, 172 (1983);

EW phase transition GWs becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.
Mechanisms of GWs during phase transition

➢ Bubble collision: well-known source

➢ Turbulence in the plasma fluid: a fraction of the bubble wall energy converted into turbulence.

➢ Sound wave in the plasma fluid: after the collision a fraction of bubble wall energy converted into motion of the fluid (and is only later dissipated).

New mechanism of GWs: sound wave
M. Hindmarsh, et al., PRL 112, 041301 (2014);
Caprini, Chiara et al. JCAP 1604 (2016)

Detectable GWs signals will be produced during the phase transition from the three mechanisms
To discuss the GWs spectra from a FOPT, it is necessary to begin with the one-loop finite temperature effective potential using the finite temperature field theory:

\[ V_{\text{eff}} = V_{\text{tree}}(\Phi) + V_{\text{cw}}(\Phi) + V_{\text{ther}}(\Phi, T) + V_{\text{daisy}}(\Phi, T) \]

where \( \Phi \) represents the order parameter of the phase transition (a real scalar field), \( V_{\text{cw}} \) is the one-loop Coleman-Weinberg potential at \( T = 0 \), and \( V_{\text{ther}} + V_{\text{daisy}} \) is the thermal contribution including the daisy resummation.

During a FOPT, bubbles are nucleated with the following nucleation rate:

\[ \Gamma = \Gamma_0(T)e^{-S_E(T)} \text{ with } \Gamma_0(T) \propto T^4 \]
To obtain the bubbles nucleation rate, the profile of the scalar field needs to be calculated by solving the following bounce equation using the overshooting/undershooting method.

\[
S_E(T) \simeq S_3(T)/T \text{ is Euclidean action}
\]

\[
S_E(T) = \int d\tau d^3x \left[ \frac{1}{2} \left( \frac{d\Phi}{d\tau} \right)^2 + \frac{1}{2} (\nabla \Phi)^2 + V_{\text{eff}}(\Phi, T) \right]
\]

To obtain the bubbles nucleation rate, the profile of the scalar field needs to be calculated by solving the following bounce equation using the overshooting/undershooting method.

\[
\frac{d^2 \Phi}{dr^2} + \frac{2}{r} \frac{d\Phi}{dr} - \frac{\partial V_{\text{eff}}(\Phi, T)}{\partial \Phi} = 0 \quad \frac{d\Phi}{dr}(r = 0) = 0, \quad \Phi(r = \infty) = \Phi_{\text{false}}
\]
The GWs spectrum depends on the four parameters: \( \alpha \), \( \beta \), bubble wall velocity \( v \) and the efficiency factor \( \lambda \).

\[
\alpha \equiv \frac{\epsilon(T_\ast)}{\rho_{\text{rad}}(T_\ast)} \quad \tilde{\beta} \equiv \frac{\beta}{H_\ast} = T_\ast \frac{dS}{dT}\bigg|_{T_\ast} = T_\ast \frac{d}{dT} \left( \frac{S_3}{T} \right)\bigg|_{T_\ast}
\]

**Bubble wall collision**

\[
\Omega_{\text{co}}(f) h^2 \simeq 1.67 \times 10^{-5} \left( \frac{H_\ast}{\beta} \right)^2 \left( \frac{\lambda_{\text{co}} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g^t_\ast} \right)^{\frac{1}{3}} 
\times \left( \frac{0.11 v_b^3}{0.42 + v_b^3} \right) \left[ \frac{3.8 (f/f_{\text{co}})^{2.8}}{1 + 2.8 (f/f_{\text{co}})^{3.8}} \right].
\]

**Turbulence**

\[
\Omega_{\text{tu}}(f) h^2 \simeq 3.35 \times 10^{-4} \left( \frac{H_\ast}{\beta} \right) \left( \frac{\lambda_{\text{tu}} \alpha}{1 + \alpha} \right)^{3/2} \left( \frac{100}{g^t_\ast} \right)^{\frac{1}{3}} v_b 
\times \frac{(f/f_{\text{tu}})^3}{(1 + f/f_{\text{tu}})^{11/3}(1 + 8\pi f a_0 / (a_* H_\ast))}.
\]

**Sound wave**

\[
\Omega_{\text{sw}}(f) h^2 \simeq 2.65 \times 10^{-6} \left( \frac{H_\ast}{\beta} \right) \left( \frac{\lambda_{\text{sw}} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g^t_\ast} \right)^{\frac{1}{3}} v_b 
\times \left[ \frac{7 (f/f_{\text{sw}})^{6/7}}{4 + 3 (f/f_{\text{sw}})^2} \right]^{7/2}.
\]
GWs motivated by baryogenesis

A long standing problem in particle cosmology is to unravel the origin of baryon asymmetry of the universe (BAU).

After the discovery of the 125 GeV Higgs, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

\[ \eta = \frac{n_B}{n_\gamma} = 6.05(7) \times 10^{-10} \ (\text{CMB, BBN}) \]
Baryogenesis: Sakharov conditions

To produce the observed BAU, three necessary conditions are needed at the same cosmic epoch:

- **Baryon number violation**: create baryonic charge
- **C and CP violation**: distinguish matter from antimatter
- **Departure from thermal equilibrium or CPT violation**: provide a time arrow
EW baryogenesis: SM technically has all the three elements for baryogenesis, but not enough.

- B violation from anomaly in B+L current.
- CKM matrix, but too weak.
- First order phase transition with expanding Higgs Bubble wall.

Departure from thermal equilibrium —
—— Strong first order phase transition

Cross over for $m_H > 75$ GeV

Strong First Order phase transition for $m_H < 75$ GeV

Operators analysis for Higgs potential and cosmological bound on Higgs mass

From lattice simulation

Extension of the Higgs sector is needed to produce strong first order phase transition for 125 GeV Higgs boson.
GWs motivated by the nature of Higgs potential and the type of EW phase transition?

For the Higgs potential, we know nothing but the quadratic oscillation around the vev 246 GeV with the mass 125 GeV from the current data.

\[ V(h) = \frac{1}{2} \mu^2 h^2 + \frac{\lambda}{4} h^4 \]

or \[ V(h) = \frac{1}{2} \mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6 \]

arXiv:1511.06495  Nima Arkani-Hamed, Tao Han, Michelangelo Mangano, Lian-Tao Wang
Benchmark scenario for electroweak baryogenesis in the effective field theory

\[ \delta \mathcal{L} = -x_{ij}^{u} \frac{\phi^\dagger \phi}{\Lambda^2} \tilde{q}_{Li} \tilde{\phi}_{uRj} + \text{H.c.} - \frac{\kappa}{\Lambda^2} (\phi^\dagger \phi)^3 \]

provide sizable CP violation source

provide another possible Higgs potential or EW symmetry breaking;

provide strong first order phase transition

Cedric Delaunay, Christophe Grojean, James D. Wells
JHEP 0804:029,2008


Renormalizable realization of the effective Lagrangian

- The concerned dim-6 operators can be induced from certain renormalizable extension of the SM.
- We built simplified model with vector-like quark and triplet scalar.

*model details see* FPH, et. al *Phys.Rev.* D93 (2016) 103515
Renormalizable realization of the effective Lagrangian: an example to get $h^6$ term

The model with an $SU(2)_L$ triplet scalar without hypercharge $\Sigma(1, 3, 0)$

\[
\delta \mathcal{L} = \xi_\Sigma \phi^\dagger \sigma^a \phi \Sigma^a + \frac{1}{2} \text{Tr}[(D^\mu \Sigma)^\dagger D_\mu \Sigma] - \frac{1}{2} M_\Sigma^2 \text{Tr}(\Sigma^2) - \kappa_\Sigma \phi^\dagger \phi \text{Tr}(\Sigma^2)
\]

<table>
<thead>
<tr>
<th>dimension-6 operator</th>
<th>tee-level and one-loop matching</th>
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<tbody>
<tr>
<td>$\mathcal{O}_{WW} = g^2</td>
<td>H</td>
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<tr>
<td>$\mathcal{O}<em>{2W} = -\frac{1}{2} (D^\mu W</em>{\mu \nu}^a)^2$</td>
<td>$c_{2W} = \frac{g^2}{480 \pi^2 M_\Sigma^2}$</td>
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<tr>
<td>$\mathcal{O}<em>{3W} = \frac{1}{3!} g \epsilon^{abc} W</em>{\rho}^{a \mu} W_{\mu}^{b \nu} W_{\nu}^{c \rho}$</td>
<td>$c_{3W} = \frac{g^2}{480 \pi^2 M_\Sigma^2}$</td>
</tr>
<tr>
<td>$\mathcal{O}<em>H = \frac{1}{2} (\partial</em>\mu</td>
<td>H</td>
</tr>
<tr>
<td>$\mathcal{O}<em>T = \frac{1}{2} (H^\dagger D</em>\mu H)^2$</td>
<td>$c_T = \frac{\xi_\Sigma^2}{M_\Sigma^4}$</td>
</tr>
<tr>
<td>$\mathcal{O}_6 = (H^\dagger H)^3$</td>
<td>$c_6 = \frac{\kappa_\Sigma \xi_\Sigma^2}{M_\Sigma^4} + \frac{\kappa_\Sigma^3}{8 \pi^2 M_\Sigma^2}$</td>
</tr>
</tbody>
</table>
Strong FOPT leads to obvious deviation of the tri-linear Higgs coupling

\[ \mathcal{L}_{hhh} = -\frac{1}{3!} (1 + \delta_h) A_h h^3 \]

At one loop level, deviation of the tri-linear Higgs coupling

\[ \delta_h \in (0.6, 1.5) \]

The Circular Electron Positron Collider (CEPC), ILC, FCC-ee can precisely test this scenario by precise measurements of the \( hZ \) crosssection.

\[ \delta_\sigma = \frac{\sigma_{hZ, \delta_h \neq 0}}{\sigma_{hZ, SM}} - 1 \]
Correlate particle collider and GWs signals: Double test on Higgs nature and baryogenesis from particle to wave

- eLISA, BBO, U-DECIGO are capable of detecting the GWs from EW baryogenesis
- The study on Higgs induced baryogenesis naturally bridges the particle physics at collider with GWs survey, astrophysics and cosmology.
GWs motivated by dark matter

With the experimental precision of the DM direct detection are gradually approaching the neutrino backgrounds, GWs may become a new approach to explore the existence of DM since in a large classes of DM models a strong first order phase transition (FOPT) can be triggered by the DM.

Inert Doublet Models

\[ V_0 = M_D^2 D^\dagger D + \lambda_D (D^\dagger D)^2 + \lambda_3 \Phi^\dagger \Phi D^\dagger D \]
\[ + \lambda_4 |\Phi^\dagger D|^2 + (\lambda_5/2)[(\Phi^\dagger D)^2 + h.c.], \]

provide natural dark matter candidate
provide strong first order phase transition and phase transition GWs

FPH, Jiang-hao Yu, will appear on arXiv: 1704.04xxx
One-loop finite temperature effective potential

\[ V_{\text{eff}}(h, T) \approx \frac{1}{2} \left( -\mu^2 + c T^2 \right) h^2 + \frac{\lambda}{4} h^4 \]

\[ - \frac{T}{12\pi} \sum n_b (m_b^2(h, T))^{3/2} \]

\[ - \sum n_b \frac{m_b^4(h, T)}{64\pi^2} \left[ \log \frac{m_b^2(h, T)}{T^2} \right] - 5.408 \]

\[ - n_t \frac{m_f^4(h)}{64\pi^2} \left[ \log \frac{m_f^2(h)}{T^2} \right] - 2.635 \]
Dark matter and first order phase transition favors Higgs funnel region

\[
\sigma_{SI} \simeq f_N^2 \frac{\lambda^2_{h\chi\chi}}{\pi} \left( \frac{m_N^2}{m_\chi m_h^2} \right)^2
\]

Higgs funnel region: \( m_H \) around 55 \( \sim \) 75 GeV with \( \lambda_{345} < 0.04 \);

Taking another set of benchmark points \( \lambda_3 = 2.84726, \lambda_4 = \lambda_5 = -1.41293, M_D^2 = 3707.43 \), the corresponding dark matter mass is 66 GeV, the pseudo scalar mass the the charged scalar mass are both 300 GeV, \( \lambda_{h\chi\chi} = \lambda_{345}/2 = (\lambda_3 + \lambda_4 + \lambda_5)/2 = 0.0107 \)
BBO and U-DECIGO can detect GWs triggered by dark matter.

The study naturally bridges the particle physics at collider with GWs and dark matter.
GWs motivated by symmetry breaking history of the universe

Our early universe may undergo one or several times spontaneously symmetry breaking associated with first order phase transition in a generic classes of gauge group extended SM models, which may produce detectable GWs.
GWs in non-Abelian gauge group extended NP models.

- The first model is the 3-3-1 model, which can explain the electric charge quantization and three generations of fermions by extending SM gauge group \( G_{SM} : SU(3)_c \otimes SU(2)_L \otimes U(1)_X \)

  to new gauge group :

\[
SU(3)_c \otimes SU(3)_L \otimes U(1)_Y
\]

- Here, we use the GWs signals to explore the NP models and their phase transition patterns in three versions of the 3-3-1 models (the minimal, the economical and the reduced minimal 3-3-1 models, respectively), where the scalars fields are accommodated in a certain representation of the SU(3)_L gauge group in each version.
• In the economical 3-3-1 model, one chooses the simplest SU(3)$_L$ representations for the scalar fields with spontaneously symmetry breaking, namely, \[ \chi = (\chi^0_1, \chi^0_2, \chi^0_3)^T \sim (3, -\frac{1}{3}) \]
two complex scalar triplet with different hypercharge are needed.

The tree-level potential is
\[
V(\chi, \phi) = \mu_1^2 \chi^\dagger \chi + \lambda_1 (\chi^\dagger \chi)^2 + \mu_2^2 \phi^\dagger \phi + \lambda_2 (\phi^\dagger \phi)^2 \\
+ \lambda_3 (\chi^\dagger \chi) (\phi^\dagger \phi) + \lambda_4 (\chi^\dagger \phi) (\phi^\dagger \chi).
\]
GWs spectra in the economical 3-3-1 model in one set of benchmark points
GWs spectra in the reduced minimal 3-3-1 model in one set of benchmark points.
GWs spectra in the minimal 3-3-1 model.

In the minimal 3-3-1 model, three scalar triplet are needed.

The tree-level potential is

\[
V (\rho, \eta, \chi) = \mu_1^2 \eta^\dagger \eta + \lambda_1 (\eta^\dagger \eta)^2 + \mu_2^2 \rho^\dagger \rho + \lambda_2 (\rho^\dagger \rho)^2 + \mu_3^2 \chi^\dagger \chi + \lambda_3 (\chi^\dagger \chi)^2 \\
+ \left[ \lambda_4 (\rho^\dagger \rho) + \lambda_5 (\chi^\dagger \chi) \right] (\eta^\dagger \eta) \\
+ \lambda_6 (\rho^\dagger \rho) (\chi^\dagger \chi) + \lambda_7 (\rho^\dagger \eta) (\eta^\dagger \rho) \\
+ \lambda_8 (\chi^\dagger \eta) (\eta^\dagger \chi) + \lambda_9 (\rho^\dagger \chi) (\chi^\dagger \rho) \\
+ \frac{1}{2} (f_1 \varepsilon^{ijk} \eta_i \rho_j \chi_k + \text{H. c.}) .
\]
GWs spectra in the minimal 3-3-1 model in one set of benchmark points.
GWs spectrum in other hidden gauge group extended models.

In general, if the SM is extended by hidden non-Abelian gauge group, a strong FOPT may occur associated with each step’s spontaneously symmetry breaking, where the phase transition GWs may be produced and can be used to test the hidden NP models with gauge symmetry breaking.
GWs spectrum in other hidden gauge group extended models.

In the relaxion mechanism, where the light Higgs mass comes from the dynamical cosmological evolution during the early universe. In the simplest relaxion model, the hidden QCD-like gauge group is needed, in some allowed parameter space, the SU(3) hidden sector can give a strong FOPT at the hidden QCD scale about O(100) MeV.


The FOPT can produce phase transition GWs with the peak frequency \(10^{-9}--10^{-7}\) Hz range, which may be probed by Pulsar Timing Array experiments, such as the SKA or FAST.

For the hidden SU(3) case motivated by dark matter, see P. Schwaller, Phys. Rev. Lett. 115, 181101 (2015)
GWs spectrum in other hidden gauge group extended models.

Especially, if a FOPT takes place at a critical temperature of $O(10^7–10^8)$ GeV, such as some versions of grand unified models and high scale supersymmetry models, this could potentially produce detectable GWs spectrum in the future aLIGO, and provide us with a unique probe of the hidden NP models at high scales.


Detailed study on the GW probing of the “Nnaturalness” mechanism is in progress.

Nima Arkani-Hamed, Timothy Cohen, Raffaele Tito D'Agnolo, Anson Hook, Hyung Do Kim, David Pinner

Schematic phase transition GWs spectra during evolution of universe. FPH, Xinmin Zhang, arXiv:1701.04338
Summary

- For cosmology, our universe may undergo one or several times phase transition during the early evolution of the universe. And we can hear the cosmological phase transition using GWs if there exists first-order phase transition.

- For particle physics, this phase transition GWs approach can compensate for the collider experiments to explore the new physics models (especially the hidden sector) and provide a novel approach to probe the symmetry breaking or phase transition patterns.

- For particle cosmology, GWs provides a unique way to unravel the dark matter, baryogenesis......
Outlook

- New physics models in particle physics can provide abundant GWs source!
- GWs becomes a new and realistic approach to explore the particle cosmology and fundamental physics.

For example, Probing extra dimension through gravitational wave observations of compact binaries and their electromagnetic counterparts Hao Yu, Bao-min Gu, FPH, Yong-qiang wang, Xin-he meng, Yu-xiao liu. JCAP 1702 (2017) no.02, 039

- Let us ski on the exciting journey of GWs physics!
Thanks for your attention!