Primordial gravitational waves from sequential electroweak phase transitions

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Outline

1. Introduction
2. Dynamics of phase transitions
3. The model
4. GW power spectrum
5. Summary and outlook

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Introduction

Stochastic Gravitational Wave (GW) background

- Superposition of unresolved astrophysical sources
- Cosmological events
  - (i) Inflation
  - (ii) Cosmic strings
  - (iii) **Strong cosmological phase transitions (PTs)** $\rightarrow$ by expanding and colliding vacuum bubbles of new phase

GW background as a gravitational probe for New Physics

- Focus on the EW phase transition (EWPT) relevant for EW baryogenesis
- Study a simple model with **multiple-step strongly 1^{st}-order** EWPTs
- Study the impact of multiple-step strong PTs on GW spectra

The need for a strong first order PT and New Physics

- Observed baryon asymmetry (BA) in the Universe

$$\frac{n_B - n_{\overline{B}}}{s} \sim 10^{-11}$$

- Conditions for dynamical production of the baryon asymmetry **Sakharov'67**

  (i) B violation

  (ii) C and CP violation

  (iii) Departure from thermal equilibrium $\rightarrow$ **strong 1$^{\mathrm{st}}$-order PT**

Nucleation of expanding broken-phase vacuum bubbles $\rightarrow$ sphaleron suppression

$$\frac{\phi(T_c)}{T_c} \gtrsim 1.1 \qquad \rightarrow \qquad 1^{\mathrm{st}} \text{ order PT}$$

Standard Model (SM) does not explain the BA $\rightarrow$ **the need to go beyond the SM**

EW phase transition in multi-scalar SM extensions

- The more scalar d.o.f.'s, the more complicated vacuum structure $\rightarrow$ new possibilities for **strong 1$^{\mathrm{st}}$-order EWPT at tree-level**
- Multi-Higgs SM extensions are very common and originate as e.g. low-energy limits of **Grand-Unified theories**
- Tree-level (strong) EWPT $\rightarrow$ free energy release is largely amplified $\rightarrow$ **stronger GW signals**
- Tree-level weak (2$^{\mathrm{nd}}$-order) transitions can become 1$^{\mathrm{st}}$-order ones due to **quantum corrections**
- Certain scenarios exhibit multi-step **successive 1$^{\mathrm{st}}$-order PTs**
- Multi-step transition $\rightarrow$ multi-peak structures in the induced GW spectrum $\rightarrow$ potential access by the next generation of **space-based GW interferometers**
- GW signature of multiple EW symmetry breaking steps $\rightarrow$ a **gravitational probe for New Physics**, yet unreachable at colliders

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Dynamics of phase transitions

- High $T \rightarrow$ classical motion in Euclidean space described by action $\hat{S}_3$

$$\hat{S}_3 = 4\pi \int_0^\infty \mathrm{d}r\, r^2 \left\{ \frac{1}{2}\left(\frac{\mathrm{d}\hat{\phi}}{\mathrm{d}r}\right)^2 + V_{\mathrm{eff}}(\hat{\phi}) \right\} ,$$

- Effective potential: loop and thermal corrections

$$\begin{aligned} V_{\mathrm{eff}}^{(1)}(\hat{\phi}) &= V_{\mathrm{tree}} + V_{\mathrm{CW}} + \Delta V^{(1)}(T) \\ V_{\mathrm{CW}} &= \sum_i (-1)^F n_i \frac{m_i^4}{64\pi^2}\left(\log\left[\frac{m_i^2(\hat{\phi}_\alpha)}{\Lambda^2}\right] - c_i\right) \\ \Delta V^{(1)}(T) &= \frac{T^4}{2\pi^2}\left\{\sum_b n_b J_B\left[\frac{m_b^2(\hat{\phi}_\alpha)}{T^2}\right] - \sum_f n_f J_F\left[\frac{m_f^2(\hat{\phi}_\alpha)}{T^2}\right]\right\} , \end{aligned}$$

- $\hat{\phi} \rightarrow$ solution of the e.o.m. found by the path that minimizes the energy.

Nucleation temperature

- Nucleation temperature $T_n \rightarrow$ the PT does effectively occur $\rightarrow$ vacuum bubble nucleation processes
- Satisfies $T_n < T_c$, where T_c is the critical temperature $\rightarrow$ degenerate minima
- Corresponds to probability to realize one transition per cosmological horizon volume equal one

$$\frac{\Gamma}{H^4} \sim 1 \qquad \Rightarrow \qquad \frac{\hat{S}_3}{T_n} \sim 140$$

- The phase transition rate

$$\Gamma \sim T^4 \left(\frac{\hat{S}_3}{2\pi T} \right)^{3/2} \exp\left(-\hat{S}_3/T \right) .$$

- This formalism is implemented in CosmoTransitions package (Wainwright'12)

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The model – THDSM

- Model inspired by a trinification GUT $[\mathrm{SU}(3)]^3 \rtimes \mathbb{Z}_3 \times \mathrm{SU}(3)_\mathrm{F}$ (RP, A. Morais et al: 1610.03642, 1711.05199, 1801.02670)

Scalar	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_\mathrm{Y}$	$\mathrm{U}(1)_\mathrm{F}$
$\mathcal{H}_1$	**2**	1	1
$\mathcal{H}_2$	**2**	1	5
φ	**1**	0	-4

- $\mathbb{Z}_2$ symmetry $\mathcal{H}_j \to -\mathcal{H}_j$ ($j = 1, 2$) and $\varphi \to -\varphi$: very simple potential

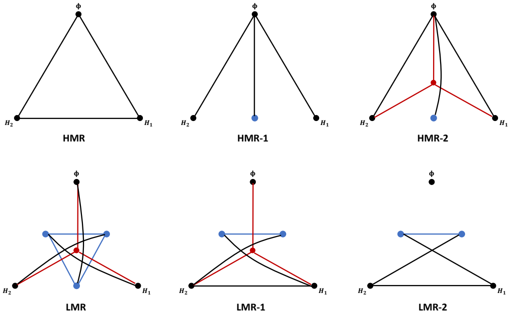
$$
\begin{aligned}
V[\mathcal{H}_1, \mathcal{H}_2, \varphi] =& m_1^2 \mathcal{H}_1^\dagger \mathcal{H}_1 + m_2^2 \mathcal{H}_2^\dagger \mathcal{H}_2 + m_s^2 \varphi\varphi^* + \frac{\lambda_1}{2}\left(\mathcal{H}_1^\dagger \mathcal{H}_1\right)^2 + \frac{\lambda_2}{2}\left(\mathcal{H}_2^\dagger \mathcal{H}_2\right)^2 \\
&+ \frac{\lambda_s}{2}(\varphi\varphi^*)^2 + \lambda_3 (\mathcal{H}_1^\dagger \mathcal{H}_1)(\mathcal{H}_2^\dagger \mathcal{H}_2) + \lambda_{s1}(\mathcal{H}_1^\dagger \mathcal{H}_1)(\varphi\varphi^*) \\
&+ \lambda_{s2}(\mathcal{H}_2^\dagger \mathcal{H}_2)(\varphi\varphi^*) + \lambda_3'(\mathcal{H}_1^\dagger \mathcal{H}_2)(\mathcal{H}_2^\dagger \mathcal{H}_1)
\end{aligned}
$$

Pyramidal representation of the transition patterns

$$\mathcal{H}_j = \frac{1}{\sqrt{2}} \begin{pmatrix} \chi_j + i\chi_j' \\ \phi_j + h_j + i\eta_j \end{pmatrix}, \qquad \varphi = \frac{1}{\sqrt{2}} \left(\phi_s + S_R + iS_I \right),$$

- Classical field configurations $\phi_\alpha = \{\phi_1, \phi_2, \phi_s\}$

$$V_{\rm cl}(\phi_\alpha) = \tfrac{1}{2} m_\alpha^2 |\phi_\alpha|^2 + \tfrac{1}{8}\lambda_\alpha |\phi_\alpha|^4 + \tfrac{1}{4}\lambda_{\alpha\beta} |\phi_\alpha|^2 |\phi_\beta|^2 .$$



> Simple tree-level analysis at finite T

> Dots $\rightarrow$ stable minima

> Lines $\rightarrow$ first order PT

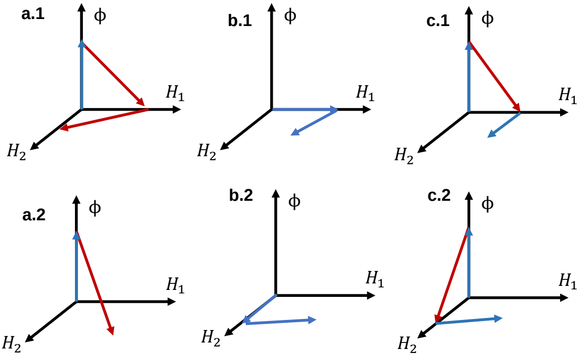
> $[0] \equiv (0, 0, 0)$

> $\Phi \equiv (0, 0, v_s)$

> $H_1 \equiv (v_1, 0, 0)$

> $H_2 \equiv (0, v_2, 0)$

Examples of transition patterns



- Example for HMR (a.1) and HMR-1 (others) transitions
- First-order PT $\rightarrow$ likely very strong
- Fecond order PT $\rightarrow$ can become strong upon thermal (loop) corrections
- **Study (a.1)-pattern** $\rightarrow$ the simplest and a representative one

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GW power spectrum

- GW energy density per logarithmic frequency (Caprini'09,'16; Grojean'07; Hindmarsh'14; Jinno'17; Leitao'16 etc)

$$h^2\Omega_{\rm GW} \equiv \frac{h^2}{\rho_c}\frac{d\rho_{\rm GW}}{d\log f} \simeq h^2\Omega_{\rm col} + h^2\Omega_{\rm sw} + h^2\Omega_{\rm MHD}$$

- Typically, $h^2\Omega_{\rm col}$ dominates for strong PTs due to supercooling ($T_n \ll T_c$)
- The peak amplitude

$$\Omega_{\rm GW} \simeq 10^{-9}\left(\frac{31.6H_n}{\beta}\right)^2\left(\frac{\alpha}{\alpha+\rho_n}\right)^2\epsilon^2\left(\frac{4v_w^3}{0.43+v_w^2}\right)\left(\frac{100}{g_\star}\right)^{\frac{1}{3}}, \qquad \rho_n = \pi^2 g_* T_n^4/30$$

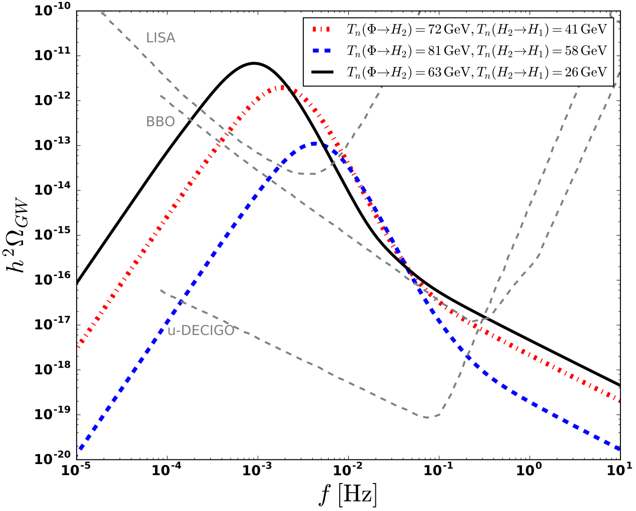
(i) Bubble wall velocity $\rightarrow v_w \approx 0.6 - 0.8$ (supercooling)
(ii) Release of latent heat in the transition,

$$\alpha = \left[V - \frac{dV}{dT}T_n\right]_{\rm false} - \left[V - \frac{dV}{dT}T_n\right]_{\rm true}$$

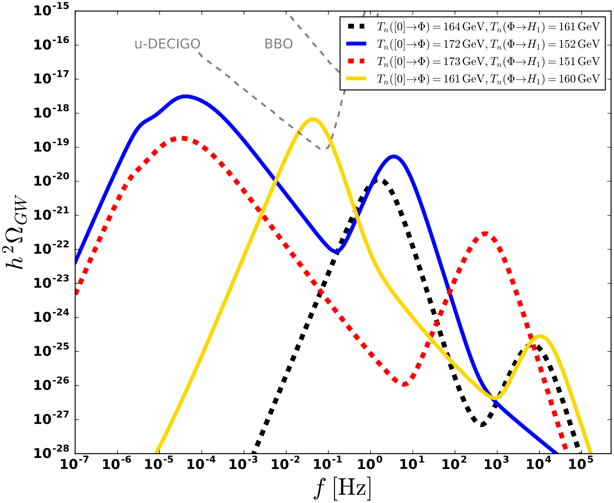
(iii) Efficiency of conversion of latent heat into GW, $\epsilon \approx 1$ (strong PTs)
(iv) Inverse duration of the transition, $\beta = H\,T_n\,(\hat{S}_3/T)'_T|_{T=T_n}$.

- The larger the PT time-scale, the smaller the frequency of the GW signal

- Strong transitions $\Phi \to H_1$, $\Phi \to H_2$ and $H_2 \to H_1$
- Typical time scale is small $\beta^{-1} \sim 10^{-6}s - 10^{-3}s$
- Similar properties of the transitions $\Rightarrow$ peaks close to each other



- To separate peaks need rather distinct time scales
- $[0] \overset{O(2)}{\to} \Phi \overset{O(1)}{\to} H_1$: $(\boldsymbol{m/T})^{\mathbf{3}}$ **terms promote** $[0] \to \Phi$ **to** $O(1)$
- $[0] \to \Phi$ weaker than $\Phi \to H_1 \Rightarrow$ larger time scale (shift to the left)



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Summary: Traces of successive strong PTs in the primordial GWs spectrum

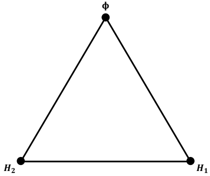
- Are multi-peaked GW signatures detectable by future interferometers?
  - Well resolved peaks if transitions have different origin $O(2) \to O(1)$ due to $(m/T)^3$
  - Too small amplitudes in the current toy-model (for well resolved peaks)
  - Need larger energy budget with enhanced release of latent heat $\longrightarrow$ less minimal models

In general, the hypothetical observation of multiple peaks may be a signature of multi-step transitions and may shed light on the details of the EW (and above EW) PTs, and hence, on New Physics beyond the SM

Outlook: Opened questions

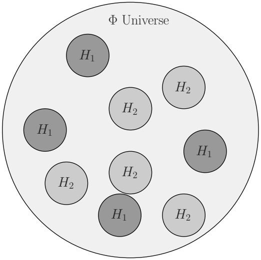
- Current analysis is a proof of concept
- Impact of a generic vacuum (v_1, v_2, v_s)?
- Complete GUT inspired model with local $\mathrm{U}(1)_\mathrm{F} \longrightarrow$ new contributions to $(m/T)^3$ terms due to a Z'
- Impact of a larger scalar sector?
- Emergence and detectability of exotic cosmological objects (e.g. coexisting, nested and reoccurring bubbles)
- What happens, e.g. when a nested bubble expands faster than its mother bubble? More complicated features in the GWs spectrum?
- What is the impact of such objects for EWBG?

Backup slides: Exotic cosmological objects

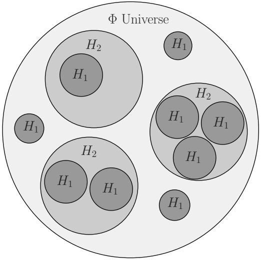


- Consider H_1 the true vacuum
- Two possible breaking patterns
  - > $\Phi \to H_1$ and $\Phi \to H_2 \to H_1$
  - > $[0] \to \Phi$ is second order

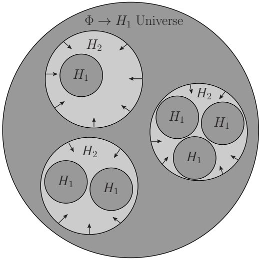
1. $T_n\left(\Phi \to H_1\right) \sim T_n\left(\Phi \to H_2\right)$: **Coexisting bubbles**
2. $T_n\left(\Phi \to H_2\right) > T_n\left(H_2 \to H_1\right) > T_n\left(\Phi \to H_1\right)$: **Nested bubbles**
3. Below $T_n\left(H_2 \to H_1\right)$, $\Phi \to H_1$ eliminates Φ-phase: **Reoccurring bubbles**



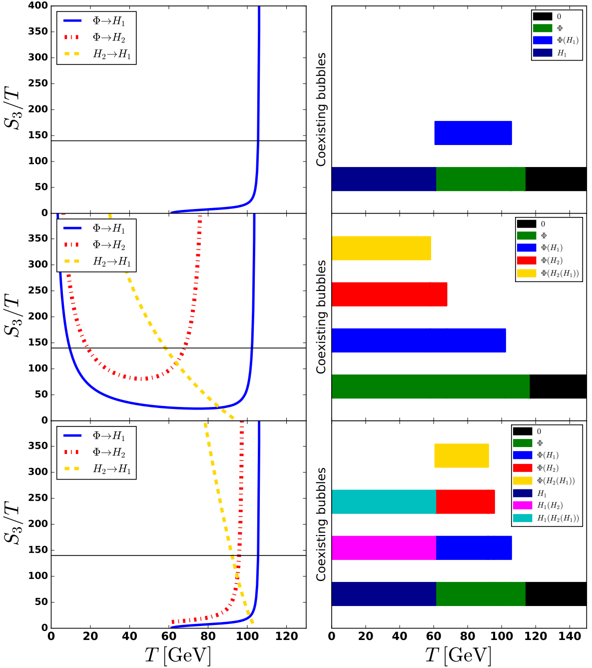
$T_n\left(\Phi \to H_1\right) \sim T_n\left(\Phi \to H_2\right)$



$T_n\left(\Phi \to H_1\right) < T_n\left(H_2 \to H_1\right) < T_n\left(\Phi \to H_2\right)$



$T_n\left(\Phi \to H_1\right) < T_n\left(H_2 \to H_1\right) < T_n\left(\Phi \to H_2\right)$



- Transition $i \to j$ when $\hat{S}_3/T_n \sim 140$
- Bubble i nucleated inside j: $\boldsymbol{i(j)}$
- $[0] \to \Phi$ is second order
- These objects need not too different T_n
  - symmetries in the potential (Ivanov [1702.07542])

Backup slides: GW spectrum characteristics

GW signals calculation
(for more details, see Caprini'16; Grojean'07; Leitao'16)

- Using α and β, one computes the bubble-wall velocity ($\approx$ 0.6-0.8) and the efficiency coefficient (accounting for the latent leat saturation for runaway bubbles)
- For each of the three contributions ($\Omega_{\rm col}$, $\Omega_{\rm sw}$, $\Omega_{\rm MHD}$ terms)

$$GWs\ signal \sim amplitude \times spectral\ shape(f/f_{\rm peak})$$

where the peak frequency (contains redshift information)

$$f_{\rm peak} \simeq 16.5 Hz \left(\frac{f_n}{H_n}\right)\left(\frac{T_n}{10^8 {\rm GeV}}\right)\left(\frac{100}{g_\star}\right)^{\frac{1}{6}}$$

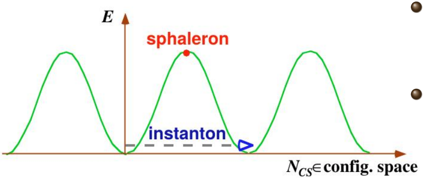
with peak frequency at nucleation time $f_n = \frac{0.62\beta}{1.8-0.1 v_w + v_w^2}$

- Details of the particle physics model encoded in T_n and α.

Backup slides: The sphaleron solution

Note: from the greek *shpaleros* (σφαλεροσ): **ready to fall**

- Non-trivial transitions between physically identical but topologically distinct vacua
  - Identified by the Chern-Simons number $N_{CS} \in \mathbb{Z}$
  - Axial $B+L$ anomaly in a SM-like theory yields $\Delta B = N_f \Delta N_{CS}$
    - $B-L$ current is conserved



http://astr.phys.saga-u.ac.jp/ funakubo/yitp/files/funakubo.pdf

- $T=0$: Instanton solution
  > Tunnelling prob. $\sim 10^{-170}$ (EW theory)
- $T \neq 0$: Sphaleron solution $-$ **thermal jump**
  > Transition prob. $\sim T^4$
  > Static saddle-point solution
  > $N_f = 3 \Rightarrow B \to 3B$

Backup slides: Sphaleron washout criterion

- First order phase transition:

Nucleation of broken phase vacuum bubbles expanding in the surrounding plasma of unbroken symmetry

> Particles in the plasma experience the passing bubble

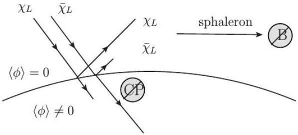
> Reflection of particles $\rightarrow$ plasma out of equilibrium

> With CP-violation, matter/anti-matter asymmetry accumulates over time inside the bubble (different reflection coefficients)

> Sphaleron process (active in unbroken phase) provides

(i) B-violation (quantified by sphaleron rate)

(ii) C-violation (only couples to LH-fermions)



[hep-ph] 1302.6713

Backup slides: Sphaleron washout criterion

If sphaleron process still active after phase transition the system restores equilibrium, $B = 0$, after a time of the order of the Hubble scale.

Broken Phase:

$$\Gamma_{sph} \simeq T^4 e^{-E_{sph}/T}, \qquad E_{sph} \simeq \frac{4\pi\phi_c}{g}\Xi, \qquad \Xi \simeq 2.8$$

- Γ_{sph} in broken phase needs to be much smaller than Hubble scale

$$\Gamma_{sph} \ll HT^3 \Rightarrow \boxed{\frac{\phi_c}{T_c} \gtrsim 1.1}$$

- Sphaleron processes suppressed in the broken phase
- Avoid washout of generated baryon asymmetry
- EWBG can be realized (in the SM needs $40\ \mathrm{GeV}$ Higgs mass)