

Multi-peaked signatures of primordial gravitational waves from multi-step electroweak phase transition

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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)** →
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 1st-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

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

- Conditions for dynamical production of the baryon asymmetry **Sakharov'67**
 - B violation
 - C and CP violation
 - Departure from thermal equilibrium \rightarrow **strong 1st-order PT**

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

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

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 → new possibilities for **strong 1st-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 → free energy release is largely amplified → **stronger GW signals**
- Tree-level weak (2nd-order) transitions can become 1st-order ones due to **quantum corrections**
- Certain scenarios exhibit multi-step **successive 1st-order PTs**
- Multi-step transition → multi-peak structures in the induced GW spectrum → potential access by the next generation of **space-based GW interferometers**
- GW signature of multiple EW symmetry breaking steps → 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

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

- Effective potential: loop and thermal corrections

$$V_{\text{eff}}^{(1)}(\hat{\phi}) = V_{\text{tree}} + V_{\text{CW}} + \Delta V^{(1)}(T)$$

$$V_{\text{CW}} = \sum_i (-1)^{F_i} n_i \frac{m_i^4}{64\pi^2} \left(\log \left[\frac{m_i^2(\hat{\phi}_\alpha)}{\Lambda^2} \right] - c_i \right)$$

$$\Delta V^{(1)}(T) = \frac{T^4}{2\pi^2} \left\{ \sum_b n_b J_B \left[\frac{m_b^2(\hat{\phi}_\alpha)}{T^2} \right] - \sum_f n_f J_F \left[\frac{m_f^2(\hat{\phi}_\alpha)}{T^2} \right] \right\},$$

- $\hat{\phi} \rightarrow$ 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

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

- 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 quartification GUT $SU(3)_C \times SU(3)_L \times SU(3)_R \times SU(3)_F$
 (RP, A. Morais et al: 1610.03642, 1711.05199, 1801.02670)
 (See A. Morais slides SUSY section 2, Monday 23rd)

Scalar	$SU(2)_L$	$U(1)_Y$	$U(1)_F$
\mathcal{H}_1	2	1	1
\mathcal{H}_2	2	1	5
φ	1	0	-4

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

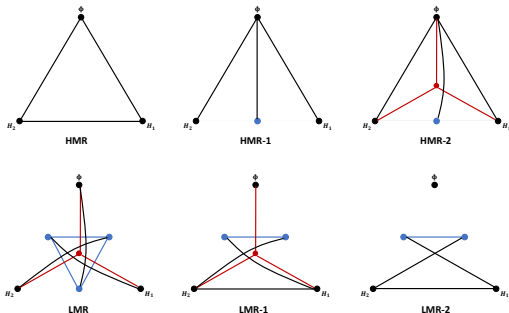
$$\begin{aligned}
 V[\mathcal{H}_1, \mathcal{H}_2, \varphi] = & m_1^2 \mathcal{H}_1^\dagger \mathcal{H}_1 + m_2^2 \mathcal{H}_2^\dagger \mathcal{H}_2 + m_s^2 \varphi \varphi^* + \frac{\lambda_1}{2} (\mathcal{H}_1^\dagger \mathcal{H}_1)^2 + \frac{\lambda_2}{2} (\mathcal{H}_2^\dagger \mathcal{H}_2)^2 \\
 & + \frac{\lambda_s}{2} (\varphi \varphi^*)^2 + \lambda_3 (\mathcal{H}_1^\dagger \mathcal{H}_1) (\mathcal{H}_2^\dagger \mathcal{H}_2) + \lambda_{s1} (\mathcal{H}_1^\dagger \mathcal{H}_1) (\varphi \varphi^*) \\
 & + \lambda_{s2} (\mathcal{H}_2^\dagger \mathcal{H}_2) (\varphi \varphi^*) + \lambda'_3 (\mathcal{H}_1^\dagger \mathcal{H}_2) (\mathcal{H}_2^\dagger \mathcal{H}_1)
 \end{aligned}$$

Pyramidal representation of the transition patterns

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

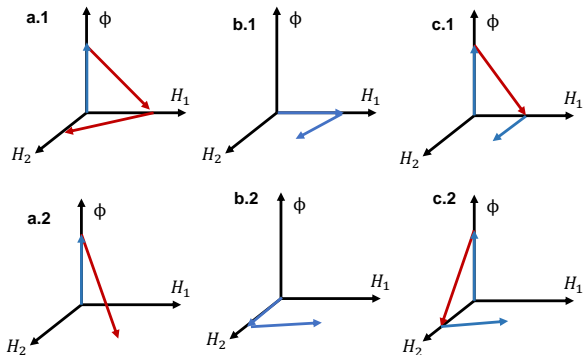
- Classical field configurations $\phi_\alpha = \{\phi_1, \phi_2, \phi_s\}$

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



- > 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** → likely very strong
- > **Second order PT** → can become strong upon thermal (loop) corrections
- > **Study (a.1)-pattern** → 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; Leitaó'16 etc)

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

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

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

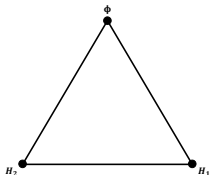
- (i) Bubble wall velocity $\rightarrow v_w \approx 0.6 - 0.8$ (supercooling)
- (ii) Release of latent heat in the transition,

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

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

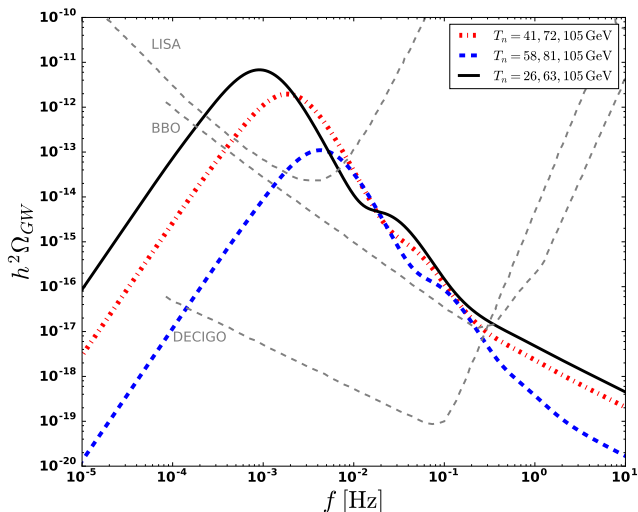
- The larger the PT time-scale, the smaller the frequency of the GW signal

Transition patterns considered

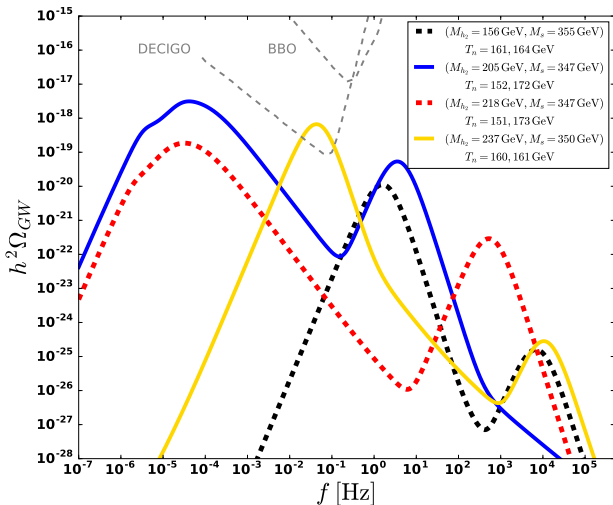


- Consider H_1 the true vacuum
- Two possible breaking patterns
 - > $\Phi \rightarrow H_1$ and $\Phi \rightarrow H_2 \rightarrow H_1$
 - > $[0] \rightarrow \Phi$ is second order

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



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



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

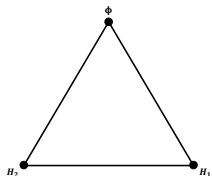
- Are multi-peaked GW signatures detectable by future interferometers?
 - Well resolved peaks if transitions have different origin $O(2) \rightarrow O(1)$ due to $(m/T)^3$
 - Too small amplitudes in the current toy-model (for well resolved peaks)
 - Need larger energy budget with enhanced release of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

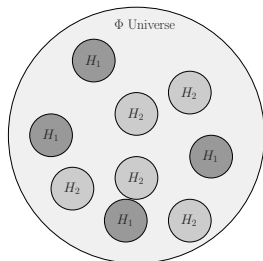
- Current analysis is a proof of concept
- Impact of a generic vacuum (v_1, v_2, v_s) ?
- Complete GUT inspired model with local $U(1)_F \rightarrow$ new contributions to $(m/T)^3$ terms due to a Z'
- Impact of a larger scalar sector?
- Can we simultaneously accommodate EWBG?

Backup slides: Exotic cosmological objects

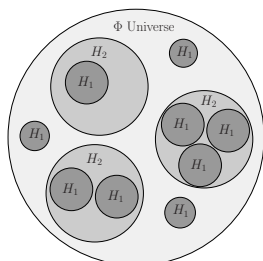


- Consider H_1 the true vacuum
- Two possible breaking patterns
 - > $\Phi \rightarrow H_1$ and $\Phi \rightarrow H_2 \rightarrow H_1$
 - > $[0] \rightarrow \Phi$ is second order

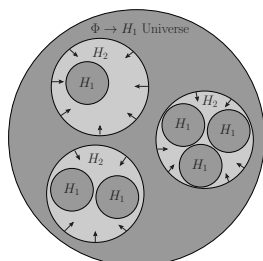
- 1 $T_n(\Phi \rightarrow H_1) \sim T_n(\Phi \rightarrow H_2)$: **Coexisting bubbles**
- 2 $T_n(\Phi \rightarrow H_2) > T_n(H_2 \rightarrow H_1) > T_n(\Phi \rightarrow H_1)$: **Nested bubbles**
- 3 Below $T_n(H_2 \rightarrow H_1)$, $\Phi \rightarrow H_1$ eliminates Φ -phase: **Reoccurring bubbles**



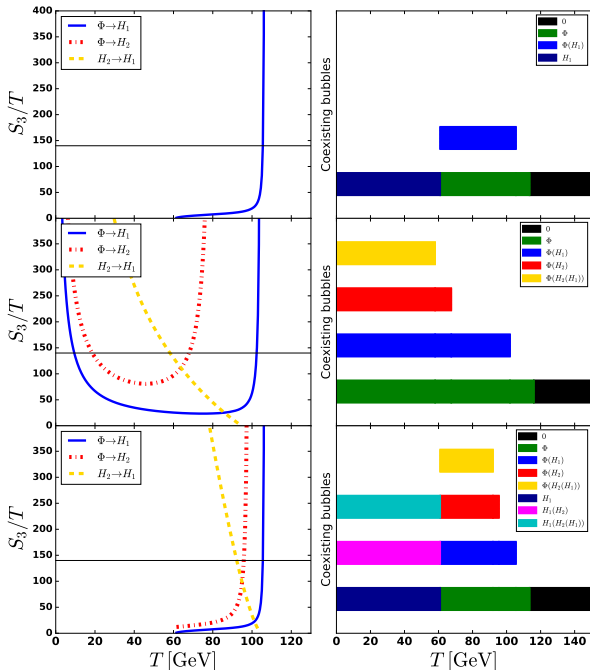
$$T_n(\Phi \rightarrow H_1) \sim T_n(\Phi \rightarrow H_2)$$



$$T_n(\Phi \rightarrow H_1) < T_n(H_2 \rightarrow H_1) < T_n(\Phi \rightarrow H_2)$$



$$T_n(\Phi \rightarrow H_1) < T_n(H_2 \rightarrow H_1) < T_n(\Phi \rightarrow H_2)$$



- Transition $i \rightarrow j$ when $\hat{S}_3/T_n \sim 140$
- Bubble i nucleated inside j : $i(j)$
- $[0] \rightarrow \Phi$ 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; Leita0'16)

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

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

where the peak frequency (contains redshift information)

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

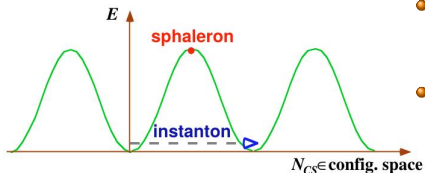
with peak frequency at nucleation time $f_n = \frac{0.62\beta}{1.8 - 0.1v_w + v_w^2}$

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

Backup slides: The sphaleron solution

Note: from the greek *shpaleros* ($\sigma\varphi\alpha\lambda\epsilon\rho\sigma$): **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>

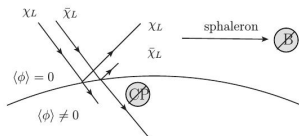
- $T = 0$: **Instanton solution**
 - > Tunnelling prob. $\sim 10^{-170}$ (EW theory)
- $T \neq 0$: **Sphaleron solution** – **thermal jump**
 - > Transition prob. $\sim T^4$
 - > Static saddle-point solution
 - > $N_f = 3 \Rightarrow B \rightarrow 3B$

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:

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

- 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 GeV Higgs mass)