Gravitational footprints of neutrino mass and lepton number violation

Andrea Addazi [2] Antonino Marcianò[2] **António P. Morais**[1]
Roman Pasechnik[3] Rahul Srivastava [4] José W. F. Valle[4]

[1]**Center for Research and Development in Mathematics and Applications (CIDMA)**
Aveiro University, Aveiro, Portugal

[2]Department of Physics and Center for Field Theory and Particle Physics
Fudan University, Shanghai, China

[3]Department of Theoretical Physics, Lund university, Lund, Sweden

[4]Institut de Física Corpuscular, Universitat de València Parc Cientific de Paterna, Valencia, Spain

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Outline

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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 vacuum bubbles of a broken phase in a universe filled with a symmetric phase

GW background as a gravitational probe for New Physics

- Focus on the EW phase transition (EWPT)

Look for graviational footprints of lepton number symmetry breaking and the mechanism of neutrino mass generation.

Outline

High- and low-scale seesaw variants

Standard type-I

$$\mathcal{L}_{\text{Yuk}}^{\text{Type-I}} = Y_\nu \bar{L} H \nu^c + M \nu^c \nu^c + h.c.$$

- $L = (\nu, l)^\top$; ν^c are three SM-singlet RH-neutrinos; M and Y_ν are 3×3 matrices
- M explicitly breaks lepton number symmetry $\mathrm{U}(1)_\mathrm{L} \to \mathbb{Z}_2$ as $L(\nu^c) = -1$
- Mass for light neutrinos after EWSB $\langle H \rangle = v_h/\sqrt{2}$

$$m_\nu^{\text{Type-I}} = \frac{v_h^2}{2} Y_\nu^T M^{-1} Y_\nu \qquad Y_\nu \sim \mathcal{O}(1)\ ,\ M \sim \mathcal{O}\left(10^{14}\ \text{GeV}\right) \Rightarrow m_\nu \sim \mathcal{O}(0.1\ \text{eV})$$

Low-scale variant: Inverse seesaw

- Add two gauge singlet fermion carrying opposite lepton number charge, $L(\nu^c) = -1$ and $L(S) = -1$

$$\mathcal{L}_{\text{Yuk}}^{\text{Inverse}} = Y_\nu \bar{L} H \nu^c \; + \; M \nu^c S \; + \; \mu S S \; + \; \text{h.c.}$$

- **Smallness of neutrino mass linked to the breaking of $\mathrm{U}(1)_{\mathrm{L}} \to \mathbb{Z}_2$ through the μ-term**

$$m_\nu^{\text{Inverse}} = \frac{v_h^2}{2} Y_\nu^T M^{T^{-1}} \mu M^{-1} Y_\nu$$

Small neutrino masses protected by $\mathrm{U}(1)_{\mathrm{L}}$ (restored in the limit $\mu \to 0$)

Inverse seesaw with majoron

- Add a complex singlet scalar σ, **the majoron**, with $L(\sigma) = -2$

$$\mu SS \to Y_\sigma \sigma SS$$

- $\langle\sigma\rangle = v_\sigma/\sqrt{2}$ **spontaneously breaks** $\mathrm{U}(1)_{\mathrm{L}} \to \mathbb{Z}_2$

$$\mu = Y_\sigma v_\sigma/\sqrt{2} \;\to\; \text{generates effective } \mu \text{ term}$$

$$m_\nu^{\text{Inverse}} \sim Y_\nu^2 Y_\sigma \frac{v_h^2 v_\sigma}{M^2}$$

Two possibilities for low-scale seesaw, $M \sim \mathcal{O}(0.1 - 1\text{TeV})$

1. $v_\sigma \sim \mathcal{O}(\text{keV})$
2. $v_\sigma \sim \mathcal{O}(0.1 - 1 \text{ TeV})$

1. $Y_\nu \sim 0.01,\; Y_\sigma \sim \mathcal{O}(0.001 - 1)$
   $\Rightarrow m_\nu \sim \mathcal{O}(0.0001 - 0.1\text{eV})$
2. $Y_\nu \sim 10^{-6},\; Y_\sigma \sim \mathcal{O}(0.001 - 1)$
   $\Rightarrow m_\nu \sim \mathcal{O}(0.0001 - 0.1\text{eV})$

Extended scalar sector:

$$V_0 = \mu_h^2 H^\dagger H + \lambda_h \left(H^\dagger H\right)^2 + \mu_\sigma^2 \sigma^* \sigma + \lambda_\sigma \left(\sigma^* \sigma\right)^2 + \lambda_{\sigma h} H^\dagger H \sigma^* \sigma + \left(\frac{1}{2}\mu_b^2 \sigma^2 + \text{c.c.}\right)$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} G + iG' \\ v_h + h + i\eta \end{pmatrix}, \qquad \sigma = \frac{1}{\sqrt{2}} (v_\sigma + \sigma_R + i\sigma_I),$$

1) Softly broken $\mathrm{U}(1)_\mathrm{L}$ case: $v_h = 246$ GeV and $v_\sigma = 0$

$$m_h^2 = 2\lambda_h v_h^2, \qquad m_{\sigma_R}^2 = \mu_\sigma^2 + \mu_b^2 + \frac{\lambda_{\sigma h} v_h^2}{2}, \qquad m_{\sigma_I}^2 = \mu_\sigma^2 - \mu_b^2 + \frac{\lambda_{\sigma h} v_h^2}{2}$$

- $\mathrm{U}(1)_\mathrm{L}$ softly broken by μ_b term
- If $\mu_b^2 > 0$ the majoron mass can be tuned to provide testable dark matter candidate [Valle et al PRD (1993), PRL (2007); Bazzocchi et al JCAP (2008)]
- For simplicity we use this scenario as a good approximation to the $v_\sigma \sim \mathcal{O}(\text{keV})$ case for small $m_{\sigma_I} \ll m_{\sigma_R}$.

2) Spontaneously broken $\mathrm{U}(1)_{\mathrm{L}}$ case: $v_h = 246$ GeV and $v_\sigma \neq 0$

- If $\mu_b^2 < 0$ majoron becomes a pseudo-Goldstone boson

Minimization and BFB conditions:

$$\mu_h^2 = -\lambda_h v_h^2 - \frac{1}{2}\lambda_{\sigma h} v_\sigma^2 \,, \qquad \mu_\sigma^2 = -\mu_b^2 - \lambda_\sigma v_\sigma^2 - \frac{1}{2}\lambda_{\sigma h} v_h^2$$

$$\lambda_h > 0\,, \qquad \lambda_\sigma > 0\,, \qquad \lambda_{\sigma h} > -2\sqrt{\lambda_h \lambda_\sigma}$$

[Bonilla, Valle, Romão PRD (2015)]

Mass spectrum and mixing:

$$M^2_{\mathrm{CP-even}} = \begin{pmatrix} 2\lambda_h v_h^2 & \lambda_{\sigma h} v_h v_\sigma \\ \lambda_{\sigma h} v_h v_\sigma & 2\lambda_\sigma v_\sigma^2 \end{pmatrix} \,,$$

$$\begin{pmatrix} m^2_{h_1} & 0 \\ 0 & m^2_{h_2} \end{pmatrix} = \mathcal{R} M^2_{\mathrm{CP-even}} \mathcal{R}^{-1} \,, \qquad \mathcal{R} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \,,$$

$$m^2_{\sigma_I} = -2\mu_b^2 > 0\,, \qquad m^2_{h_1,h_2} = \lambda_h v_h^2 + \lambda_\sigma v_\sigma^2 \mp \frac{\lambda_\sigma v_\sigma^2 - \lambda_h v_h^2}{\cos 2\theta}\,.$$

σ_I can become keV DM candidate without any tuning as in the softly-broken $\mathrm{U}(1)_{\mathrm{L}}$ scenario

Outline

Gravitational Waves from FOPT

- Vacuum bubbles nucleated from-first order phase transitions (FOPT)
- The main source of GW production is due to sound waves

$$h^2\Omega_{\mathrm{GW}}\left(f;\,\alpha,\,\beta/H, f_{\mathrm{peak}}\right) \qquad f_{\mathrm{peak}}\left(\alpha,\,\beta/H,\,T_n\right)$$

- Three relevant parameters to determine the GW power spectrum

$\alpha \rightarrow$ transition strenght, $\beta/H \rightarrow$ inverse time scale, $T_n \rightarrow$ nucleation temp.

$$\alpha \propto \frac{1}{T_n^4}\left[V_i - V_f - \frac{T}{4}\left(\frac{\partial V_i}{\partial T} - \frac{\partial V_f}{\partial T}\right)\right] \qquad \frac{\beta}{H} = T_n \frac{\partial}{\partial T}\left(\frac{\hat{S}_3}{T}\right)\bigg|_{T_n}$$

Particle Physics details encoded in α and β/H

- Bubble nucleation takes place when the probability to realize 1 transition per cosmological horizon is equal to one $\Rightarrow \hat{S}_3/T_n = 140$

- Classical motion in Euclidean space described by the Euclidean action $\hat{S}_3$

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

- $\hat{\phi} \rightarrow$ solution of the e.o.m. found by the path that minimizes the energy.
- Effective potential: loop and thermal corrections

$$V_{\text{eff}}^{(1)}(\hat{\phi}, T) = V_0 + V_{\text{CW}} + \Delta V^{(1)}(T)$$

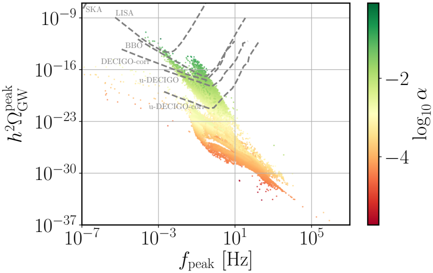
- Formalism implemented in `CosmoTransitions` [Wainwright]

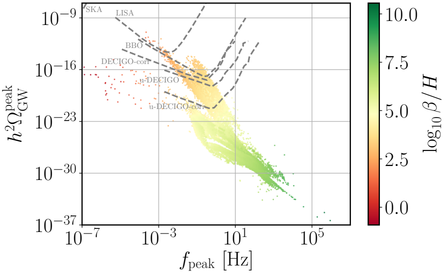
Outline

Softly broken $\mathrm{U}(1)_\mathrm{L}$

An inclusive scan

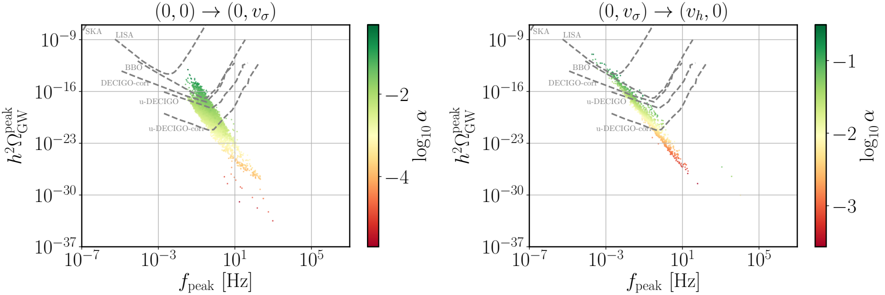
Y_σ	M/GeV	λ_σ	$\lambda_{\sigma h}$	$m_{\sigma_R}/\mathrm{GeV}$	$m_{\sigma_I}/\mathrm{keV}$	Y_ν
$[10^{-3}, 3.5]$	$[50, 1000]$	$[10^{-3}, 5]$	$[10^{-3}, 5]$	$[50, 1000]$	1	10^{-2}





- The stronger the transition the higher the peak amplitude
- The longer the transition time the lower the peak frequency
- Colour gradation and distribution of points is not always smooth: **depend on different transition patterns**

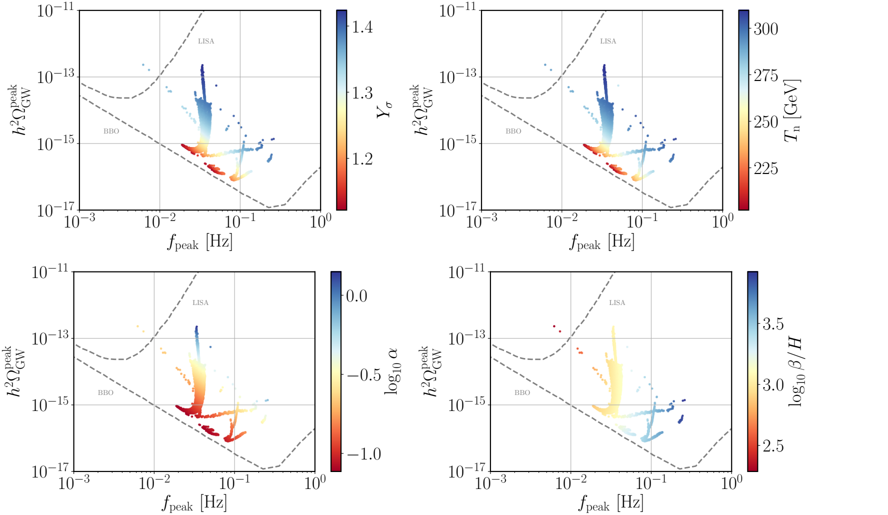
Most relevant patterns, at $T \neq 0$, are $(0,0) \to (0, v_\sigma)$ and $(0, v_\sigma) \to (v_h, 0)$



Study the effect of λ_σ, $\lambda_{\sigma h}$ and Y_σ and search for points at the reach of LISA

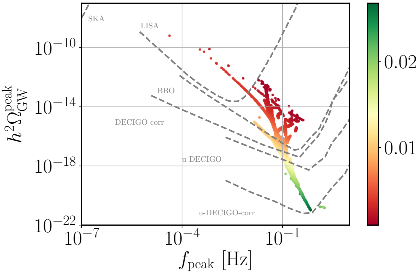
$(0,0) \to (0, v_\sigma)$ **case**

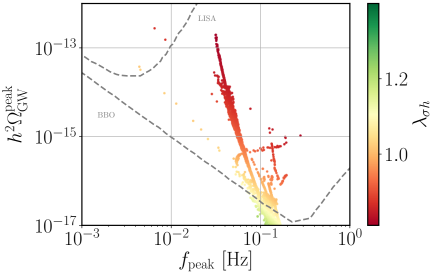
$\lambda_\sigma = 0.0017 \quad \lambda_{\sigma h} = 0.82 \quad Y_\sigma = \left[10^{-3}, 3.5\right] \quad M = 430\ \text{GeV} \quad m_{\sigma_R} = 169\ \text{GeV}$

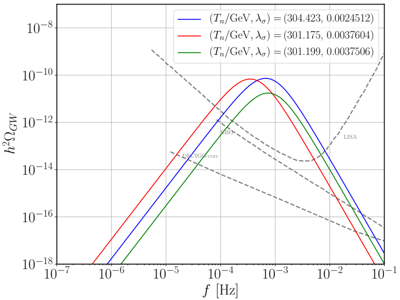


Increasing Y_σ enhances the transition strength thus GW peak amplitude

Fixing $Y_\sigma = 1.41$ and varying λ_σ and $\lambda_{\sigma h}$



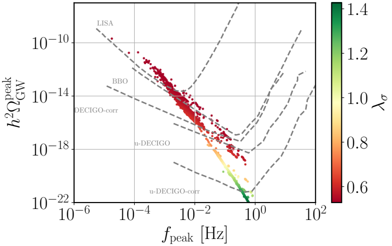


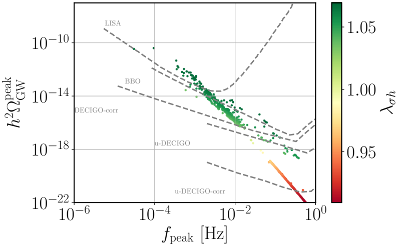


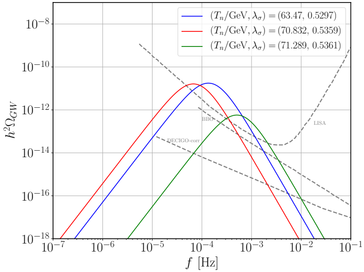
- Several points at the reach of LISA for smaller quartics
- **$h^2\Omega_{\rm GW}^{\rm peak}$ and $f_{\rm peak}$ quite sensitive to theory parameters**
- Can the GW-portal become a possibility for precision measurements?

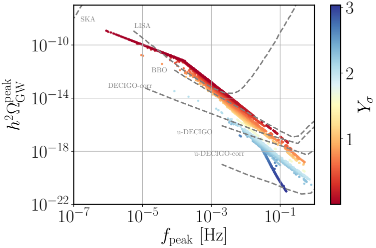
$(0, v_\sigma) \to (v_h, 0)$ case

$$\lambda_\sigma = 0.54 \quad \lambda_{\sigma h} = 1.06 \quad Y_\sigma = 0.02 \quad M = 225 \text{ GeV} \quad m_{\sigma_R} = 147 \text{ GeV}$$









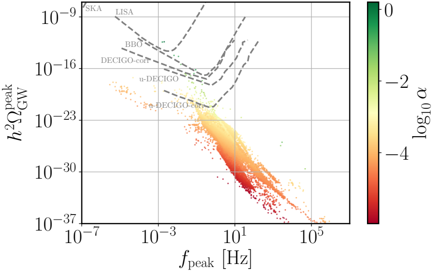
Y_σ and $\lambda_{\sigma h}$ impact is inverted in comparison to the $(0,0) \to (0, v_\sigma)$ case

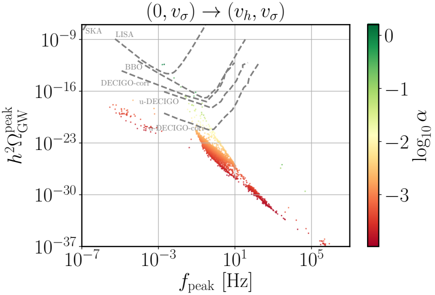
Spontaneously broken $\mathrm{U}(1)_{\mathrm{L}}$

An inclusive scan

Y_σ	M/GeV	$\lvert\cos\theta\rvert$	v_σ/GeV	m_{h_2}/GeV	m_{σ_I}/keV	Y_ν
$[10^{-3}, 3.5]$	[50, 1000]	> 0.85	[50, 1000]	[50, 1000]	1	10^{-6}

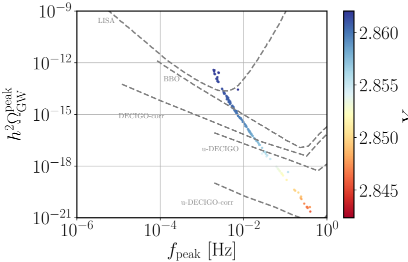
$$\lambda_\sigma = \frac{1}{4v_\sigma^2}\left(\cos 2\theta(m_{h_2}^2 - m_{h_1}^2) + m_{h_1}^2 + m_{h_2}^2\right), \quad \lambda_{\sigma h} = \frac{1}{2v_h v_\sigma}\cos 2\theta \tan 2\theta (m_{h_2}^2 - m_{h_1}^2)$$

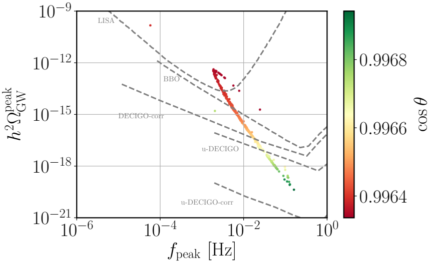


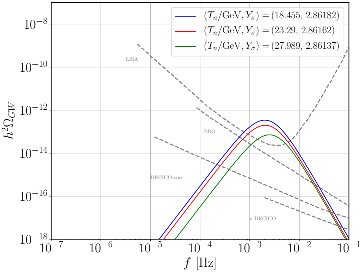


$(0, v_\sigma) \to (v_h, v_\sigma)$ case

$\cos\theta = 0.996 \quad v_\sigma = 858$ GeV $\quad Y_\sigma = 2.9 \quad M = 141$ GeV $\quad m_{h_2} = 590$ GeV







$\lambda_h = 0.15 \quad \lambda_\sigma = 0.13 \quad \lambda_{\sigma h} = 0.24$

- Consistency with Higgs invisible decays bounds
- Possibility to distinguish/falsify the underlying neutrino mass generation mechanism

Outline

Conclusions

1. Visible signals testable at LISA require at least one sizeable coupling.
2. GW footprints for spontaneous $\mathrm{U}(1)_\mathrm{L}$ breaking require sizeable Y_σ to compensate small quartics
3. Invisible Higgs decays for the softly broken $\mathrm{U}(1)_\mathrm{L}$ case may pose extra constraints (not yet applied)
4. **A traditional type-I seesaw leaves no GW footprint due to decoupled new physics scale**

Multi-messenger era

GW physics may shed light on the mystery of neutrino mass generation and, in general, become a complementary channel for New Physics studies.

Outline

Dynamics of phase transitions

- High $T \to$ 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

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

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

Nucleation temperature

- Nucleation temperature $T_n \to$ the PT does effectively occur $\to$ vacuum bubble nucleation processes
- Satisfies $T_n < T_c$, where T_c is the critical temperature $\to$ 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)

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$^{\rm st}$-order PT**

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

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

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$^{\rm st}$-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$^{\rm nd}$-order) transitions can become 1$^{\rm st}$-order ones due to **quantum corrections**
- Certain scenarios exhibit multi-step **successive 1$^{\rm st}$-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

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)

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

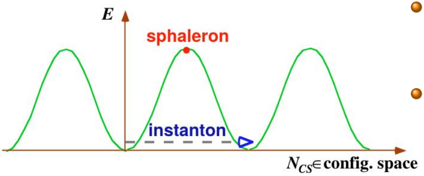
with peak frequency at nucleation time $f_n = \frac{0.62\beta}{1.8-0.1v_w+v_w^2}$

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

Backup slides: The sphaleron solution

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

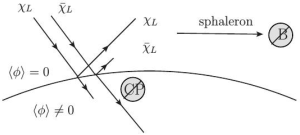
- $T = 0$: Instanton solution
  - > Tunnelling prob. $\sim 10^{-170}$ (EW theory)
- $T \neq 0$: Sphaleron solution $-$ **thermal jump**
  - > Transition prob. $\sim T^4$
  - > Static saddle-point solution
  - > $N_f = 3 \Rightarrow B \to 3B$

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)