Multi-peaked Gravitational footprints of neutrino mass and lepton symmetry violation

António P. Morais[1]
Andrea Addazi[2] Antonino Marcianò[2] 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

September 13, 2019

SCALARS 2019 – Warasw

FCT Fundação para a Ciência e a Tecnologia
CENTRO 2020
PORTUGAL 2020
UNIÃO EUROPEIA
Fundos Europeus Estruturais e de Investimento
COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Outline

Outline

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 a phase

GW background as a gravitational probe for New Physics

- Focus on the EW phase transition (EWPT)

Look for graviational footprints of the various variants of the type-I and inverse seesaw mechanism for Majorana neutrinos

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 $\mathrm{U}(1)_{\mathrm{L}} \to \mathbb{Z}_2$
- Mass for light neutrinos after EWSB $\langle H \rangle = v_h/\sqrt{2}$

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

Low-scale variant: Inverse seesaw

- Add two gauge singlet fermion carrying opposite lepton number charge, ν^c and S

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

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

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

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

Type-I and inverse seesaw with majoron

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

$M\nu^c\nu^c \to Y_\sigma \sigma \nu^c \nu^c$ (type-I variant) $\mu SS \to Y_\sigma \sigma SS$ (low-scale inverse variant)

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

$M \to Y_\sigma v_\sigma/\sqrt{2}$ (type-I variant) $\mu \to Y_\sigma v_\sigma/\sqrt{2}$ (low-scale inverse variant)

Extended scalar sector:

$$V_0 = V_{\mathrm{SM}} + \mu_\sigma^2 \sigma^* \sigma + \lambda_\sigma \left(\sigma^* \sigma\right)^2 + \lambda_{h\sigma} H^\dagger H \sigma^* \sigma + \left(\tfrac{1}{2}\mu_b^2 \sigma^2 + \mathrm{c.c.}\right)$$

- Tiny $\mathrm{U(1)_L}$ soft breaking term $\mu_b \sim \mathcal{O}\left(1\ keV\right)$
- Resulting pseudo-Goldstone boson can provide testable dark matter candidate [Valle et al PRD (1993), PRL (2007); Bazzocchi et al JCAP (2008)]

Outline

Gravitational Waves from FOPT

- Vacuum bubbles nucleated from first order phase transitions (FOPT)
- Three sources of GW production: 1) collision, 2) sound waves and 3) plasma turbulence

$$h^2\Omega_{\rm GW} = h^2\Omega_{\rm col} + h^2\Omega_{\rm sw} + h^2\Omega_{\rm MHD}$$

- $h^2\Omega_{\rm col}$ dominates for large wall velocities, $v_b \to 1$

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

$\alpha \to$ released latent heat, $\beta/H \to$ inverse time scale, $T_n \to$ nucleation temp.

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

- Bubble nucleation takes place when the probability to realize 1 transition per cosmological horizon is equal to one $\Rightarrow \hat{S}_3/T_n = 140$
- Strong transition criterion: $v_h\left(T_n\right)/T_n \gtrsim 1 \Rightarrow$ enhances GW production

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

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

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

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

- Formalism implemented in `CosmoTransitions` [Wainwright]

Outline

Seesaw induced Gravitational Waves

High scale type-I seesaw with explicit $\mathrm{U}(1)_{\mathrm{L}}$ violation $(M\nu^c\nu^c)$

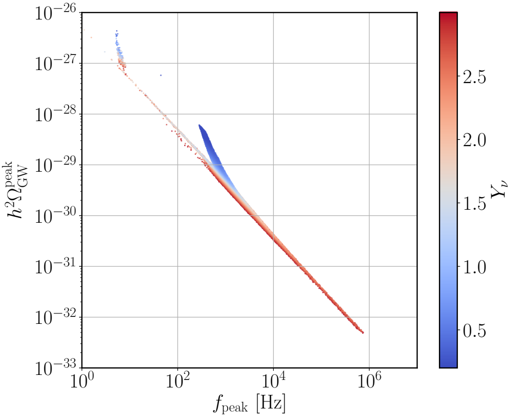
- Heavy isosinglet neutrinos decoupled from EW-scale play no role in the EW phase transition (EWPT) $\Longrightarrow$ **no FOPT thus no GW signals**

Low-scale inverse seesaw with explicit $\mathrm{U}(1)_{\mathrm{L}}$ violation $(M\nu^c S + \mu SS)$

- Singlet neutrinos lie closer to EW scale and coupling to Higgs can be sizeable
- **Thermal contributions from heavy neutrinos induce FOPT**
- **Fermions affect PT only at loop level** $\Rightarrow$ weak FOPT

$v_h\left(T_n\right)/T_n \sim \mathcal{O}\left(0.1\right)$ even for large Y_ν and up to 30 neutrino species

Y_ν	M/GeV	generations
$[0.2, 3.0]$	$[50, 500]$	$[3, 30]$



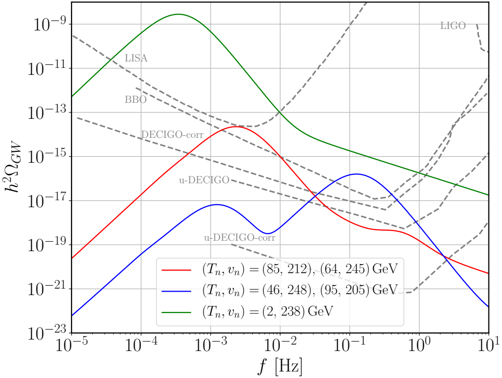
GW signal too weak to be detectable by future gravitational interferometers

Inverse seesaw with majoron: Spontaneous breaking $\mathrm{U}(1)_\mathrm{L} \to \mathbb{Z}_2$

$M\nu^c\nu^c \to Y_\sigma \sigma \nu^c\nu^c$ (type-I variant) $\mu SS \to Y_\sigma \sigma SS$ (low-scale inverse variant)

New scalar σ responsible for a richer pattern of FOPTs

- Tree-level contributions in V_0 substantially enhance the strength of the PT



- **Observable signals including multi-peaked scenarios**

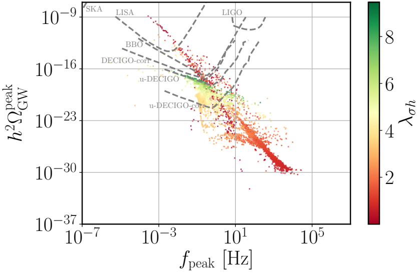
All three scenarios with nearly preserved $\mathrm{U}(1)_{\mathrm{L}}$, i.e., $v_\sigma(T=0) \sim \mathcal{O}(1\ \mathrm{keV})$

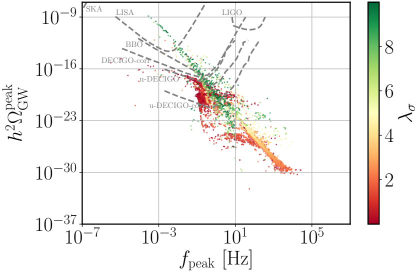
Peak Id	$(v_h^i, v_\sigma^i) \to (v_h^f, v_\sigma^f)$	α	β/H
Green 1	$(249, 0) \to (238, 0)$	16.0	715
Red 1	$(0, 70.7) \to (212, 0)$	8.83×10^{-2}	109
Red 2	$(228, 0) \to (245, 0)$	6.85×10^{-3}	2.31×10^{4}
Blue 1	$(0, 98.9) \to (205, 0)$	5.72×10^{-2}	5.08×10^{3}
Blue 2	$(239, 0) \to (248, 0)$	3.73×10^{-3}	86.7

Curve	$m_{\sigma_R}/\mathrm{GeV}$	$\lambda_{\sigma h}$	λ_σ	M_ν/GeV	Y_σ
Green	68.9	3.56	7.86×10^{-3}	147	4.83
Red	439	7.42	8.48	324	2.71
Blue	378	5.08	1.67	303	0.126

- **Green curve at the reach o LISA**: very strong FOPT with $v_n/T_n = 119$
  - Consistent with invisible Higgs decays LHC bounds [Bonilla, Romão, Valle (2016)]
- **Two-peak scenarios at the reach of DECIGO**
- **Large quartic couplings enhance m/T and facilitate these scenarios:**
  - Bosonic $(m/T)^3$ contributions in $\Delta V^{(1)}(T)$ produce potential barriers

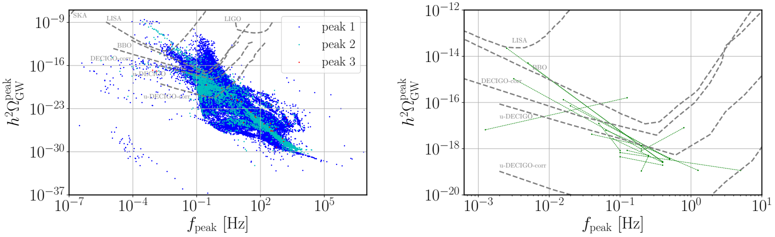
Generic feature for multi-peaked scenarios





- At least one quartic coupling involving σ is sizeable

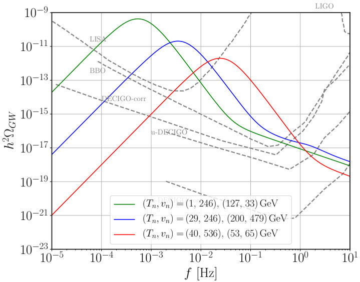
Multi-peak feature is a generic prediction of the inverse seesaw with majoron

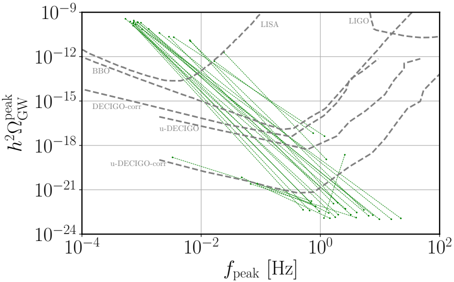


- The third peak is typically hard to resolve
- **Multi-peaks due to distinct phase transitions and not competition between GW sources (collision, sound waves, turbulence)**
- Possibility to distinguish/falsify the underlying neutrino mass generation mechanism

Type-I seesaw with majoron

- High scale variant: $Y_\nu \sim \mathcal{O}(1) \Rightarrow M = Y_\sigma v_\sigma/\sqrt{2} \sim \mathcal{O}\left(10^{14}\ \mathrm{GeV}\right)$
  - > For $Y_\sigma \sim \mathcal{O}(1)$ then $v_\sigma \sim \mathcal{O}\left(10^{14}\ \mathrm{GeV}\right) \Rightarrow$ no FOPT and no GW
- Low scale variant: $Y_\nu \sim \mathcal{O}\left(10^{-6}\right) \Rightarrow M = Y_\sigma v_\sigma/\sqrt{2} \sim \mathcal{O}(100\ \mathrm{GeV})$
  - > New states do not decouple and can lead to FOPT and to GW





Double-peak feature within experimental reach is much rarer

In contrast to inverse seesaw + majoron, one PT is typically much stronger hiding the smaller peak

Curve	m_{h_2}/GeV	λ_h	$\lambda_{\sigma h}$	λ_σ	$\cos\theta$	$v_\sigma(T=0)$	M_ν/GeV	Y_σ
Green	83.1	0.0624	0.310	8.16	0.962	30.3	456	2.08
Red	793	0.389	0.594	0.350	0.974	924	90.5	2.59
Blue	334	0.265	0.332	0.243	0.913	449	57.8	2.97

Peak Id	$(v_h^i, v_\sigma^i) \to \left(v_h^f, v_\sigma^f\right)$	α	β/H	$f_{\mathrm{peak}}/\mathrm{Hz}$
Green 1	$(0, 45.4) \to (33.4, 45.1)$	6.39×10^{-4}	2.36×10^4	0.955
Green 2	$(246, 30.8) \to (246, 29.7)$	6.70	3.50×10^3	5.37×10^{-4}
Red 1	$(0, 967) \to (64.8, 964)$	1.20×10^{-2}	8.16×10^4	1.26
Red 2	$(213, 935) \to (536, 750)$	0.249	2.68×10^3	0.0240
Blue 1	$(293, 305) \to (0, 479)$	1.30×10^{-2}	2.04×10^4	1.17
Blue 2	$(0, 554) \to (246, 450)$	0.632	574	3.48×10^{-3}

- m_{h_2}: Second CP-even Higgs and $h = \cos\theta\, h_1 + \sin\theta\, h_2$
- Consistency with Higgs invisible decays bounds assured

Outline

Conclusions

1. Explicit lepton number violation cannot induce strong FOPT thus testable GW signals
2. Spontaneous $\mathrm{U}(1)_{\mathrm{L}}$ breaking leads to clearer GW footprints
3. Both majoron models, type-I seesaw and inverse seesaw, predict testable GW in the $0.1 - 100\ \mathrm{mHz}$ frequency range
4. **Different seesaw variants lead to distinct GW spectra potentially distinguishable by upcoming experiments**

Multi-messenger era

Gravitational wave physics may shed light on the mystery of neutrino mass generation

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 $T_n \rightarrow$ 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)

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 → 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 → free energy release is largely amplified → **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 → 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

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)

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

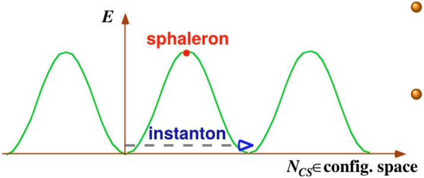
with peak frequency at nucleation time $f_n = \frac{0.62\beta}{1.8-0.1v_w+v_w^2}$

- 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

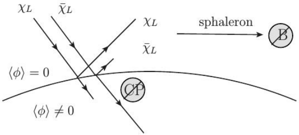
> Reflection of particles $\rightarrow$ plasma out of equilibrium

> 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 GeV Higgs mass)