Gravitational footprints of massive neutrinos and lepton number breaking

Andrea Addazi,1,∗ Antonino Marcianò,1,† António P. Morais,2,‡ Roman Pasechnik,3,§ Rahul Srivastava,4,¶ and José W. F. Valle4,∗∗

1Department of Physics & Center for Field Theory and Particle Physics, Fudan University, 200433 Shanghai, China
2Departamento de Física, Universidade de Aveiro and CIDMA, Campus de Santiago, 3810-183 Aveiro, Portugal, EU
3Department of Astronomy and Theoretical Physics, Lund University, 221 00 Lund, Sweden, EU
4AHEP Group, Institut de Física Corpuscular – C.S.I.C./Universitat de València, Parc Científic de Paterna. C/ Catedrático José Beltrán, 2 E-46980 Paterna (Valencia) - SPAIN

We investigate the production of primordial Gravitational Waves (GWs) arising from First Order Phase Transitions (FOPTs) associated to neutrino mass generation in the context of type-I seesaw schemes. We examine both “high-scale” as well as “low-scale” variants, with either explicit or spontaneously broken lepton number symmetry. In the latter case, a pseudo-Goldstone boson, dubbed majoron, may provide a candidate for warm or cold cosmological dark matter. We find that schemes without majoron lead to either no FOPTs or too weak FOPTs, precluding the detectability of GWs in present or near future experiments. Nevertheless, we found that, in the presence of majorons, one can have strong FOPTs and non-trivial primordial GW spectra which can fall well within the frequency and amplitude sensitivity of upcoming experiments, including LISA, BBO and u-DECIGO. We further analyze the associated types of FOPTs and show that in certain cases, the resulting GW spectra entail, as characteristic features, double or multiple peaks, which can be resolved in forthcoming experiments. We also found that the majoron variant of the low-scale seesaw mechanism implies a different GW spectrum than the one expected in the high-scale majoron seesaw. This feature will be testable in future experiments. Our analysis shows that GWs can provide a new and complementary portal to test the neutrino mass sector.

Introduction

Non-zero neutrino masses constitute one of the most robust evidences for new physics [1–3]. Despite great efforts over the last two decades to underpin the origin of neutrino mass, the basic underlying mechanism remains as elusive as ever. Small neutrino masses can be generated in many ways, both for Majorana [4, 5] and Dirac [6–11] neutrinos. Here, we focus on the various variants of the popular type-I seesaw mechanism for Majorana neutrinos [12–15]. We consider both high- and low-scale [16–20] realizations, with explicit or spontaneous lepton number violation, in which SU(3)C ⊗ SU(2)L ⊗ U(1)Y singlet neutrinos act as neutrino mass mediators. Besides oscillations and neutrinoless double beta decay (0νββ) searches, neutrino masses can be probed through Charged Lepton Flavor Violation (CLFV) experiments at the high intensity and/or high energy frontier [21–23]. Moreover, neutrino mass generation can leave signatures at high-energy colliders like the Large Hadron Collider (LHC) [24–27].

The detection of Gravitational Waves (GWs) by the LIGO team has opened an entirely novel method to probe the underlying new physics associated to neutrino mass generation. It was advocated that the spectrum of primordial GWs, potentially measurable at the currently planned GW interferometers, may represent an important cutting-edge probe for new physics. This follows from the fact that these interferometers can be sensitive enough to measure the echoes of the possible First Order Phase Transitions (FOPTs), which might have happened in the past cosmological history [28].

In this letter, we focus on possible gravitational footprints of the various variants of the popular type-I seesaw mechanism for Majorana neutrinos. The relevant part of the Lagrangian is given by

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

(1)

Here, \(L = (\nu, l)^T\) are the SM lepton doublets, \(H\) is the SM Higgs doublet, \(\nu^c\) are the three SM singlet “right-handed” neutrinos. The \(3 \times 3\) matrices \(Y_\nu\) and \(M\) are the Yukawa coupling and the \(\nu^c\) mass matrix, respectively. Due to the Pauli principle the latter is symmetric. No-
tice that, for brevity, we omit family indices throughout this letter. Notice also that the mass term explicitly breaks the lepton number symmetry \( U(1)_L \) to its \( \mathbb{Z}_2 \) subgroup. The electroweak (EW) symmetry is broken by the vacuum expectation value (vev) of the Higgs field, i.e. \( \langle H \rangle = v_h / \sqrt{2} \), generating the light neutrino masses

\[
m^{\text{Type-I}}_\nu = \frac{v_h^2}{2} Y^T \sigma^T M^{-1} \sigma. \tag{2}
\]

The lightness of the left-handed neutrinos is then ascribed to the heaviness of the “right-handed” isosinglet partners e.g. for \( Y \sim \mathcal{O}(1) \), \( M \sim \mathcal{O}(10^{14}) \) GeV, one gets \( m_\nu \sim \mathcal{O}(0.1) \) eV.

Another popular realization of this idea is the “low-scale” variant, in which two gauge singlet fermions \( \nu^c \) and \( S \) are added sequentially to the SM particle content [16–20]. The template of these schemes has exact conservation of lepton number and, as a result, strictly massless neutrinos. Yet flavor is violated to a potentially large degree, subjected only to constraints from weak interaction precision observables, such as universality tests [29–33]. To this template one adds a small seed of lepton number violation, leading to nonzero neutrino mass. One example is the so-called “inverse seesaw” mechanism, where the smallness of the neutrino mass is linked to the breaking of the lepton number symmetry \( U(1)_L \) to its \( \mathbb{Z}_2 \) subgroup, through the so called \( \mu \)-term. The relevant part of Lagrangian in this case is given by

\[
\mathcal{L}^{\text{Inverse}}_\text{Yuk} = Y_\nu \bar{L} H \nu^c + M \nu^c S + \mu S \bar{S} + \text{h.c.}, \tag{3}
\]

where \( \mu \) is also a \( 3 \times 3 \) symmetric matrix. The light neutrino mass is then given by

\[
m^{\text{Inverse}}_\nu = \frac{v_h^2}{2} Y^T \nu^c \sigma^T \mu M^{-1} \nu^c. \tag{4}
\]

Note that small neutrino masses are “protected”, since \( m_\nu \to 0 \) as the lepton number symmetry gets restored by having \( \mu \to 0 \) [16–20]. In this case there can be sizable unitarity violation in neutrino propagation [34–36].

For both high- and low-scale seesaw, one can have spontaneous breaking of \( U(1)_L \to \mathbb{Z}_2 \), leading to the so-called majoron variants of the seesaw [17, 37, 38]. This is accomplished by adding the SM singlet scalar \( \sigma \), which carries two units of lepton number charge. Then \( \langle \sigma \rangle \equiv v_\sigma \) spontaneously breaks \( U(1)_L \to \mathbb{Z}_2 \), leading to a dynamical explanation of the small neutrino masses. To get the majoron variants of minimal type-I and inverse seesaw one should replace

\[
M \to Y_\sigma v_\sigma / \sqrt{2}, \quad \mu \to Y_\sigma v_\sigma / \sqrt{2}
\]

in Eq. (1) and (3), respectively. An additional attractive feature of majoron models is the existence of a pseudo Nambu-Goldstone boson providing a good [39–41], and testable [42, 43] dark matter candidate.

**Gravitational waves from FOPTs** In order to characterize the features of the GWs originating from FOPTs in seesaw schemes, we calculate the saturated latent heat and compare it to the latent heat released by the transition. Bubbles run away if the amount of released latent heat is bigger than the saturated one. Usually, the bubbles do not run away, while for a smaller fraction of those that do run away, we use the proper procedure outlined in Ref. [44].

For the case of non-runaway nucleated bubbles, the intensity of the GW radiation grows with the strength of the transition, given by the ratio \( v_n / T_n \), where \( v_n \equiv v_h(T_n) \) is the Higgs vev at the bubble nucleation temperature \( T_n \). From the discussion in Ref. [45, 46], it follows that bubble wall collisions do not provide an efficient way of producing GWs in the models of interest to us here. As a result, GWs originate mainly from two sources:

I. Magnetohydrodynamic (MHD) turbulence;

II. Sound shock waves (SW) of the early Universe plasma, generated by the bubble’s violent expansion.

These contributions arise over transient times at the early Universe and get subsequently “redshifted” by the expansion. To a present observer this appears as a cosmic gravitational stochastic background. Intuitively, one expects that from any of these leading order contributions, a high wall velocity is necessary to generate detectable GWs. Our numerical analysis confirms the general expectation that the bubble wall velocities are close to the speed of light, i.e. \( v_n \approx 1 \). Besides, in our results the SW contribution dominates the peak frequency and the peak amplitude, while the tails are mostly set by the MHD turbulence term. For certain parameter configurations one also expects sequential phase transition patterns leading to potentially resolvable multi-peak GWs spectra studied for the first time in [47].

**Seesaw-induced Gravitational Waves** First, we note that within the type-I seesaw mechanism with explicitly broken lepton number, no FOPTs are obtained. The heavy isosinglet neutrinos practically decouple at the EW scale, and do not alter the nature of the EW phase transition. In contrast, in the inverse seesaw mechanism the singlet neutrinos lie closer to the EW scale, and can have a sizable coupling to the Higgs boson. This can alter the EW phase transition, making it first-order. Indeed, we find FOPTs for many points in parameter space. Nevertheless, as shown in Fig. 1, the expected “intensity” parameter \( h^2 \Omega_{\text{GW}} \) lies far below the sensitivity of any
conceivable experiment, rendering the testability of this scenario very remote. In Fig. 1, we have allowed the mass parameter $M$ to vary between 50 GeV and 500 GeV, with the Yukawa coupling $Y_\nu$ between 0.2 and 3.0. For completeness, we have studied the possibility of having more than three families of heavy singlet neutrinos. As mentioned, the lightness of $m_\nu$ follows from the small $\mu$-term. As seen from Fig. 1, even for large values of $Y_\nu \sim \mathcal{O}(1)$, the FOPTs remain weak, leading to an undetectable GW signal. This follows from the fact that the fermions affect the phase transitions only at the loop level. Even if we increase their number up to $30^1$, the GW signal is not enhanced enough to be detectable.

When the seesaw mechanism is associated with the spontaneous breaking of the lepton number symmetry, the situation changes dramatically. First of all, the spontaneous breaking of $U(1)_L$ together with the EW symmetry allows for a richer pattern of FOPTs. Indeed, not only the heavy isosinglet fermions, but also the complex scalar field $\sigma$ driving the spontaneous breaking of $U(1)_L$, can couple substantially to the Higgs boson. This can generate two peaks in the GW spectrum and, depending on the parameter region, up to three peaks for a given parameter space choice. Fig. 2 shows some benchmark single and double peak GW-spectra for the majoron inverse seesaw. Notice that the single peak case (green) lies well within the LISA range, while both peaks in the double peak scenario (blue) are well within the sensitivity range of the u-DECIGO-corr measurement.

To understand these characteristic features, we must keep in mind that at the end of any FOPT the scalar potential minimization requires non-vanishing vevs $(v_h, v_\sigma)$ associated with the generation of both the EW and neutrino mass scales. The benchmark values for parameters corresponding to the three curves in Fig. 2 are given in Tab. I and Tab. II.

---

1 Three $\nu^c$ and $S$ families correspond to three active neutrinos. We increased their multiplicity only to explore the impact of fermions on the FOPTs and the resulting GW signals.

---

TABLE I: Phase transition parameters for the three curves in Fig. 2. In “peak Id” column, the numbering of multi-step scenarios is ordered from low to high frequencies. The vevs before the transition, $v_{h,\sigma}^\epsilon$, and after the transition, $v_{h,\sigma}^\beta$, are given in GeV. The $\epsilon$ denotes the tiny yet non-zero vev acquired by the $\sigma$ field.

| Peak Id $\{(v_h^\epsilon, v_\sigma^\epsilon) \rightarrow (v_h^\beta, v_\sigma^\beta)\}$ | $\alpha$ | $\beta/H$ |
|---------------------------------|---------|----------|
| Green 1 $\{(249, 0) \rightarrow (238, \epsilon)\}$ | $16.0$ | $715$ |
| Red 1 $\{(0, 70.7) \rightarrow (212, \epsilon)\}$ | $8.83 \times 10^{-3}$ | $109$ |
| Red 2 $\{(228, 0) \rightarrow (245, \epsilon)\}$ | $6.85 \times 10^{-3}$ | $2.31 \times 10^4$ |
| Blue 1 $\{(239, 0) \rightarrow (248, \epsilon)\}$ | $3.73 \times 10^{-3}$ | $86.7$ |
| Blue 2 $\{(0, 98.9) \rightarrow (205, \epsilon)\}$ | $5.72 \times 10^{-2}$ | $5.08 \times 10^3$ |

TABLE II: Model parameters for the three curves in Fig. 2. Here, $\sigma_R$ is the CP even part of the $\sigma$-scalar after symmetry breaking, $\lambda_{\sigma h}$, while $\lambda_\sigma$ denote the quartic couplings.

| Curve $m_{\sigma_R}/\text{GeV}$ | $\lambda_{\sigma h}$ | $\lambda_\sigma$ | $M/\text{GeV}$ | $Y_\sigma$ |
|-------------------------------|----------------|------------------|----------------|-----------|
| Green $68.9$ | $3.56$ | $7.86 \times 10^{-3}$ | $147$ | $4.83$ |
| Red $439$ | $7.42$ | $8.48$ | $324$ | $2.71$ |
| Blue $378$ | $5.08$ | $1.67$ | $303$ | $0.126$ |

In Fig. 2 we show the GW energy density spectrum obtained for different nucleation temperatures. In all three cases we assumed that the singlet neutrino coupling to
the majoron is of order one. The latter can be sizeably coupled to the Higgs boson, while consistent with the current LHC bounds from invisible Higgs decays [26, 27]. The three cases shown in Fig. 2 correspond to two consecutive FOPTs. The green curve represents a scenario with

![Graph](image1)

(a) Selected double-peak scenarios within the LISA and BBO sensitivity ranges. The two ends of each line represent the location of the peaks of the double-peak GW spectrum. The two maxima in each double-peak GW spectra are joined by a straight line, in order to easily identify the peaks associated with each other.

![Graph](image2)

(b) Scatter plot showing the number of peaks for given model parameter choices. Notice the appearance of double- and even triple-peak features.

**FIG. 3:** The multi-peak feature arising from different phase transitions in the cosmological history of the Universe is very generic in the inverse seesaw with majoron.

(a single very strong EW phase transition, $v_n/T_n = 119$, and a nearly preserved lepton symmetry. This is possible due to the large quartic coupling $\lambda_{\sigma h}$, which makes the $m/T$-ratio sizable. Hence, the cubic $(m/T)^3$ terms in the thermal expansion can produce a potential barrier between the vacua, inducing this type of transitions. The same effect generates the rightmost and the leftmost peaks in the red and blue curves, respectively. Once again, one sees that these results can be probed at BBO and u-DECIGO.

![Graph](image3)

(a) The expected GW spectra.

![Graph](image4)

(b) Scatter plot showing typical double-peak scenarios. There are less double-peaks than in Fig. 3b, and most of them are out of the range of the upcoming experiments.

**FIG. 4:** Gravitational footprints of “fake” low-scale seesaw with majoron. In both plots we take $v_\sigma \sim \mathcal{O}(100)$ GeV – $\mathcal{O}(1)$ TeV.

Note that the multi-peak configurations in the GW spectrum occur very frequently in the inverse seesaw with majoron. This fact is further highlighted in Fig. 3. Indeed, the double-peak feature of the GW spectrum is a generic prediction of our model, that can arise for many parameter choices, as shown in Fig. 3a. Configurations with larger peak multiplicities are also possible, as seen in Fig. 3b, where the color denotes the peak number, 1 (blue), 2 (cyan) or 3 (red). Such a rich peak structure is favoured for large quartic couplings involving $\sigma$. From Fig. 3b we also see that the GW spectra with three peaks are rarer than single or double GW-peak spectra. However, a significant fraction of the single peak cases are testable at LISA and BBO, while the double-peak cases may mostly be accessible to u-DECIGO, as shown in Fig. 4a.

The multi-peak feature of GWs provides a potentially viable way to distinguish amongst the basic underlying
neutrino mass generation patterns, making the whole scenario potentially falsifiable at the fundamental level. To further illustrate its importance we take the type-I seesaw with majoron. As mentioned before, it is clear that, if $Y_\nu \sim \mathcal{O}(1)$, then $M = Y_\sigma v_\sigma / \sqrt{2} \sim \mathcal{O}(10^{14})$ GeV, hence $v_\sigma \sim \mathcal{O}(10^{14})$ GeV for $Y_\nu \sim \mathcal{O}(1)$. In this limit, all the new particles can be integrated out for processes occurring at the EW scale, leading to no-FOPT solutions (the majoron couplings are highly suppressed, with no effect on EW scale physics). However, one can take $Y_\nu \sim \mathcal{O}(10^{-6})$, corresponding to $M = Y_\sigma v_\sigma / \sqrt{2} \sim \mathcal{O}(100)$ GeV. The fields do not decouple at the EW scale, and can still lead to FOPTs – hence to potentially observable primordial GW signals. One sees that this scenario requires tiny values of the neutrino “Dirac” Yukawa couplings $Y_\nu$ to fit the small neutrino masses. Such “fake” low-scale seesaw contrasts with the “genuine” low-scale seesaw, which does not require this restriction.

| Curve | $m_{h_i}$/GeV | $\lambda_h$ | $\lambda_{s\sigma}$ | $\lambda_{sH}$ | $\cos \theta$ | $v_\sigma(T = 0)$ | $M_\nu$/GeV | $Y_\nu$ |
|-------|---------------|-------------|------------------|----------------|--------------|----------------|-------------|--------|
| 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   |

TABLE III: Model parameters for the three curves in Fig. 4a.

| Peak Id | $(v^i, v^f) \rightarrow (v^i_h, v^f_h)$ | $\alpha$ | $\beta/H$ | $f_{peak}$/Hz | $h^2\Omega_{GW}^{peak}$ |
|---------|----------------------------------------|----------|-----------|---------------|------------------------|
| Green 1 | (0.454, 45.1) → (33.4, 45.1)           | $6.39 \times 10^{-4}$ | $2.36 \times 10^4$ | 0.955 | $1.63 \times 10^{-24}$ |
| Green 2 | (246.30, 246.30) → (246, 246.27)       | 6.70      | $3.50 \times 10^4$ | $5.37 \times 10^{-4}$ | $4.27 \times 10^{-10}$ |
| Red 1  | (0.967, 96.946) → (64.8, 96.944)       | $1.20 \times 10^3$ | $8.16 \times 10^4$ | $1.26$ | $1.13 \times 10^{-11}$ |
| Red 2  | (213, 935) → (536, 750)               | 0.249     | $2.68 \times 10^3$ | 0.0240 | $1.95 \times 10^{-12}$ |
| Blue 1 | (293, 305) → (0, 479)                | $1.30 \times 10^{-2}$ | $2.04 \times 10^3$ | 0.17 | $4.18 \times 10^{-15}$ |
| Blue 2 | (0, 554) → (246, 450)                 | 0.632     | 574        | $3.48 \times 10^{-3}$ | $2.07 \times 10^{-11}$ |

TABLE IV: Phase transition parameters for the three curves in Fig. 4a. The hidden peaks, Green 1 and Red 1, are seven and two orders of magnitude below the spectrum envelope, respectively. The vevs before $(v^i_h, v^f_h)$ and after $(v^i_f, v^f_f)$ the phase transition are given in GeV. We find that, in a large region of parameters, both “fake” and “genuine” low-scale seesaw + majoron lead to the possibility of strong FOPTs. The corresponding GW spectra obtained for $v_\sigma \sim \mathcal{O}(100)$ GeV are shown in Fig. 4. Parameter values associated to Fig. 4a are given in Tab. III and Tab. IV.

We can compare, for instance, the GW spectra featuring the double-peak structures with the sensitivity regions of the future experiments. In both “fake” and “genuine” low-scale seesaw we collected several possible double-peak spectra for the two cases. Comparing Figs. 4b and 3 one sees that double-peaks are more frequent in the “genuine” low-scale seesaw + majoron than in the “fake” one. Although “fake” low-scale seesaw leads to GW signals within the reach of upcoming experiments, double-peaks in this case are much rarer, and when present, one of the peaks typically lies beyond experimental reach, see Fig. 4b. This should be contrasted with the “genuine” low-scale seesaw, where not only double peaks are more frequent but, as shown in Fig. 2, they are often accessible to upcoming experiments.2

To conclude, we analysed the most popular implementations of the type-I seesaw mechanism for neutrino mass generation. We studied both the cases of explicit and spontaneous breakdown of the lepton number symmetry. The second, “dynamical” symmetry breaking implies the majoron field, which may also be interpreted as a viable [39–41] and testable [42, 43] dark matter candidate. We have found that various scenarios lead to different patterns of phase transitions. We showed that explicit lepton number violation cannot induce any strong electroweak phase transition. Therefore, it does not lead to any gravitational-wave background signal testable by next-generation satellite interferometers.

The case when neutrino masses emerge from a dynamical mechanism in which lepton number violation happens spontaneously leads to much clearer gravitational

2 Notice that Fig. 3a only shows a few selected double-peak scenarios. The full set of double- and multi-peak configurations in the inverse seesaw with majoron is shown in Fig. 3b.
footprints. Within such majoron seesaw case, we found that both the standard type-I seesaw (taken at a low scale) and the “genuine” low-scale type-I seesaw (like the inverse seesaw) predict a strong gravitational wave signal, testable in the $0.1 - 100 \text{mHz}$ frequency range. This highly motivates future experimental proposals, including LISA, u-DECIGO and BBO, accessing to the mHz frontier, as an indirect and complementary probe of neutrino mass generation, providing important information on the electroweak phase transition.

While “genuine” low-scale seesaw predicts large charged lepton flavor violation [29–33], as well as unitarity violation in neutrino propagation [34–36], this feature is absent in the “fake” low-scale seesaw. This makes the two schemes distinguishable in high-intensity and high-energy frontier setups. Here we have shown that “fake” and “genuine” schemes also have potentially distinct gravitational footprints. We saw explicitly that they produce different gravitational-wave spectra, potentially testable in the upcoming gravitational-wave experiments. As we stand right now, the new unexpected channel provided by the gravitational-wave physics in the multi-messenger era may contribute to shed light on the mystery of neutrino mass generation.

ACKNOWLEDGMENTS

Useful discussions and correspondence with Zurab Berezhiani, Yifu Cai and Nico Yunes are gratefully acknowledged. A.P.M wants to thank Marek Lewicki and Bogumila Świeżewska for insightful discussions about bubble wall collision contributions to the spectrum of GW. A.A. and A.M. wish to acknowledge support by the NSFC, through grant No. 11875113, the Shanghai Municipality, through grant No. KBH1512299, and by Fudan University, through grant No. JJJ1512105. J.B. acknowledges his partial support by the NSFC, through the grants No. 11375153 and 11675145. A.A. and A.M. would like to thank IFIC for hospitality during the preparation of this work. R.P. is supported in part by the Swedish Research Council grants, contract numbers 621-2013-4287 and 2016-05996, as well as by the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 668679). The work of R.P. was also supported in part by the Ministry of Education, Youth and Sports of the Czech Republic, project LT17018. The work of A.P.M. has been performed in the framework of COST Action CA16201 “Unraveling new physics at the LHC through the precision frontier” (PARTICLEFACE).

A.P.M. is supported by Fundaçao para a Ciência e a Tecnologia (FCT), within project UID/MAT/04106/2019 (CIDMA) and by national funds (OE), through FCT, I.P., in the scope of the framework contract foreseen in the numbers 4, 5 and 6 of the article 23, of the Decreed-Law 57/2016, of August 29, changed by Law 57/2017, of July 19. A.P.M. is also supported by the Enabling Green E-science for the Square Kilometer Array Research Infrastructure (ENGAGESKA), POCI-01-0145-FEDER-022217, and by the project From Higgs Phenomenology to the Unification of Fundamental Interactions, PTDC/FIS-PAR/31000/2017. R.V. and J.W.F.V. are supported by the Spanish grants SEV-2014-0398 and FPA2017-85216-P (AEI/FEDER, UE), PROMETEO/2018/165 (Generalitat Valenciana) and the Spanish Red Consolider MultiDark FPA2017-90566-REDC.

[1] T. Kajita, “Nobel Lecture: Discovery of atmospheric neutrino oscillations,” Rev. Mod. Phys. 88 (2016) 030501.
[2] A. B. McDonald, “Nobel Lecture: The Sudbury Neutrino Observatory: Observation of flavor change for solar neutrinos,” Rev. Mod. Phys. 88 (2016) 030502.
[3] J. W. F. Valle and J. C. Romao, Neutrinos in high energy and astroparticle physics. John Wiley & Sons (2015). www.wiley.com/buy/9783527411979.
[4] S. Weinberg, “Varieties of baryon and lepton nonconservation,” Phys. Rev. D22 1694.
[5] S. M. Boucenna, S. Morisi, and J. W. F. Valle, “The low-scale approach to neutrino masses,” Adv. High Energy Phys. 2014 (2014) 831598, arXiv:1404.3751 [hep-ph].
[6] E. Ma and R. Srivastava, “Dirac or inverse seesaw neutrino masses with $B – L$ gauge symmetry and $S_3$ flavor symmetry,” Phys. Lett. B741 (2015) 217–222, arXiv:1411.5042 [hep-ph].
Phys. Rev. D96 no. 10, (2017) 103520, arXiv:1704.05871 [astro-ph.CO].

[46] J. Ellis, M. Lewicki, J. M. No, and V. Vaskonen, “Gravitational wave energy budget in strongly supercooled phase transitions,” JCAP 1906 no. 06, (2019) 024, arXiv:1903.09642 [hep-ph].

[47] T. Vieu, A. P. Morais, and R. Pasechnik, “Multi-peaked signatures of primordial gravitational waves from multi-step electroweak phase transition,” arXiv:1802.10109 [hep-ph].