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Testing Dark Matter models with radio telescopes in light of gravitational wave astronomy

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ABSTRACT

In this article we put forward a novel phenomenological paradigm in which particle physics beyond the Standard Model may be tested by radio astronomy if these are related to a first order phase transition in the early Universe. For this type of Dark Matter models, the first order phase transition takes place at keV scales, and hence, induces the production of a stochastic gravitational waves background that can be detected from Pulsar timing measurements. We demonstrate this hypothetical feasibility by studying a class of Majoron Dark Matter models, which are related to a first order phase transition of the $U(1)_L$ or $U(1)_{B-L}$ symmetry and are consequently dubbed as *violent Majorons*. These phenomena are expected to be examined by the ongoing and forthcoming radio experiments, including FAST, SKA and IPTA.

1. Introduction

Almost a century ago, the hypothesis of Dark Matter (DM) was proposed to meet with a variety of astronomical and cosmological observations that are invisible through electromagnetic interactions. The nature of DM remains one of the biggest mysteries in physics today. In the literature there are many theoretical proposals and experimental designs (see Refs. [1–3] for comprehensive reviews). The hypothesis of the weakly interacting massive particles (WIMP) is the prevailing paradigm. There are then alternative models accounting for axions and axion-like particles (ALP). Another possibility is the existence of an heavy hidden sector of particles that only interact with ordinary matter fields through gravitation. Depending on the theoretical properties of these candidates, the associated DM experiments can be divided into two classes: the direct detection, which searches for the scattering of DM particles with atomic nuclei; the indirect detection, which searches for the particle physics productions, such as the annihilation or decay effects of DM particles.

Along with the arrival of the gravitational waves (GW) astronomy, the detection method of DM deserves to be revisited, since more information about DM might be revealed by testing GW signals, if these candidate particles can be related to a first order phase transition (FOPT) in the early Universe. This is because a FOPT can generate a characteristic stochastic background of GWs. In this mechanism the Universe was initially in a state of false vacuum. Then, the tunneling toward the state of true vacuum could induce the enucleation and percolation of bubbles, which expand with constant acceleration, driven by a difference of pressure between the interior true vacuum and the exterior false vacuum. Eventually, these bubbles produce the stochastic GW background in the Universe through the processes of scattering, turbulence and acoustic shock waves.

From the perspective of observations, the energy scale, or equivalently, the temperature of the FOPT is crucial for the possible detection in various astronomical instruments. It determines the characteristic frequency window of GWs. For instance, for phase transitions that occurred around $100\,\mathrm{GeV} \sim 1\,\mathrm{TeV}$, the GW signal is peaked within the range of $1 \sim 10\,\mathrm{mHz}$ [4–13]. This region of frequencies will be experienced by the next generation of interferometers, including LISA, U-DECIGO and BBO [14–16]. Theoretical models associated with a FOPT with the energy scale at about $100\,\mathrm{GeV} \sim 1\,\mathrm{TeV}$ were recently discussed in Refs. [17–24,23,25–34]. It is interesting to note that, for this type of dark FOPT arisen from DM models, the energy scale is theoretically allowed to be much lower than the above regime, and thus, the corresponding GW signals would become elusive for GW interferometers. For example, the energy spectra of GWs generated from the MeV-ish or keV-

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ish FOPT are peaked within $10^{-6} \sim 10^{-3}$ mHz, which is out of the scope of the current GW interferometers, including LIGO/VIRGO, LISA, U-DECIGO, BBO and so on.[1]

In this article we report a completely new paradigm, that DM models with a dark FOPT occurred at low energy scale, which are in the blind zone of the GW interferometers, are able to be tested by radio telescopes. In light of early works on radio astronomy [36–42], it is acknowledged that GW signals within the frequency range of $10^{-9} \sim 10^{-7}$ Hz are detectable by virtue of Pulsars timing data. Using this effect we can probe the DM models that can give rise to FOPTs within the energy scale range of $10^{-1} \sim 10$ keV. To demonstrate this phenomenon, we specifically consider a type of Majoron DM scenario in which a FOPT is naturally envisaged for the extremely low frequency range.

In particle physics, Majorons are a hypothetical type of pseudo-Nambu–Goldstone boson originated from a spontaneous symmetry breaking of a global $U(1)_L$ or $U(1)_{B-L}$ symmetry by extending the gauge group of the Standard Model (SM). It belongs to a complex scalar singlet that is coupled to a Majorana neutrino operator. After the spontaneous symmetry breaking, a Majorana mass for the neutrino is generated[2] [47–49]. As shown in [50], a Majoron is possible to be coupled with visible matter very weakly and its mass could be of the keV-ish scale, and hence, it can be viewed as a good candidate of warm DM [50,51]. A variety of cosmological bounds can be imposed on the Majoron models, considering that the spontaneous symmetry breaking scale of $B-L$ and L shall be higher than the electroweak vacuum expectation value (*vev*). Compatible with pre-sphaleron baryogenesis models, the Majoron couplings to visible matter are highly constrained if the $B-L$ scale is higher than the electroweak scale [52–56]. On the other hand, from the Majoron overproduction bounds, stringent constraints can be overimposed on the Majoron models with a $B-L$ phase transition higher than the 10 TeV scale [50]. Intriguingly, a sub-electroweak phase transition can delicately avoid the aforementioned cosmological bounds. An open possibility left is that such a phase transition is a first order one. In this case, a FOPT within $0.1 \sim 10$ keV is achieved straightforwardly and becomes dark since it is almost invisible in colliders.

This article is organized as follows. In Sec. 2 we briefly describe the theoretical model of the Majoron field in which the Higgs boson is also included. Then, in Sec. 3 we study in detail the GW signals generated from the FOPT achieved by the Majoron type of dark matter model case by case. Sec. 4 is devoted to a summary of the main results accompanied with a discussion. We provide the GW energy spectra as well as the associated characteristic frequency scales due to the bubble collisions, sound waves and turbulence effects in the appendix section, respectively.

2. The model

We consider an extension of the SM characterized by the gauge groups $SU_c(3) \times SU(2)_L \times U(1)_Y$ and an extra global symmetry $U(1)_{B-L}$. In this model the lepton and baryon numbers are encoded in a new $U(1)_{B-L}$ global symmetry. A complex scalar field coupled to neutrinos and to the Higgs boson via the potential

$$V_{tot} = f H \bar{L} \nu_R + h\sigma \bar{\nu}_R \nu_R^c + h.c. + V(\sigma, H)\,,$$

h and f being Yukawa matrices of the model, spontaneously breaks the $U(1)_L$ symmetry. The potential $V(\sigma, H)$ is responsible for the *vev* of the scalar singlet σ, *i.e.* $\langle\sigma\rangle = v_{BL}$, and triggers the generation of a Majorana mass term $\mu\,\bar{\nu}_R\nu_R + h.c.$, where $\mu = h v_{BL}$ (see [31] for details). The scalar sector of the model is contributed by the new scalar singlet σ, containing the Majoron field in its imaginary part, and by the Higgs boson. Thus, the scalar potential can be organized as

$$V(\sigma, H) = V_0(\sigma, H) + V_1(\sigma) + V_2(\sigma, H)\,,$$

where

$$\begin{aligned} V_0(\sigma, H) =& \lambda_s \left(|\sigma|^2 - \frac{v_{BL}^2}{2}\right)^2 + \lambda_H \left(|H|^2 - \frac{v^2}{2}\right)^2 \\ &+ \lambda_{sH}\left(|\sigma|^2 - \frac{v_{BL}^2}{2}\right)\left(|H|^2 - \frac{v^2}{2}\right)\,, \end{aligned}$$

and $V_{1,2}$ are higher order effective operators that are expected to trigger the FOPT.

We analyze below two possibilities: *i)* the FOPT is triggered by five-dimensional (5-d) effective operators that break the $U(1)_{B-L}$ symmetry; *ii)* 5-d operators are suppressed, and instead the FOPT is triggered by the six-dimensional (6-d) interactions. For the first case, the 5-d operators can be expressed as

$$\begin{aligned} V_1^{(5)}(\sigma) =& \frac{\lambda_1}{\Lambda}\sigma^5 + \frac{\lambda_2}{\Lambda}\sigma^*\sigma^4 + \frac{\lambda_3}{\Lambda}(\sigma^*)^2\sigma^3 + h.c\,, \\ V_2^{(5)}(\sigma, H) =& \frac{\beta_1}{\Lambda}(H^\dagger H)^2\sigma + \frac{\beta_2}{\Lambda}(H^\dagger H)\sigma^2\sigma^* \\ &+ \frac{\beta_3}{\Lambda}(H^\dagger H)\sigma^3 + h.c.\,; \end{aligned}$$

while, for the latter one, the 6-d operators are given by

$$\begin{aligned} V_1^{(6)}(\sigma) =& \frac{\gamma_1}{\Lambda^2}\sigma^6 + \frac{\gamma_2}{\Lambda^2}\sigma^*\sigma^5 + \frac{\gamma_3}{\Lambda^2}(\sigma^*)^2\sigma^4 \\ &+ \frac{\gamma_4}{\Lambda^2}(\sigma^*)^3\sigma^3 + h.c.\,, \end{aligned} \tag{1}$$

$$\begin{aligned} V_2^{(6)}(\sigma, H) =& \frac{\delta_1}{\Lambda^2}(H^\dagger H)^2\sigma^2 + \frac{\delta_2}{\Lambda^2}(H^\dagger H)^2\sigma^*\sigma \\ &+ \frac{\delta_3}{\Lambda^2}(H^\dagger H)\sigma^3\sigma^* + \frac{\delta_4}{\Lambda^2}(H^\dagger H)(\sigma\sigma^*)^2 \\ &+ \frac{\delta_5}{\Lambda^2}(H^\dagger H)\sigma^4 + h.c.\,. \end{aligned} \tag{2}$$

In principle, the energy scales of the new physics entering the non-perturbative operators may differ from each other. For convenience, we parameterize their differences with the couplings λ_i, β_i, γ_i and δ_i. One may also consider the case of $B-L$ preserving effective operators, which would entail all the operators introduced in Eqs. (1) and (2) to be hyper-selected. As a result, only 6-d operators remain and are associated with the parameters γ_4, δ_2 and δ_4.

3. Gravitational waves signal from Majoron DM

A spontaneous symmetry breaking of the $U(1)_{B-L}$ can induce a FOPT in the early Universe. This phenomenon can generate vacuum bubbles expanding at relativistically high velocities, and can in turn induce a stochastic background of gravitational radiation. GW are produced via three main processes, i.e. bubble–bubble collisions, turbulence induced by the bubbles' expansions in the cosmic plasma, and sound waves induced by the bubbles' running though the plasma. These three contributions are directly related to the thermally corrected effective potential. Specifically, the energy spectrum of GW produced during the collision of two

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[1] It is interesting to note that, the QCD FOPT can also lead to GW spectra peaked at low frequency range, for instance see Ref. [35].

[2] Implications of the Majoron in neutron–antineutron transitions were discussed recently [43–46].