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Gravitational waves as a new probe of Bose–Einstein condensate Dark Matter

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ABSTRACT

There exists a class of ultralight Dark Matter (DM) models which could form a Bose–Einstein condensate (BEC) in the early universe and behave as a single coherent wave instead of individual particles in galaxies. We show that a generic BEC-DM halo intervening along the line of sight of a gravitational wave (GW) signal could induce an observable change in the speed of GWs, with the effective refractive index depending only on the mass and self-interaction of the constituent DM particles and the GW frequency. Hence, we propose to use the deviation in the speed of GWs as a new probe of the BEC-DM parameter space. With a multi-messenger approach to GW astronomy and/or with extended sensitivity to lower GW frequencies, the entire BEC-DM parameter space can be effectively probed by our new method in the near future.

1. Introduction

Although the existence of Dark Matter (DM) constituting about 27% of the energy budget of our Universe [1] is by now well established through various cosmological and astrophysical observations, very little is known about its particle nature and interactions. While the standard ΛCDM model with collisionless cold DM (CDM) successfully explains the large-scale structure formation by the hierarchical clustering of DM fluctuations [2,3], there are some unresolved issues on galactic and sub-galactic scales, such as the core-cusp [4–7], missing satellite [8–11], and too big to fail [12–14] problems. All these small-scale structure anomalies can in principle be resolved if the DM is made up of ultralight bosons that form a Bose–Einstein condensate (BEC), i.e. a single coherent macroscopic wave function with long range correlation; for a review, see e.g., Ref. [15].

There are two classes of BEC-DM, depending on whether DM self interactions are present or not. Without any self interactions, the quantum pressure of localized particles is sufficient to stabilize the DM halo against gravitational collapse only for a very light DM with mass $m \sim 10^{-22}$ eV [16–21], whereas a small repulsive self-interaction can allow a much wider range of DM masses up to $m \lesssim 1$ eV [22–26].[1] Concrete particle physics examples for BEC-DM are WISPs (Weakly Interacting Slim Particles) [33], which include the QCD axion or axion-like particles [34–42] and hidden-sector gauge bosons [43–46] ubiquitous in string theories, but our subsequent discussion will be generically applicable to any BEC-DM with a repulsive self-interaction, which is necessary to obtain long-range effects [41].[2]

The observational consequences on structure formation mentioned above cannot distinguish a BEC-DM from an ordinary self-interacting DM [48]. Existing distinction methods include enhanced integrated Sachs–Wolfe effect [34], tidal torquing of galactic halos [42,49,50], and effects on cosmic microwave background matter power spectrum [51,52]. We propose a new method to probe the BEC-DM parameter space using gravitational wave (GW) astronomy, inspired by the recent discovery of transient GW signals at LIGO [53,54]. We show that if GWs pass through a BEC-DM halo on their way to Earth, the small spacetime distortions associated with them could produce phononic excitations in the BEC

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[1] BEC configurations with heavier DM and/or an attractive self-interaction are usually unstable against gravity [27] and more likely to form local dense clumps such as Bose stars [28–32], unless the thermalization rate is faster than the Hubble rate to overcome the Jeans instability.

[2] Although the simplest models, where the scalar potential has an approximate symmetry to ensure the radiative stability of the ultralight scalar, usually give rise to an attractive self-interaction in the non-relativistic limit, it is possible to have realistic models with repulsive self-interaction [26,47].

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medium which in turn induce a small but potentially observable change in the speed of GWs, while the speed of light remains unchanged. This approach is very effective if any of the future multi-messenger searches for gamma-ray, optical, X-ray, or neutrino counterparts to the GW signal become successful. On the contrary, a lack of any observable deviation in the speed of GWs will put stringent constraints on the BEC-DM scenario. In fact, we find that even with the current LIGO sensitivity, it might be possible to partly rule out the BEC-DM parameter space otherwise preferred by existing cosmological data. Future GW detectors such as eLISA [55] with extended sensitivity to lower GW frequencies will be able to completely rule out the cosmologically preferred region.

The rest of the paper is organized as follows: in Section 2, we calculate the change in the speed of GWs due to energy loss inside the BEC medium. In Section 3, we apply this result to derive constraints on the BEC-DM parameter space. In Section 4, we discuss the effect of gravitational lensing. Our conclusions are given in Section 5.

2. Speed of GW inside BEC medium

The cosmological dynamics of BEC-DM can be described by a single classical scalar field ϕ [56], with the effective Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - \lambda\phi^4 \,, \tag{1}$$

analogous to the Ginzburg–Landau free energy density in a neutral superfluid. A real scalar field will suffice for our discussion. In (1), we have considered a simple renormalizable scalar potential with only quadratic and quartic terms, the latter providing a repulsive self-interaction for the DM, as required in addition to the quantum pressure of localized particles to stabilize the DM halo core against gravitational collapse. For no self-interaction ($\lambda = 0$), the quantum pressure is sufficient only if $m \sim 10^{-22}$ eV, a scenario known as fuzzy DM [18]. In principle, we could also have added a cubic term $-g\phi^3$ to (1); however, for the self-interaction to be repulsive in the non-relativistic limit, we must have $\lambda > 5g^2/2$ [26]. Similarly, we do not include any higher-dimensional operators in (1).

Using (1), we calculate the stress-energy tensor

$$T^{\mu\nu} = \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}\partial^\nu\phi - g^{\mu\nu}\mathcal{L} \,, \tag{2}$$

where $g^{\mu\nu}$ is the spacetime metric. Far from the GW source, the linearized spacetime metric can be written as $g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$, where $\eta = \mathrm{diag}(1,-1,-1,-1)$ is the flat Minkowski metric (in particle physics conventions) and $h^{\mu\nu}$ is a small perturbation. To leading order, the background mean field values of the energy density $\rho_0 \equiv T^{00}$ and pressure $p_0 \equiv T^{ii}$ of the BEC medium are related by the equation of state (EoS)

$$p_0 = \frac{3}{2}\frac{\lambda}{m^4}\rho_0^2 \,. \tag{3}$$

Gravity is a long-range force. Because almost all particles in the BEC system are condensed into the lowest energy available state with very long de Broglie wavelength, the GWs can excite the massless phonon modes in the ground state of the BEC wave function [57]. As a result, the GW undergoes enhanced coherent forward scattering inside a BEC-DM halo compared to an ordinary CDM halo. This effect is analogous to light traveling through an optically transparent medium (e.g. glass) with refractive index different from 1. In general, there could be either refraction or absorption of the incident wave (apart from reflection), depending on the real or imaginary part of the refractive index, respectively. The refraction effect modifies the wavenumber and propagation speed of the wave in the medium (without change in its frequency and amplitude), while absorption results in the damping of the amplitude, and hence, attenuation of the wave in the medium. In the case of GWs incident on a BEC medium, the absorption effect is negligible, because it would require exciting the phonons from massless to massive modes, which in turn requires much larger energy comparable to the chemical potential of the BEC [57]. Thus, only the propagation speed of the GW passing through a BEC-DM halo is reduced, but much more strongly than in a CDM halo, as we show below.

To estimate this effect, we first write down the effective metric of the BEC phononic excitations on the flat spacetime metric [57–59]

$$g_{\rm eff} = \frac{n_0^2}{c_s(\rho_0 + p_0)}\mathrm{diag}(c_s^2, -1, -1, -1) \,, \tag{4}$$

where $n_0 \equiv \rho_0/m$ is the number density of the background mean field and

$$c_s \equiv \left(\frac{\partial p_0}{\partial \rho_0}\right)^{1/2} = \left(\frac{3\lambda\rho_0}{m^4}\right)^{1/2} \tag{5}$$

is the speed of sound obtained from the background EoS (3). The solution to the Klein–Gordon equation with the metric in (4) thus describes massless excitations propagating with the speed c_s. The frequency of the mode satisfies the linear dispersion relation $\omega_k = c_s|\mathbf{k}|$, where $\mathbf{k}$ is the 3-momentum of the mode.

The refractive index of a GW scattering off a gravitational potential was first calculated in [68] and was shown to be negligibly small for ordinary matter. Here, we provide an alternative derivation of the refractive index based on the optical theorem and argue that it could be relevant in our case due to the enhanced forward scattering rate in a BEC medium. The optical theorem links the refractive index n_g to the forward scattering amplitude $f(0)$ of the incident wave with the scatterers inside the medium:

$$n_g = 1 + \frac{2\pi n f(0)}{k^2} \,, \tag{6}$$

with n the number density of scatterers inside the medium and k the wavenumber of the incident wave. We estimate the forward scattering $nf(0)$ of the GW in the BEC-DM halo by relating the energy density of the incident GW to the energy density of the massless phonon excitations in the ground state.

We assume for simplicity that the phonons can be described by a one-dimensional wave function with hard-wall boundary conditions. This approximation is also valid for a spherically-symmetric DM halo, such that only the radial component matters for the GW propagation through it. The energy spectrum of the massless modes is then given by

$$\omega_l = \frac{l\pi c_s}{\langle D_{\rm halo}\rangle} \,, \tag{7}$$

where $\langle D_{\rm halo}\rangle = 4R/\pi$ is the average distance the gravitational wave propagates through the spherically-symmetric DM halo with a radius R and $l \in \{1, 2, \cdots\}$. Therefore, the *minimum* energy density required to excite the massless phonon modes in the BEC medium is given by

$$\Delta\rho \equiv n\Delta\omega = \frac{n\pi^2 c_s}{4R} \,, \tag{8}$$

where n is the number density of phonons in the BEC and $\Delta\omega \equiv \omega_{l+1} - \omega_l$ is the energy difference between two adjacent massless modes [cf. (7)].

The radius R of the gravitationally bound BEC with a repulsive self-interaction only depends on the physical characteristics of the particles in the condensate [60–62]:

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