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Gravitational radiation background from boson star binaries

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ABSTRACT

We calculate the gravitational radiation background generated from boson star binaries formed in locally dense clusters with formation rate tracked by the regular star formation rate. We compute how the frequency window in gravitational waves is affected by the boson field mass and repulsive self-coupling, anticipating constraints from EPTA and LISA. We also comment on the possible detectability of these binaries.

1. Introduction

The recent detection of gravitational waves (GW) by LIGO and VIRGO have opened up a new window for our understanding of the physical properties of the universe [1]. Probing the energy density of the stochastic Gravitational Wave Background (GRB) formed by the superposition of a large number of individual gravitational wave merger events is a long term goal of the next generation of GW detectors. It is thus of great interest to investigate different potential sources of GRBs and how to distinguish between their potential observational signatures. In this letter, we compute the GRB of an important class of hypothetical objects, merging binaries of Exotic Compact Objects (ECOs) composed of self-interacting scalar field configurations known as boson stars (BSs). Such objects were first proposed in the late 1960s [2] and further studied in the 1980s and 1990s [3–6], but are now experiencing a revival due to their potential role as dark matter candidates [7] and as remnants of early universe physics [8]. The gravitational wave production from individual events of the merger of two boson stars has been studied in [9] and [10], for example. A preliminary estimate of the GRB in boson-star binary mergers was given in [11].

The success of inflationary cosmology [12] and the discovery of the Higgs Boson [13] [14] have opened up the possibility that different self-interacting scalar fields might exist in nature. The presence of such fundamental scalar fields in the early universe, maybe in dark matter clusters, could have led to their condensation into self-gravitating compact objects [15–17]. It is quite remarkable that for a repulsive self-interaction $\lambda|\phi|^4$ and a scalar field mass m, such objects have masses $M_{\rm BS} \sim \sqrt{\lambda} M_{\rm Pl}^3/m^2$, which, for $m/\lambda^{1/4} \sim m_p$, where m_p is the proton mass, are parametrically equivalent to the Chandrasekhar mass [18].

Indeed, even a free, massive scalar field can generate a self-gravitating object, supported against gravitational collapse solely by quantum uncertainty [2]. This distinguishes them from fermionic compact objects such as neutron stars (NS) and white dwarfs, which are prevented from collapse due to degeneracy pressure [19]. Another key difference, important observationally to distinguish the two classes of compact objects, is that the simplest BSs do not radiate electromagnetically.

Given the uncertainty in the details of BS formation, and to provide a more general analysis, we assume here that BSs were formed at a rate that tracks the regular star formation rate, in locally-dense dark matter clusters. We will thus adopt this initial range of redshifts as a benchmark for our analysis. Our results can be extended to arbitrarily large redshifts.

As with their fermionic counterparts, BSs have a critical maximum mass against central density beyond which they are unstable to gravitational collapse into black holes (BHs) [3,20]. In this paper, we treat the two stars in the binary BS system as having the same maximum mass and radius, which leads to the two objects having the same compactness, defined as $C = G_N M/R$. The GRB is typically characterized by the dimensionless quantity $\Omega_{\rm GW}(f)$, the contribution in gravitational radiation in units of the critical density in a frequency window f and $f + \delta f$ to the total energy-density of the universe in a Hubble time. By studying their gravitational imprints, we hope to gain insight on the properties

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of these exotic objects, expanding the results of [11] and bringing them closer to current and planned observations.

2. Boson star properties

2.1. Isolated boson stars

Very light bosons could form a Bose–Einstein condensate (BEC) in the early or late universe through various mechanisms [15–17]. Such objects are macroscopic quantum states that are prevented from collapsing gravitationally by the Heisenberg uncertainty principle in the non-interacting [2] and attractive self-interaction case [15], or, in another possibility, through a repulsive self-interaction that could balance gravity's attraction [18]. In this Letter, we study an Einstein–Klein–Gordon system with the following Lagrangian,

$$\mathcal{L} = \sqrt{-g}\left[|(\partial\phi)|^2 - m^2|\phi|^2 - \frac{1}{2}\lambda|\phi|^4\right], \tag{1}$$

where ϕ is a complex scalar field carrying a global $U(1)$. Real scalar fields can also form gravitationally-bound states, but these are time-dependent and have different properties [21]. Colpi et al. showed that the maximum mass of a spherically-symmetric BS with repulsive self-interaction is given by [18]

$$M_*^{max} \sim \frac{0.22\, M_p^2\, \alpha^{1/2}}{m} \approx \frac{0.06\sqrt{\lambda} M_p^3}{m^2}, \tag{2}$$

where the rescaled coupling α is defined as $\alpha \equiv \lambda M_p^2/(4\pi\, m^2)$. For a boson star with a repulsive self-interaction, the radius can be estimated to be

$$R_* \sim \frac{\sqrt{\lambda}}{\sqrt{G_N} m^2}. \tag{3}$$

The compactness of boson stars is discussed in many references such as [22,7]. We note that the compactness and mass of the stars are especially relevant for binary GW events. Different formation mechanisms have been discussed in Refs. [15–17]. However, since we are focussing here on the gravitational radiation background, we need not worry about specific formation mechanisms that lead to highly compact BSs. We will assume they exist and compute their contribution to the GRB. We also note that if one assumes the complex scalar ϕ to be responsible for the dark matter in the Bullet Cluster, Ref. [23] shows that the constraint on the dark matter cross section [24–26] can be translated into a bound on the boson's self-coupling, because the relative velocity of the Bullet Cluster is higher than the sound speed of the condensate. The translated bound on the self-interaction strength is

$$\lambda \lesssim 10^{-11}\left(\frac{m}{\text{eV}}\right)^{3/2}. \tag{4}$$

We note in passing that Ref. [23] shows that BEC requires light scalars $m < 1$ eV. However, the bound is based on the inter-particle spacing estimated from the average density of dark matter in the Universe. Since in the absence of a fundamental theory the exact formation process of boson stars remain unclear, we consider the possibility of their formation due to a large local density fluctuation. Therefore, we do not worry about the bound on the scalar mass. In what follows, we saturate the Bullet Cluster bound and parametrize the boson star mass effectively as

$$M_* = x M_*^{max} = 3.1\times 10^{11}\, x \left(\frac{\text{eV}}{m}\right)^{5/4} M_\odot, \tag{5}$$

where x is the fraction between boson star mass and the maximum stable mass, and the radius will be given by,

$$R_* = y\frac{\sqrt{\lambda}}{\sqrt{G_N} m^2} = 1.1\times 10^7\, y \left(\frac{\text{eV}}{m}\right)^{5/4} R_\odot, \tag{6}$$

where y is the fraction or multiple of the star radius from Eq. (3). From Eqs. (5) and (6) we obtain the compactness of these boson stars as

$$C_* = \frac{G_N M_*}{C_*} = 0.06 \times \left(\frac{x}{y}\right). \tag{7}$$

2.2. Boson star binaries

We briefly describe the properties of boson star binaries that are relevant for the calculation of gravitational radiation. In what follows, we assume a conservative model for the estimation of the binary formation rate, which tracks the star formation rate (SFR) of luminous stars. Empirically, the luminous star-formation rate can be parametrized as a function of redshift z and stellar mass M [27], in units of $\text{yr}^{-1}\,\text{Mpc}^{-3}$ as

$$\text{SFR}(z, M) = \text{SFR}_0 \left(\frac{M_\odot}{M}\right) \frac{a\, e^{b(z-z_m)}}{a - b + b\, e^{a(z-z_m)}}. \tag{8}$$

The parameters SFR_0, z_m, a, and b are all determined by fitting to observations such as gamma-ray burst rates and the galaxy luminosity function. We adopt the fit from gamma-ray bursts from [28]. We further parameterize the efficiency of the binary boson star formation as a fraction of $\text{SFR}(z, M)$, denoted as $f_{\text{BBS}} \leq 1$. We stress that this effective parametrization does not assume a specific boson star formation mechanism nor a similarity between that and luminous star formation. The boson star binary formation rate is, for a boson star of mass M_* and formation redshift z_f,

$$R_{\text{BBS}}(z_f, M_*) = f_{\text{BBS}} \times \text{SFR}(z_f, M_*). \tag{9}$$

Since we do not need all of the binaries to survive today to leave their gravitational radiation imprint, we calculate the merger rate at redshift z, which is mainly determined by the binary formation rate at redshift z_f. On the other hand, the larger the binary separation at formation, the less likely they would have successfully merged, due to gravitational perturbations from other sources. Following Ref. [29], we use an appropriately normalized weight function $p(\Delta t)$ to account for the merger efficiency, where Δt is the time delay from formation of the binary to coalescence,

$$R_m(t, M_*, f_{\text{BBS}}) = \int_{\Delta t_{min}}^{\Delta t_{max}} R_{\text{BBS}}(t - \Delta t, M_*)\, p(\Delta t)\, d\Delta t. \tag{10}$$

Here, Δt_{min} is the minimum time between formation and coalescence, and Δt_{max} is determined by the maximum initial separation which allows for binary formation. As we will see below, the result is not sensitive to the precise choice of Δt_{max}. We will comment on a suitable Δt_{min} for this integral in the following section. We relate redshift to cosmic time with the approximate formula from Ref. [30],

$$t(z) = \frac{2/H_0}{1 + (z+1)^2}, \tag{11}$$

where H_0 is the Hubble constant today. Next, let us estimate $p(\Delta t)$. For a pair of stars A and B, their initial separation a defines a sphere inside which the number of stars is $N(a) = \rho\pi a^3/6$.