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Transmuted gravity wave signals from primordial black holes

Volodymyr Takhistov

Department of Physics and Astronomy, University of California, Los Angeles, Los Angeles, CA 90095-1547, USA

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ABSTRACT

Primordial black holes (PBHs) interacting with stars in binaries lead to a new class of gravity wave signatures that we explore. A small 10^{-16}–$10^{-7} M_\odot$ PBH captured by a neutron star or a white dwarf will eventually consume the host. The resulting black hole will have a mass of only ~ 0.5–$2.5 M_\odot$, not expected from astrophysics. For a double neutron star binary system this leads to a transmutation into a black hole–neutron star binary, with a gravity wave signal detectable by the LIGO-VIRGO network. For a neutron star–white dwarf system this leads to a black hole–white dwarf binary, with a gravity wave signal detectable by LISA. Other systems, such as cataclysmic variable binaries, can also undergo transmutations. We describe gravity wave signals of the transmuted systems, stressing the differences and similarities with the original binaries. Correlating astrophysical phenomena, such as a double kilonova, can further help to distinguish these events. This setup evades constraints on solar mass PBHs and still allows for PBHs to constitute all of the DM. A lack of signal in future searches could constrain PBH parameter space.

1. Introduction

Primordial black holes (PBHs) can appear from early Universe dynamics and can account for all or part of the dark matter (DM) [1–14]. Null results in experimental searches for conventional DM particle candidates as well as the recent discovery of gravitational waves (GW) by the LIGO-VIRGO network [15–17] have led to reinvigorated interest in PBHs, as it was pointed out [18–20] that they could contribute to the observed GW signal (possible relevance of PBHs to GWs has been mentioned even earlier, e.g. [21–24]).

Primary signals expected [25] in ground-based GW detectors like LIGO originate from neutron star – neutron star (NS-NS), neutron star – black hole (NS-BH) as well as black hole – black hole (BH-BH) binary mergers. Multiple BH-BH mergers have already been observed [15–17]. Recently, a NS-NS GW signal GW170817 along with accompanying electromagnetic emission has also been detected [26,27]. The upcoming space-based LISA experiment [28] will allow for GW searches in the lower frequency domain, relevant, among others, for signals associated with white dwarf (WD) binaries. The onset of GW astronomy has motivated a series of recent studies [29,30,19] on PBH merger signals as well. Considered PBHs, assumed to be primary binary components (i.e. PBH–PBH mergers), typically lie within the $\simeq 5$–$100\, M_\odot$ mass range that is relevant for LIGO stellar-mass BH merger signals. Solar mass PBHs [31] could also participate in mergers [21].

The smallest known BHs reside in the ~ 5–$10 M_\odot$ range [32] (see [33] for mass distribution). In general, astrophysical BHs are not expected to have mass below the $2 \lesssim M_{\rm TOV}/M_\odot \lesssim 2.2$ boundary set by the Tolman–Oppenheimer–Volkoff stability limit $M_{\rm TOV}$ for non-rotating neutron stars [34,35], with the lower cut-off coming from pulsar observations [36]. Uniform rotation allows for the maximum supported mass to reach $1.2\, M_{\rm TOV} (\simeq 2.6 M_\odot)$ [37]. Above this limit the star collapses to a black hole (or hypothetically, a quark star [38]). While for WDs the Chandrasekhar limit imposes a $\simeq 1.4 M_\odot$ stability bound that is lower, the expected result is a type Ia supernova explosion without a compact remnant [39] (although, accretion-induced collapse results in a neutron star [40]). It is possible, however, to naturally produce $\simeq 0.5$–$2.5 M_\odot$ BHs from compact stars that have captured a small PBH.

In this *Letter* we explore how novel GW signatures from binaries with atypical solar mass BHs can act as probes of tiny PBHs constituting DM. If a $10^{-16} \lesssim M_{\rm PBH}/M_\odot \lesssim 10^{-7}$ PBH interacts and is captured by a compact star (NS or WD), it will eventually consume the host [41]. For neutron stars, this scenario implies that corresponding binaries will be "transmuted" into binaries with a $\simeq 1.2$–$2.5 M_\odot$ BH instead of the NS, where the lower mass bound comes from observations [42] and theoretically could be far smaller [43,44]. Similarly, a "transmuted" white dwarf, which could be part of an interacting cataclysmic variable binary with a white dwarf or a main sequence (MS) star companion, will result

E-mail address: vtakhist@physics.ucla.edu.

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in a $\simeq 0.5$–$1.4 M_\odot$ BH. What can the GW signals and accompanying counterparts from such systems tell us about PBHs?

2. Black hole capture

The capture rate of PBHs on NS can be estimated following [41] and depends on the PBH mass $M_{\rm PBH}$, DM density $\rho_{\rm DM}$ and velocity dispersion $\overline{v}$ (assumed to follow Maxwellian distribution). The full capture rate is given by $F = (\Omega_{\rm PBH}/\Omega_{\rm DM}) F_0$, where $\Omega_{\rm PBH}$ is the PBH contribution to the overall DM abundance $\Omega_{\rm DM}$. Here, F_0 is the base NS capture rate in Milky Way Galaxy (MW) and is given by

$$F_0 = \sqrt{6\pi}\,\frac{\rho_{\rm DM}}{M_{\rm PBH}}\Big[\frac{R_{\rm NS} R_s}{\overline{v}(1 - R_s/R_{\rm NS})}\Big]\Big(1 - e^{-E_{\rm loss}/E_b}\Big)\,, \qquad (1)$$

where $E_b = M_{\rm PBH}\overline{v}^2/3$, $R_{\rm NS}$ is radius of the NS with mass $M_{\rm NS}$ and Schwarzschild radius $R_S = 2GM_{\rm NS}$. Convention $c = 1$ is used throughout. PBH will be captured if the interaction energy loss $E_{\rm loss} \simeq 58.8\, G^2 M_{\rm PBH}^2 M_{\rm NS}/R_{\rm NS}^2$ exceeds its initial kinetic energy [41]. We assume that a typical NS is described by $R_{\rm NS} = 10$ km and $M_{\rm NS} = 1.5 M_\odot$ [45]. In NS-NS binaries the system mass, and hence the interaction rate, is twice that of a single NS. In the case of WD, the star mass $M_{\rm WD} \sim 1 M_\odot$ is lower, but the radius $R_{\rm WD} \sim 10^3$ km is drastically larger [45]. This leads to suppression of $E_{\rm loss}$ and the resulting WD capture rate is several orders below that of NS. The total number of PBHs captured by a NS is given by Ft, where t is the relevant interaction time.

Once gravitationally captured, PBH will settle inside the star and grow via Bondi spherical accretion [41,46,47,45]. For typical NS, the time for captured PBH to settle within the star is [41] $t_{\rm set}^{\rm NS} \simeq 9.5 \times 10^3 (M_{\rm PBH}/10^{-11} M_\odot)^{-3/2}$ yrs. For WDs we find that $t_{\rm set}^{\rm WD} \simeq 6.4 \times 10^6 (M_{\rm PBH}/10^{-11} M_\odot)^{-3/2}$ yrs. Once settled inside, the Bondi accretion time for BH to consume the star is given by $t_{\rm con} = v_s^3/4\pi\lambda_s G^2 \rho_c M_{\rm PBH}$, where v_s is the sound speed, ρ_c is the central density and $\lambda_s = 0.707$ is the density profile parameter (for a star described by an $n = 3$ polytrope). For NS with $\rho_c = 10^{15}$ g/cm^3 and $v_s = 0.17$ the consumption time is $t_{\rm con}^{\rm NS} \simeq 5.3 \times 10^{-3} (10^{-11} M_\odot/M_{\rm PBH})$ yrs. For WD with $\rho_c = 10^8$ g/cm^3 and $v_s = 0.03$ (consistent with [48]) the consumption time is $t_{\rm con}^{\rm WD} \simeq 2.9 \times 10^2 (10^{-11} M_\odot/M_{\rm PBH})$ yrs. Hence, a PBH of mass $\gtrsim 10^{-11} M_\odot$ captured by NS or WD will settle and consume the star within $\sim 10^6$ yrs. Since the binary population synthesis models [49–51] predict a typical merger time of $\sim 10^6$–10^{10} yrs, we can take the system to effectively contain a solar mass BH after the capture. Our conclusions are not significantly affected by the star's equation of state.

3. Binary transmutation

Several binary systems can have a transmuted NS: NS-NS, NS-BH and NS-WD. Using [$t_{\rm N}$] to denote the newly formed $\simeq 1.2$–$2.5 M_\odot$ BHs, the resulting binaries are: BH[$t_{\rm N}$]-NS, BH[$t_{\rm N}$]-BH and BH[$t_{\rm N}$]-WD. In the transmuted BH[$t_{\rm N}$]-BH system, the second (original) BH can in principle be of drastically larger size than BH[$t_{\rm N}$]. In an unlikely scenario, NS-NS can undergo two subsequent transmutations to a BH[$t_{\rm N}$]-BH[$t_{\rm N}$] binary containing two solar mass BHs. Similarly, several systems can have a transmuted WD. We denote such newly formed $\simeq 0.5$–$1.4\ M_\odot$ BHs with [$t_{\rm W}$]. The WD-NS, WD-WD, WD-MS binaries will produce BH[$t_{\rm W}$]-NS, BH[$t_{\rm W}$]-WD as well as BH[$t_{\rm W}$]-MS systems, respectively. In an improbable scenario WD-WD or NS-WD can undergo two subsequent transmutations, leading to a binary with two atypically small solar mass BHs. For the rest of this work we shall focus primarily on transmutation of NSs and NS-NS systems, which have the best understood GW signal.

Previously [52], we have shown that up to ~ 0.1–$0.5 M_\odot$ of neutron rich material could be ejected as a result of a PBH-NS interaction. Since the material escapes, the final transmuted black hole will be ~ 10–50% less massive than the parent neutron star and comparable in mass to a WD. This deviation, and hence the amount of ejecta, can be tested with the resulting GW signal.

4. Merger time

The binary systems are expected to merge due to gravitational wave emission within Galactic timescale (see [53–55] for review). For simplicity, we assume that the binary orbit is circular (eccentricity $e \simeq 0$). The merger time $\tau_{\rm mgr}$ for two point masses m_1 and m_2 with an orbital period $P_{\rm orb}$ is given, to a good approximation, by [56,57,55]

$$\tau_{\rm mgr} \simeq 4.8 \times 10^{10}\Big(\frac{P_{\rm orb}}{\rm day}\Big)^{8/3}\Big(\frac{\mu}{M_\odot}\Big)^{-1}\Big(\frac{M}{M_\odot}\Big)^{-2/3} {\rm yrs}\,, \qquad (2)$$

where $M = m_1 + m_2$ and $\mu = m_1 m_2/M$ is the reduced mass. Using Kepler's laws, the orbital period dependence can be exchanged for binary separation distance. Assuming that the relevant characteristics of the original system, such as the orbit eccentricity and star separation distance [49–51], persist for the transmuted binary, the merger time will stay intact. However, if significant amount of material is ejected from the parent star during the interaction, the merger time of the resulting binary will be visibly altered. For $0.5 M_\odot$ of material ejected from the NS, the merger time of the BH[$t_{\rm N}$]-NS system will be $\sim 40\%$ larger than that of the original NS-NS.

5. Gravity wave signal

The general features of the resulting merger GW signals can be stated as follows [53–55]. The GW luminosity, which describes the energy loss due to gravitational radiation, is given by

$$L_{\rm GW} = -\frac{dE_{\rm GW}}{dt} = \Big(\frac{32}{5}\Big) G^{7/3} (\mathcal{M}_c \pi f_{\rm GW})^{10/3}\,, \qquad (3)$$

where $f_{\rm GW} = 2/P_{\rm orb}$ is the frequency of the emitted GWs and $\mathcal{M}_c = \mu^{3/5} M^{2/5}$ is the "chirp mass". For a non-zero binary eccentricity, luminosity will also include contributions from higher GW harmonics luminosity [56]. The time variation of the GW frequency is

$$\dot{f}_{\rm GW} = \Big(\frac{96}{5}\Big) G^{5/3} \pi^{8/3} \mathcal{M}_c^{5/3} f_{\rm GW}^{11/3}\,. \qquad (4)$$

Averaging over the period and orientations, the "characteristic" GW strain amplitude is given by

$$h = 1.5 \times 10^{-21}\Big(\frac{f_{\rm GW}}{10^{-3}\,{\rm Hz}}\Big)^{2/3}\Big(\frac{\mathcal{M}_c}{M_\odot}\Big)^{5/3}\Big(\frac{D}{\rm kpc}\Big)^{-1}\,, \qquad (5)$$

where D is the distance to the source. Assuming that the relevant system quantities do not change, we conclude that the general GW features of the transmuted binaries will resemble the original systems. As with merger time, significant mass ejection from PBH-star interaction will result in observable discrepancies. A $0.5 M_\odot$ mass ejection will produce a $\sim 20\%$ smaller chirp mass, leading to a $\sim 30\%$ smaller signal strain.

Following the inspiral phase, as the binary separation drastically decreases and becomes comparable to few star radii in size the objects descend onto one another in a merger phase. For a NS-BH system this is the time instabilities occur and the NS can be