




# Establishing the Nonprimordial Origin of Black Hole–Neutron Star Mergers

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## Abstract

Primordial black holes (PBHs) from the early universe constitute attractive dark matter candidates. First detections of black hole–neutron star (BH–NS) candidate gravitational wave events by the LIGO/Virgo collaboration, GW200105 and GW200115, already prompted speculations about nonastrophysical origin. We analyze, for the first time, the total volumetric merger rates of PBH–NS binaries formed via two-body gravitational scattering, finding them to be subdominant to the astrophysical BH–NS rates. In contrast to binary black holes, a significant fraction of which can be of primordial origin, either formed in dark matter halos or in the early universe, PBH–NS rates cannot be significantly enhanced by contributions preceding star formation. Our findings imply that the identified BH–NS events are of astrophysical origin, even when PBH–PBH events significantly contribute to the gravitational wave observations.

*Unified Astronomy Thesaurus concepts:* Primordial black holes (1292); Cold dark matter (265); Neutron stars (1108); Gravitational wave astronomy (675); Gravitational wave sources (677); Gravitational waves (678)

## 1. Introduction

The initial breakthrough discovery of gravitational waves (GWs; Abbott et al. 2016) opened a new window for exploring astronomical, cosmological, as well as particle physics phenomena. Dozens of compact binary merger sources have already been observed by the LIGO/Virgo collaboration (LVC). The vast majority of these events are binary black holes (BH–BH) with components in the  $\sim 10$ – $100 M_{\odot}$  mass range (Abbott et al. 2021a). While a variety of conventional astrophysical stellar evolution channels could contribute to such events (see, e.g., Mandel & Farmer 2022; Mandel & Broekgaarden 2022 for reviews), comprehensive understanding of their origin is still lacking and could be connected with central puzzles of modern physics, such as the nature of dark matter (DM).

Intriguingly, GW observations are consistent with mergers of primordial black holes (PBHs) formed in the early universe prior to galaxy and star formation that can contribute to the DM abundance (e.g., Zel'dovich & Novikov 1967; Hawking 1971; Carr & Hawking 1974; Cotner et al. 2018, 2019; Sasaki et al. 2018; Kusenko et al. 2020). Depending on the formation mechanism, PBHs can span many orders of magnitude in mass. Binary PBH mergers are able to account for GW observations, such as the GW190521 event with a total merger mass of  $\sim 150 M_{\odot}$  lying in the pair-instability supernova mass gap (Abbott et al. 2020), which have challenged conventional astrophysical interpretations. In the mass ranges relevant for the current GW detectors, PBHs could contribute a sizable fraction of the DM energy density  $f_{\text{PBH}} = \Omega_{\text{PBH}}/\Omega_{\text{DM}}$  (e.g., Ali-Haïmoud & Kamionkowski 2017; Serpico et al. 2020; Lu et al. 2021;

Takhistov et al. 2022), with GW data suggesting  $f_{\text{PBH}} \lesssim \mathcal{O}(10^{-3})$  (e.g., Bird et al. 2016; Sasaki et al. 2016; Clesse & García-Bellido 2017; Franciolini et al. 2022), although uncertainties exist. The quest for identifying the origin of BH mergers is being advanced across several directions (e.g., Raccanelli et al. 2016; Cañas Herrera et al. 2020, 2021; De Luca et al. 2021; Hütsi et al. 2021; Mukherjee & Silk 2021).

Besides the binary BH GW events, detection of binary neutron star (NS–NS) mergers in GWs as well as electromagnetic signatures have spearheaded the investigations in multimessenger astronomy (Abbott et al. 2017a, 2017b). Without identification of clear electromagnetic counterpart signals or sufficient sensitivity to higher-order tidal deformability effects, distinguishing between a solar-mass BH and an NS is difficult. While solar-mass BHs are not expected from conventional stellar evolution, they can readily appear either as PBHs or “transmuted” BHs from small subsolar-mass PBHs (or particles) constituting DM being captured and devouring NSs (e.g., Capela et al. 2013; Fuller et al. 2017; Bramante et al. 2018; Takhistov 2018, 2019), leading to alternative interpretations of the detected NS merger events (e.g., Kouvaris et al. 2018; Tsai et al. 2021; Dasgupta et al. 2021; Takhistov et al. 2021).

Recently, LVC has reported first identified BH–NS binary GW events, GW200105 and GW200115, with component masses of  $(8.9^{+1.2}_{-1.5} M_{\odot}, 1.9^{+0.3}_{-0.2} M_{\odot})$  and  $(5.7^{+1.8}_{-2.1} M_{\odot}, 1.5^{+0.7}_{-0.3} M_{\odot})$ , respectively (Abbott et al. 2021b). In addition to the BH–BH and NS–NS mergers, BH–NS events constitute another major class of mergers and carry significant implications for multimessenger observations (Ruiz et al. 2021). While the detected events are consistent with stellar evolution formation channels (Broekgaarden & Berger 2021), speculations about possible PBH origin, considering that NSs are misidentified solar-mass BHs and detected events correspond to unequal mass PBH–PBH mergers, have already been put forth (Wang & Zhao 2022). As the number of detected events will significantly



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accumulate in the upcoming future and given their possible implications for fundamental physics, understanding their origin is a pressing matter. An essential ingredient for understanding the role of PBHs and DM in the context of BH–NS events is the contributions of PBH–NS mergers, which are thus far not comprehensively explored.

In this work we analyze, for the first time, the expected average merger rates of PBH–NS events formed in galaxies, conservatively considering that NSs have been properly identified. Unlike astrophysical BH–NS systems, purely stellar evolution formation channels are not available for PBH–NS binaries and we focus on their dynamical assembly. As we discuss, one of the essential differences with PBH–PBH binaries is that PBH–NS binaries must have been formed in the late universe, well after the onset of star formation.

## 2. PBH–NS Merger Rates

In order to find the total PBH–NS merger rate, we first consider an isolated galaxy and then discuss contributions from galaxy populations.

PBH–NS binaries are formed in galaxies via two-body scattering involving GW emission. We leave more complicated formation channels, such as three-body encounters, for future simulations. Some such effects have been studied in the context of binary black hole mergers (Kritos et al. 2021). We stress that the formation channel considered by us is the simplest, relying on minimal assumptions.

Upon approach of a PBH on a hyperbolic orbit to an NS within a critical impact parameter, the gravitational wave emission exceeds the initial kinetic energy and leads to formation of a bound PBH–NS system. The capture cross section for components of masses  $m_1$  and  $m_2$  is given by Quinlan & Shapiro (1989) and Mouri & Taniguchi (2002),

$$\sigma = 2\pi \left( \frac{85\pi}{6\sqrt{2}} \right)^{2/7} G_N^2 M^{12/7} \mu^{2/7} c^{-10/7} v_{\text{rel}}^{-18/7}, \quad (1)$$

where  $M = m_1 + m_2$ ,  $\mu = m_1 m_2 / M^2$ ,  $c$  is the speed of light,  $v_{\text{rel}}$  is the relative velocity between the components, and  $G_N$  is the gravitational constant.

In order to calculate the merger rate we need to establish the density overlap between NS and PBH distributions. For DM, including PBHs and particle DM, we assume the galactic halo profile to be given by the Navarro–Frenk–White (NFW) model (Navarro et al. 1996),

$$\rho_{\text{DM}}(r) = \rho_0 \left[ \frac{r}{R_s} \left( 1 + \frac{r}{R_s} \right)^2 \right]^{-1}, \quad (2)$$

where  $\rho_0$  and  $R_s$  are the characteristic density and radius of the halo. We estimate that our results are not very sensitive to the details of the considered DM profile.

While PBHs are born in the early universe, NSs are born from gravitational collapse and supernovae explosions of massive stars. NSs are often born with significant “natal kick” velocities, reaching hundreds of  $\text{km s}^{-1}$  (e.g., Arzoumanian et al. 2002). As a benchmark, we focus on the Milky Way (MW) Galactic NS population. The majority of NSs have only been observed as isolated pulsars with ages significantly shorter than that of the MW, with significant uncertainties on population and distribution—especially toward the Galactic center (e.g., Sartore et al. 2010). We consider exponential

Galactic NS distribution (Paczynski 1990), well motivated by the star formation history of the MW (Sartore et al. 2010), and employ the following spherically symmetric model,

$$\rho_{\text{NS}}(r) = \rho_{\text{NS}}^0 e^{-r/R_{\text{NS}}}, \quad (3)$$

where  $\rho_{\text{NS}}^0$  and  $R_{\text{NS}}$  are the characteristic density and radius, respectively.

The resulting binary formation rate in a particular Galactic halo is given by

$$\mathcal{R}_{\text{PBH–NS}} = 4\pi \int_0^{R_{\text{vir}}} dr r^2 \frac{\rho_{\text{NS}}}{m_1} \frac{\rho_{\text{PBH}}}{m_2} \langle \sigma v_{\text{rel}} \rangle, \quad (4)$$

where  $R_{\text{vir}}$  is the virial radius of the halo and the angle brackets denote averaging over the velocity distribution.

Typical binaries are expected to have very large eccentricities, therefore their merger times are negligibly small (especially in the case of large halos; Cholis et al. 2016). As a result the obtained binary formation rates  $\mathcal{R}_{\text{PBH–NS}}$  can be identified as the merger rates for the given halo.

We are interested in obtaining the merger rates as a function of the halo mass  $M_h$ , as well as the cosmological volume averages of these rates. In order to obtain the former, we need halo properties as a function of the halo mass. First, we establish a relation between the halo concentration  $C \equiv R_{\text{vir}}/R_s$  and  $M_h$ , which is inferred from  $N$ -body simulations. We employ the fitting function provided in Ludlow et al. (2016) (see their Appendix C). The characteristic NFW density  $\rho_0$  of Equation (2) is then given by

$$\frac{\rho_0}{\rho_{\text{crit}}} = \frac{200}{3} \frac{C^3}{g(C)}, \quad (5)$$

where  $g(C) \equiv \log(1+C) - C/(1+C)$ , and  $\rho_{\text{crit}}$  is the critical density of the universe. The radius  $R_s$  is given by

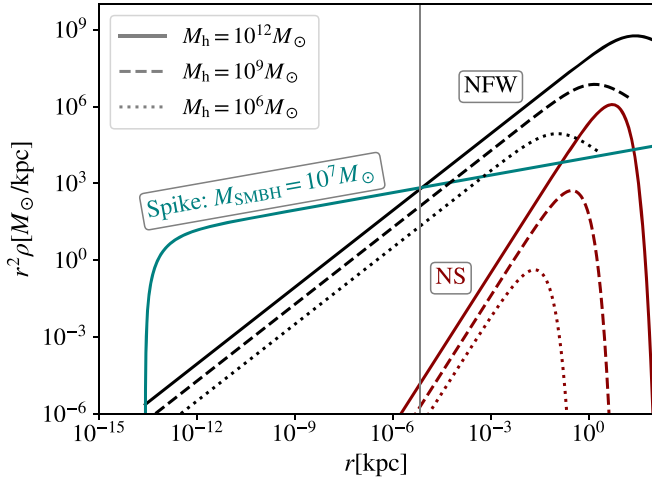
$$R_s = \left( \frac{M_h}{4\pi g(C) \rho_0} \right)^{1/3}. \quad (6)$$

Analogously to the DM distribution, two parameters need to be fixed to characterize the NS distribution in Equation (3). For  $R_{\text{NS}}$  we consider a range of  $R_{\text{NS}}/R_s$  values. The parameter  $\rho_{\text{NS}}^0$  is obtained by normalizing the NS distribution to the estimated number of NSs in a given galaxy determined based on the galaxy’s stellar mass and the stellar-mass function. For the latter we use the standard Salpeter initial stellar-mass function  $\phi(m_*) \sim m_*^{-2.35}$  and assume that it is independent of time. Time dependence can be easily incorporated into the analysis, but we do not expect it to alter our conclusions. We consider that all the stars in the  $[m_*^{\text{min}}, m_*^{\text{max}}] = [8\text{--}20]M_\odot$  range undergo a supernova explosion leading to an NS remnant. Hence, the number of NSs in a galaxy with a stellar mass  $M_*$ , is given by

$$N_{\text{NS}}(M_*) = M_* \int_{m_*^{\text{min}}}^{m_*^{\text{max}}} dm_* \phi(m_*), \quad (7)$$

where  $\phi(m_*)m_*$  is normalized to unity.

The galactic stellar mass  $M_*$  is extrapolated from the stellar mass–halo mass relation presented in Behroozi et al. (2013). Note that this relation is in principle only valid for central galaxies, but it is sufficient for our purposes as we do not expect a sizable population of NSs in faint satellites. We should also emphasize that there is a significant uncertainty at the



**Figure 1.** Density profiles of PBH DM halo (NFW, black) and NSs (red) for halos of different masses of  $M_h$ , assuming  $R_{\text{NS}}/R_s = 0.1$  (see the text for definition). Possible DM “density spike” enhancement due to a supermassive BH at the galactic center is also shown.

lower mass end of the  $M_*(M_h)$  relation. As we will see, the smaller halos do not significantly contribute to the PBH–NS rates, and the mentioned scatter is not essential for our main results. In order to provide optimistic estimates, we have chosen the least steep model with  $M_* \sim M_h^{1.4}$  for  $M_h \lesssim 10^{12} M_\odot$ . In larger halos the relation is almost flat, with  $M_* \sim M_h^{0.2}$  for  $M_h \gtrsim 10^{12} M_\odot$ .

In Figure 1 we demonstrate the relative distribution of NSs (red) and DM (black) in halos of different masses, assuming  $R_{\text{NS}}/R_s = 0.1$ . Subsequently, we consider the full range  $R_{\text{NS}}/R_s \in [0.01, 0.1]$ . While the exact value of  $R_{\text{NS}}$  is relevant for the precise value of the merger rate, our overall conclusion is largely insensitive to it.

Our estimates for the expected yearly merger rates per halo are presented in the left panel of Figure 2, where solid and dashed lines correspond to  $f_{\text{PBH}} = 1$  and  $f_{\text{PBH}} = 10^{-3}$ , respectively. PBH–NS rates are displayed in black, and the blue gradient-shaded regions correspond to variation in  $R_{\text{NS}}/R_s$ .

We find that PBH–NS rates significantly decrease with halo mass  $M_h$ . This can be understood from the sharp drop of stellar mass for halos with  $M_h \lesssim 10^{12} M_\odot$ , which drastically reduces the number of available NSs in such halos. Moreover, our extrapolations of the stellar budget to halos with  $M_h \lesssim 10^6 M_\odot$  (gray shaded area in Figure 2) are highly uncertain; such small halos are not expected to be massive enough to ignite star formation.

With gray dotted lines we also demonstrate in the left panel of Figure 2, the approximate halo-mass scaling of the rates. The slopes of these lines can be approximated by assuming  $\rho_0$  is independent of mass, and that halos are given by a top-hat model (in the case of PBH–NS rates).

To obtain the total galactic merger rates as relevant for LVC observations we have convoluted the merger rates per halo  $\mathcal{R}_{\text{PBH-NS}}$  with the halo-mass function  $dn/dM_h$ ,

$$\mathcal{V}_{\text{PBH-NS}} = \int_{M_c} \mathcal{R}_{\text{PBH-NS}} \frac{dn}{dM_h} dM_h, \quad (8)$$

where  $M_c$  is the lower cutoff limit for the contributing halos. Here we have employed the Tinker halo-mass function (Tinker et al. 2008). In order to assess the impact of low-mass halos we have varied  $M_c$  in Equation (8), with the resulting total merger

rates as a function of  $M_c$  shown in the right panel of Figure 2. We also display the scaling of the integrated rates with respect to  $M_c$  in gray dotted lines, which are obtained by convoluting the approximate scaling relations of the left panel with the Press–Schechter mass function  $\sim M_h^{-2}$ .

We observe that the curves plateau for  $M_h \lesssim 10^{12} M_\odot$ , which is a manifestation of the fact that small halos do not contribute significantly to the PBH–NS rates.

The LVC observations inferred a BH–NS merger rate of  $45_{-33}^{+75} \text{ Gpc}^{-3} \text{ yr}^{-1}$ , assuming the detected events are representative of the underlying BH–NS population (Abbott et al. 2021b). Hence, our results establish that the PBH–NS mergers can contribute only as a strictly subdominant component of the observed BH–NS rates. This conclusion is even stronger considering the more realistic case of constrained PBH abundance  $f_{\text{PBH}} = 10^{-3}$ , leading to PBH–NS rates being suppressed by an additional factor of  $f_{\text{PBH}}$ .

### 3. Comparison with PBH–PBH Mergers

To put our results for BH–NS rates into context, we recompute for comparison, the late universe PBH–PBH merger rates using Equation (4) for two-body scattering with appropriate substitution of  $\rho_{\text{PBH}}$  for  $\rho_{\text{NS}}$ . Our results for the yearly PBH–PBH merger rates per halo are presented in Figure 2 (in red). Here solid and dashed lines correspond to  $f_{\text{PBH}} = 1$  and  $f_{\text{PBH}} = 10^{-3}$ , respectively.

The solid red curve confirms the results previously obtained by Bird et al. (2016), where it was shown that a significant contribution to PBH–PBH mergers originates in halos as small as  $\sim 10^3 M_\odot$ . This is in contrast to the PBH–NS rates, which strongly depend on the stellar budget of halos. The magnitude of PBH–NS merger rates approaches a nonnegligible fraction of PBH–PBH rates in the MW-type halos with  $M_h \sim 10^{12} M_\odot$ . Since the PBH–PBH merger rates scale as  $\propto f_{\text{PBH}}^2$ , for the more realistic case of constrained  $f_{\text{PBH}} \sim 10^{-3}$ , they become heavily suppressed and negligible even in larger halos.

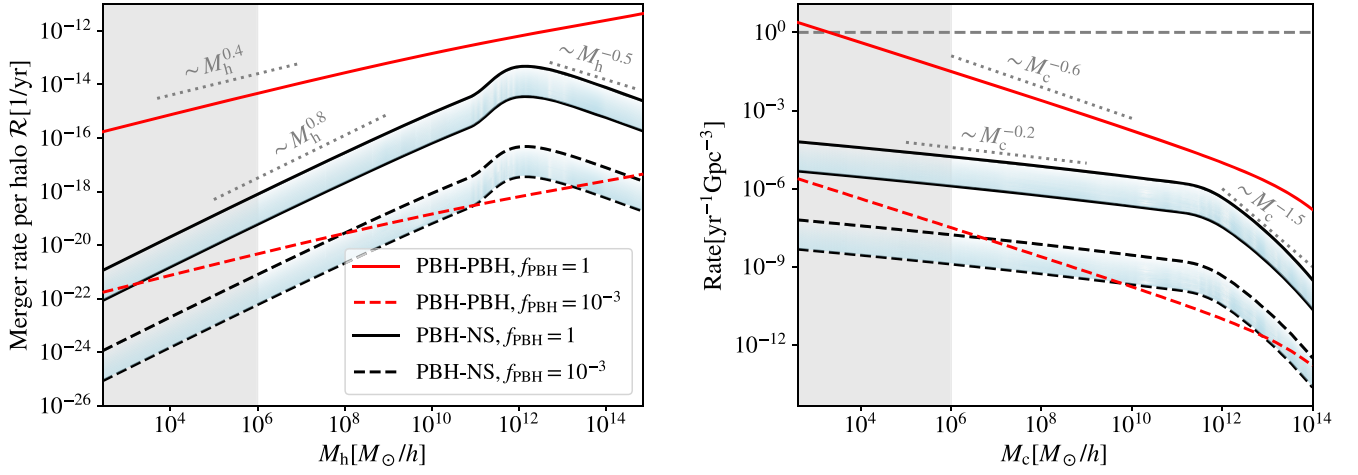
We further compute the average PBH–PBH rates by convoluting the halo rates with the halo-mass function in Equation (8). The resulting merger rates as a function of  $M_c$  are shown in the right panel of Figure 2. We confirm the conclusion of Bird et al. (2016) (note that in the right panel we display the cumulative integral, not the integrand alone), finding that the average PBH–PBH rate can be  $\sim \mathcal{O}(1) \text{ Gpc}^{-3} \text{ yr}^{-1}$  if  $f_{\text{PBH}} = 1$  and the contributions from small halos are taken into account. As we saw, this is not the case for PBH–NS rates, as these are suppressed in smaller halos due to steep decline in stellar mass.

PBH–NS mergers follow the stellar evolution and can only form at low redshifts. PBH–PBH mergers, on the other hand, can receive significant contributions not only from the late universe (e.g., Bird et al. 2016), but also from the early universe, before matter–radiation equality (e.g., Nakamura et al.

1997; Sasaki et al. 2016). As a result, PBH–PBH mergers can significantly contribute to GW observations even if  $f_{\text{PBH}} \sim 10^{-3}$ , while PBH–NS rates are subdominant regardless of the value of  $f_{\text{PBH}}$ .

### 4. Possible Enhancement Effects

In our analysis we have neglected several possible nuances that might affect the spatial distribution of PBHs and hence merger rates. We now discuss the expected dominant effects



**Figure 2.** Left: PBH–NS and PBH–PBH binary merger rates per halo, as a function of halo mass  $M_h$ , for a range of  $f_{\text{PBH}}$  values. Uncertain extrapolated small halo contributions below  $M_h \lesssim 10^6 M_\odot$  are shaded in gray. Right: PBH–NS and PBH–PBH merger rates integrated over the halo-mass function, presented as a function of the smallest contributing halo with mass  $M_c$ . For comparison, PBH–PBH merger rates in the early universe formation channel are independent of halo mass and are estimated to be  $\mathcal{O}(1) \text{ Gpc}^{-3} \text{ yr}^{-1}$  for  $f_{\text{PBH}} = 10^{-3}$  and  $\mathcal{O}(10^5) \text{ Gpc}^{-3} \text{ yr}^{-1}$  for  $f_{\text{PBH}} = 1$  (see, e.g., Sasaki et al. 2016).

and argue that our conclusion about PBH–NS binaries is robust against them.

It has been suggested that PBHs could be clustered on small scales already in the early universe and be part of ultrafaint dwarf galaxies (Clesse & García-Bellido 2017). Even though these structures can be relevant for PBH–PBH rates, their stellar content is negligible and hence we do not expect significant contribution to the PBH–NS rates. Further, we do not expect that any local environments of NS and DM overdensities can significantly modify the total volumetric galactic merger rates.

Another enhancement effect could be related to DM “density spikes” that might form due to accretion by the central galactic supermassive black holes (Gondolo & Silk 1999; see Figure 1). This can demonstrably influence the PBH–PBH merger rates (Nishikawa et al. 2019). Following Nishikawa et al. (2019), we have estimated the PBH–NS rates due to the DM spike and have found the contribution to be negligible, being  $\mathcal{O}(10^{-20}) \text{ yr}^{-1}$  per spike, even under the most optimistic assumptions about the spike properties. This can be understood by noticing that the spike spans a very limited volume. While this limitation is overcome in the case of PBH–PBH binary formation due to two factors of DM density in the merger rate integrals (see Equation (4)), it leads to a negligible effect for the PBH–NS merger rates as these include only a single power of DM density.

The merger rates could also be enhanced if PBHs have increased concentration toward the centers of galaxies. This effect could result from a variety of processes, such as a multitude of local gravitational encounters or dynamical friction when PBHs constitute a subdominant DM component. In particular, the equilibrium states of multicomponent gravitational halos are expected to reach kinetic energy equipartition of the individual species due to encounters (see, e.g., Binney & Tremaine 2008). When  $f_{\text{PBH}} < 1$ , PBHs will tend to concentrate at the halo center. PBHs might also slow down due to dynamical friction from gravitational attraction of the underlying cold DM, also leading to their concentration at the halo center.

In case complete mass segregation between PBHs and other DM components does occur, we expect all of the PBHs in the

halo to be clustered within a sphere of radius  $R_{\text{PBH}}$ . Introducing a concentration parameter for the PBH halo as  $C_{\text{PBH}} \equiv R_{\text{PBH}}/R_s = CR_{\text{PBH}}/R_h$ , we have  $4\pi\rho_s R_s^3 g(C_{\text{PBH}}) = f_{\text{PBH}} M_h$ . Assuming  $C_{\text{PBH}} \ll 1$  we obtain  $R_{\text{PBH}} \sim \sqrt{f_{\text{PBH}}} R_h$ . The characteristic PBH velocities are given by  $v_{\text{PBH}}^2 = G_N f_{\text{PBH}} M_h / R_{\text{PBH}}$ . As a result we find that after PBHs concentrate at the halo center, their velocities are reduced with respect to the virial velocity of the halo  $v_{\text{PBH}} \sim f_{\text{PBH}}^{1/4} v_{\text{vir}}$ . The smaller PBH fractions lead to stronger velocity suppression.

Using Equations (1) and (4), the above idealistic considerations suggest the PBH–NS merger rate to be modified as  $\mathcal{O}(1) f_{\text{PBH}}^{-39/28} \mathcal{R}_{\text{PBH-NS}}$ . For  $f_{\text{PBH}} = 10^{-3}$  this leads to  $\mathcal{O}(10^4)$  enhancement. Note that the resulting rate could be even higher than the expected rate in the case of  $f_{\text{PBH}} = 1$ . While significant, this enhancement is still far too insufficient for matching the expected merger rates to observations (see Figure 2). More importantly, the timescales of the mentioned processes are expected to be longer than the age of the universe in typical halos dominating the PBH–NS rates; therefore the anticipated enhancement would be much weaker than the estimate above.

## 5. Concluding Remarks

GW observations allow for new unprecedented tests of fundamental physics. With first detection of BH–NS mergers and their potential connection to PBHs and DM, understanding the origin of such events is a central topic of exploration. We computed, for the first time, the total volumetric PBH–NS merger rates, finding such contributions to be significantly subdominant to astrophysical BH–NS rates. Analogously, we recomputed PBH–PBH formation rates in the late universe, confirming the literature results. While their late universe rates could be suppressed, PBH–PBH mergers, unlike the PBH–NS ones, can receive significant contributions from the early universe prior to star formation. As a result, BH–NS binaries are not sensitive probes of PBH dark matter. They also will not significantly contribute to multimessenger observations. The above carries important fundamental implications for a large class of mergers. Namely, not only are the detected BH–NS events of astrophysical origin, but this is the case even when PBH–PBH events account for LVC BH–BH observations.

Additionally, our conclusion regarding the observed BH–NS mergers being of astrophysical origin has further, broader implications for BH–BH systems as well. Once a given astrophysical stellar evolution formation channel predicts the expected BH–NS abundance, the same channel also would have a unique prediction for the astrophysical BH–BH rates. For instance, once the observational uncertainties in BH–NS rates are sufficiently reduced, population-synthesis-based analyses will be able to narrow down on the star formation properties, such as metallicities. The latter would determine the BH–BH rates, hence also constraining the scope of contributions from PBHs.

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*Software:* COLOSSUS (Diemer 2018), Astropy (Astropy Collaboration 2013, 2018). Our main results can be reproduced using the code available at <https://github.com/valerivardanyan/PBH-NS-Mergers>.

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