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I. CONNECTING $f_{\rm PBH}$ WITH ADVANCED LIGO AND ADVANCED VIRGO RATE CONSTRAINTS

We model an equal mass population of PBHs that are initially uniformly distributed in comoving volume. We parametrize the abundance of this population as a fraction of the total dark matter, i.e. $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$. We model the merger rates by considering two nearest neighbor, gravitationally bound black holes that are torqued by the next closest black hole. From these assumptions, we find the merger rate distribution [**? ?**]

$$\mathrm{d}P = \begin{cases} \dfrac{3\, f_{\rm PBH}^{37/8}}{58} \left[f_{\rm PBH}^{-29/8} \left(\dfrac{t}{t_{\rm c}}\right)^{3/37} - \left(\dfrac{t}{t_{\rm c}}\right)^{3/8} \right] \dfrac{\mathrm{d}t}{t}, & t < t_{\rm c} \\ \dfrac{3\, f_{\rm PBH}^{37/8}}{58} \left[f_{\rm PBH}^{-29/8} \left(\dfrac{t}{t_{\rm c}}\right)^{-1/7} - \left(\dfrac{t}{t_{\rm c}}\right)^{3/8} \right] \dfrac{\mathrm{d}t}{t}, & t \geq t_{\rm c} \end{cases} \tag{1}$$

where $t_{\rm c}$ is a function of the mass of the compact objects and the fraction of the dark matter they comprise:

$$t_{\rm c} = \frac{3}{170} \frac{c^5}{(G m_{\rm PBH})^{5/3}} \frac{f_{\rm PBH}^7}{(1+z_{\rm eq})^4} \left(\frac{8\pi}{3 H_0^2 \Omega_{\rm DM}} \right)^{4/3} . \tag{2}$$

Here, c is the speed of light, G is the gravitational constant, $m_{\rm PBH}$ is the mass of the black holes in

* Deceased, August 2020.

our equal mass population, $f_{\rm PBH}$ is the parametrized abundance from above, $z_{\rm eq}$ is the redshift at matter-radiation equality, H_0 is the Hubble constant, and $\Omega_{\rm DM}$ is the dark matter density. We use the Planck "TT,TE,EE+lowP+lensing+ext" cosmology [?] to evaluate $t_{\rm c}$.

The above equation, when evaluated at present day and multiplied by the number density of PBHs, provides a theoretical merger rate for PBHs:

$$\mathcal{R}_{\rm PBH} = n_{\rm PBH} \left.\frac{{\rm d}P}{{\rm d}t}\right|_{t=t_0} . \qquad (3)$$

We equate our observed upper limit on the merger rate to the theoretical merger rate and invert at each value of $m_{\rm PBH}$ to obtain a constraint on $f_{\rm PBH}$. This PBH model is discussed in further detail in the literature [? ? ? ?].

II. CONSTRAINING DISSIPATIVE DARK MATTER USING GRAVITATIONAL-WAVE SEARCHES FOR SSM BINARIES

We use a Bayesian approach to get the posterior probability of the fraction of dark matter in dark black holes, f, and the possible minimum mass of the DBH distribution, $M_{\rm min}$, using modelled rates for dark-matter BH mergers and estimated $\langle VT\rangle$ from searches for SSM binary black holes. The 2D distribution for $\{f_{\rm DBH},\ M_{\rm min}\}$ is obtained by marginalising over two additional parameters needed to characterize the binary distribution: the slope of the initial mass function, b, and a parameter $r = M_{\rm max}/M_{\rm min}$ that sets the mass range of the initial population. The 4D distribution is $P(f, \overline{\theta} = \{M_{\rm min}, b, r\}|\mathcal{R}_i, VT(\mathcal{M} = m_i))$, which can be written in terms of the independent distributions for f and the set $\overline{\theta} = \{M_{\rm min}, b, r\}$, as well as the likelihood $\mathcal{L}(f, \overline{\theta}; \mathcal{R}VT)$

$$P(f, \overline{\theta}|\mathcal{R}, VT) \propto P(f)P(\overline{\theta})\mathcal{L}(f, \overline{\theta}; \mathcal{R}VT). \qquad (4)$$

The rates $\mathcal{R}_i$ are computed in pre-defined chirp mass bins within the range $\mathcal{M} \in [0.2M_\odot, 2.5M_\odot]$ which is representative of the SSM search, and depend on the model parameters f and $\overline{\theta}$. The rates are modelled as:

$$\mathcal{R}_i(\mathcal{M} = m_i|f, \overline{\theta}) = P_i(m_i|t_{\rm m}, \overline{\theta}) \left(\frac{{\rm d}P(t_{\rm m} = 10\ {\rm Gyr}|\overline{\theta})}{{\rm d}t}\right) \times \left(\frac{\rho_{\rm DM} \times f \times f_{\rm binary}}{\langle M\rangle}\right) \qquad (5)$$

where $\rho_{\rm DM} = 3.3\times10^{19}\ M_\odot\ {\rm Gpc}^{-3}$ is the density of dark matter in the universe, and $f_{\rm binary} = 0.26$ is the number of dark black hole binaries divided by total DBHs. This is choice is informed by numerical studies of binary formation in Population III stars [?]. Since Pop III stars form in nearly pristine hydrogen gas, their formation is a close analog to the cooling and collapse of dark hydrogen gas into dark black holes. This number is of course uncertain, but other studies of Population III binaries (e.g., [?]) often assume that binaries make about 1/3 of all systems, which would correspond to the nearly identical $f_{\rm binary} = 0.25$. We choose $f_{\rm binary} = 0.26$ to match [?]. As $f_{\rm binary}$ is an overall multiplicative factor, the plotted constraint can be directly scaled for any other choice of $f_{\rm binary}$. The chirp mass distribution of binary systems that would merge within some merger time $t_{\rm m}$ is $P(\mathcal{M}|t_{\rm m}, \overline{\theta})$. Since these objects likely form between $20 \lesssim z \lesssim 30$, we may use $t_{\rm m} = 10$ Gyr, roughly the age of the universe, and the exact formation time makes a negligible shift in this number. The probability that the merger time of the binary is 10 Gyr is denoted as $P(t_{\rm m} = 10\ {\rm Gyr}|\overline{\theta})$, and $\langle M\rangle$ is the mean component mass of dark-matter BHs given the initial mass distribution, given some $\overline{\theta}$.

The $\langle VT\rangle$ estimated from SSM searches for compact binary coalescences were weighted according to the allowed mass-ratios and their probabilities for a given population described by $\overline{\theta}$.

$$VT_i(\mathcal{M} = m_i|\overline{\theta}) = \int_1^{q_{\rm max}} \mathcal{P}(q|m_i, t_{\rm m}, \overline{\theta})VT(m_i){\rm d}q. \qquad (6)$$

We assume a Poisson distribution for event counts such that the rate posterior for zero detections becomes $\mathcal{P}(\mathcal{R}|VT) = VT\exp(-\mathcal{R}\times VT)$. The above definitions for $\mathcal{R}$ and VT are used to compute the rate posterior in each bin. The likelihood of $f, \overline{\theta}$ is computed by taking a product of rate posteriors over all chirp mass bins.

$$\mathcal{L}(f, \overline{\theta}; \mathcal{R}VT) = \prod_i \frac{\int_{\mathcal{R}_i}^{\infty} \mathcal{P}_i(\mathcal{R}|f, \overline{\theta}, VT_i){\rm d}\mathcal{R}}{\int_0^{\infty} \mathcal{P}_i(\mathcal{R}|f, \overline{\theta}, VT_i){\rm d}\mathcal{R}}. \qquad (7)$$

We use $b \in [-1, 2]$ for initial mass distribution of DBHs $\mathcal{P}(m) \propto m^{-b}$ and $r \in [2, 1000]$ to constrain $f \in [10^{-10}, 1]$ and $M_{\rm min} \in [10^{-3}M_\odot, 3.1M_\odot]$. The range of initial mass function slopes b is inclusive of all values found in the literature on Population III star binaries [? ? ?], while the range chosen for r includes Population III star values [?] and was shown in Ref. [?] to be sufficient so that results are not too sensitive to changes in the range.

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