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Gravitational waves from supermassive black hole binaries in ultra-luminous infrared galaxies

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ABSTRACT

Gravitational waves (GWs) in the nano-hertz band are great tools for understanding the cosmological evolution of supermassive black holes (SMBHs) in galactic nuclei. We consider SMBH binaries in high-z ultra-luminous infrared galaxies (ULIRGs) as sources of a stochastic GW background (GWB). ULIRGs are likely associated with gas-rich galaxy mergers containing SMBHs that possibly occur at most once in the life of galaxies, unlike multiple dry mergers at low redshift. Adopting a well-established sample of ULIRGs, we study the properties of the GWB due to coalescing binary SMBHs in these galaxies. Since the ULIRG population peaks at $z > 1.5$, the amplitude of the GWB is not affected by a moderate delay by $\lesssim 7$ Gyrs of SMBH mergers. Despite the rarity of the high-z ULIRGs, we find a tension with the upper limits from Pulsar Timing Array (PTA) experiments. This result suggests that if a fraction $f_{\rm m,gal}$ of ULIRGs are associated with SMBH binaries, then no more than 50% $f_{\rm m,gal}(\lambda_{\rm Edd}/0.3)^{5/3}(t_{\rm life}/30\ {\rm Myr})$ of the binary SMBHs in ULIRGs can merge within a Hubble time, for plausible values of the Eddington ratio of ULIRGs ($\lambda_{\rm Edd}$) and their lifetime ($t_{\rm life}$).

Keywords: gravitational waves — infrared: galaxies

1. INTRODUCTION

Most massive galaxies in the local universe host supermassive black holes (SMBHs). One fundamental goal in astrophysics is to understand the origins of these SMBHs and their host galaxies. Galaxy mergers play an important role in their evolution on a cosmological timescale (e.g., Kormendy & Ho 2013); in the assembly of massive galaxies and fueling gas to nuclear SMBHs. A natural outcome of galaxy mergers containing SMBHs is the formation of binary SMBHs. If the binary SMBHs coalescence within a Hubble time, a significant fraction of their rest-mass energy is emitted as gravitational waves (GWs). The GW emission is a good tool to probe the cosmological evolution of SMBHs in the framework of hierarchical structure formation.

Pulsar timing array (PTA) experiments enable us to directly address the GW emission in the nHz$-\mu$Hz band. There are three ongoing PTA experiments: the European Pulsar Timing Array (EPTA), the Australian Parkes Pulsar Timing Array (PPTA) and the North American Nanohertz Observatory for Gravitational Waves (NANOGrav). Their measurements have recently provided upper limits on the strength of the GW background (GWB) from binary SMBHs (Arzoumanian et al. 2016; Shannon et al. 2015; Lentati et al. 2015).

The theoretical GWB signal in the PTA band has been predicted by using semi-analytical calculations (e.g., Jaffe & Backer 2003) and cosmological simulations (e.g., Sesana et al. 2009). Those models incorporated various combinations of physical processes that affect the evolution of binary SMBHs in merging galaxies (Begelman et al. 1980); eccentric binary evolution (Enoki & Nagashima 2007), viscous drag from a circumbinary gaseous disk (Kocsis & Sesana 2011), dynamical friction (McWilliams et al. 2014; Kulier et al. 2015) and multi-body BH interactions (Ryu et al. 2018; Bonetti et al. 2018). Combined with cosmological hydrodynamical simulations, Kelley et al. (2017) investigated the impact of various environmental processes on the binary evolution. In spite of great efforts in theory,

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there are still many uncertainties for model parameters and observed empirical relations (Sesana 2013).

In this *Letter*, we address this issue with a different approach following observational results. We consider ultra-luminous infrared galaxies (ULIRGs), which are one of the best tracers of merging galaxies containing SMBHs, as sources of a GWB. Recent observations by *Herschel* and the *Wide-field Infrared Survey Explorer* (*WISE*) have provided a large sample of bright IR galaxies at $0 < z < 4$ and allow us to explore their infrared spectral energy distributions (SEDs; Delvecchio et al. 2014). Adopting the luminosity function of ULIRGs, we study the development of a GWB due to coalescing binary SMBHs driven by merging ULIRGs. Intriguingly, we find a tension with the most stringent PTA upper limits, which constrain the fraction of binary SMBHs that coalescence by the present time, depending on the Eddington ratio of BHs in ULIRGs, the typical lifetime of ULIRGs, and the fraction of ULIRGs associated with SMBH binaries.

2. ULTRA-LUMINOUS INFRARED GALAXIES HOSTING SMBHS

We here consider ULIRGs with total infrared luminosities of $L_{\rm IR,tot} \gtrsim 10^{12}\ {\rm L}_\odot$ as good tracers of merging galaxies that host at least one accreting SMBH in each system. At low-redshifts of $z < 1$, infrared observations have revealed that the morphologies of ULIRGs are almost exclusively caused by mergers (e.g., Surace et al. 1998), and that the number fraction containing AGN increases with $L_{\rm IR,tot}$ and reaches almost unity in ULIRGs (e.g., Veilleux et al. 2002; Ichikawa et al. 2014). At higher redshifts of $z > 1$, the merger fraction is still uncertain since active star formation in gas-rich galaxies alone could produce a similar level of infrared luminosities observed as ULIRGs (e.g., Kartaltepe et al. 2012).

At the extremely bright end of ULIRGs with $L_{\rm IR,tot} \simeq 10^{13} - 10^{14}\ {\rm L}_\odot$, the so-called hyper-luminous infrared galaxies (HyLIRGs) show relatively clear signatures of galaxy mergers even at higher redshifts. The merger fraction has been estimated by quantifying their morphologies as $f_{\rm m,gal} \sim 62 \pm 14\%$ for hot dust-obscured galaxies at $z \sim 3$ (Fan et al. 2016) and $\sim 75\%$ for HyLIRGs at $1.8 < z < 2.5$ (Farrah et al. 2017). Moreover, the merger fraction tends to increase with bolometric luminosity and becomes ~ 80 % at the brightest end of $L_{\rm bol} \sim (1-5) \times 10^{14}\ {\rm L}_\odot$ (Glikman et al. 2015). Those measurements give a lower limit of the fraction because such merger signatures would smooth out after several dynamical timescales.

The enormous power of U/HyLIRGs is produced by deeply buried and rapidly accreting SMBHs. Most of the AGN radiation is absorbed by surrounding dust and is re-emitted at mid-infrared wavelengths. By decomposing the hot dust emission from their SEDs, the AGN contribution to the total (IR) luminosity increases with $L_{\rm IR,tot}$ (e.g., Murphy et al. 2011). Namely, the luminosity ratio is estimated as $L_{\rm IR,AGN}/L_{\rm IR,tot} \simeq 0.2 - 0.3$ for ULIRGs (e.g., Ichikawa et al. 2014), and reaches $\simeq 0.7-1.0$ for HyLIRGs (e.g., Jones et al. 2014; Farrah et al. 2017).

Using the SED decomposition technique for a sample of Herschel selected galaxies within the Great Observatories Origins Deep Survey-South (GOODS-S) and the Cosmic Evolution Survey (COSMOS) fields, Delvecchio et al. (2014) have reconstructed the AGN bolometric luminosity function (LF) at $0.1 < z < 3.8$. The bolometric correction factor is estimated by solving the radiative transfer equation for a smooth dusty structure irradiated by the AGN accretion disk, instead of adopting the bolometric correction shown in Hopkins et al. (2007). The AGN bolometric LF for ULIRGs is well fit by

$$\frac{d\phi(L,z)}{d\log L} = \phi_\star \left(\frac{L}{L_\star}\right)^\beta \exp\left[-\frac{\{\log(1+\frac{L}{L_\star})\}^2}{2\sigma^2} - \frac{L}{L_{\rm c}}\right] \quad (1)$$

where L is the AGN bolometric luminosity, and the values of fitting parameters ($\phi_\star$, $L_\star$, β and σ) are listed in Table 1 of Delvecchio et al. (2014). Here, we set an exponential cutoff above a critical luminosity $L_{\rm c}(\equiv 10^{14}\ {\rm L}_\odot)$ because there is no detection for bright AGNs with $L > 10^{14}\ {\rm L}_\odot$ due to the lack of such bright ones or due to the limited observation volume. In addition, we set a minimum value of the AGN luminosity driven by galaxy major mergers to $L_{\rm min} = 10^{12}\ {\rm L}_\odot$. Considering $L/L_{\rm IR,AGN} \simeq 3$ (Delvecchio et al. 2014) and $L_{\rm IR,AGN}/L_{\rm IR,tot} \simeq 0.2$–$0.3$ (Ichikawa et al. 2014), $L_{\rm min} = 10^{12}\ {\rm L}_\odot$ corresponds to $L_{\rm IR,tot} \simeq (1-2) \times 10^{12}\ {\rm L}_\odot$. Since the merger fraction of IR galaxies with $L_{\rm IR,tot} < 10^{12}\ {\rm L}_\odot$ may be significantly below unity at high redshift, we do not consider such galaxies as sources of a GWB. Fig. 1 (left panel) shows the luminosity function of ULIRGs for different redshifts.

In order to convert the LF to the BH mass function (MF), it is necessary to obtain the Eddington ratio ($\lambda_{\rm Edd} = L/L_{\rm Edd}$). Since the broad line regions of ULIRGs are completely obscured in the optical, it is almost impossible to estimate their BH masses and thus the Eddington ratio using the optical spectra. However, a well-defined sample of quasars obtained from the Sloan Digital Sky Surveys (SDSS) catalog suggests that the typical Eddington ratio for those quasars is $\simeq 0.3$ (Kollmeier et al. 2006). On the other hand, the largest SMBHs have a maximum mass limit at $M_{\rm BH,max} \sim$

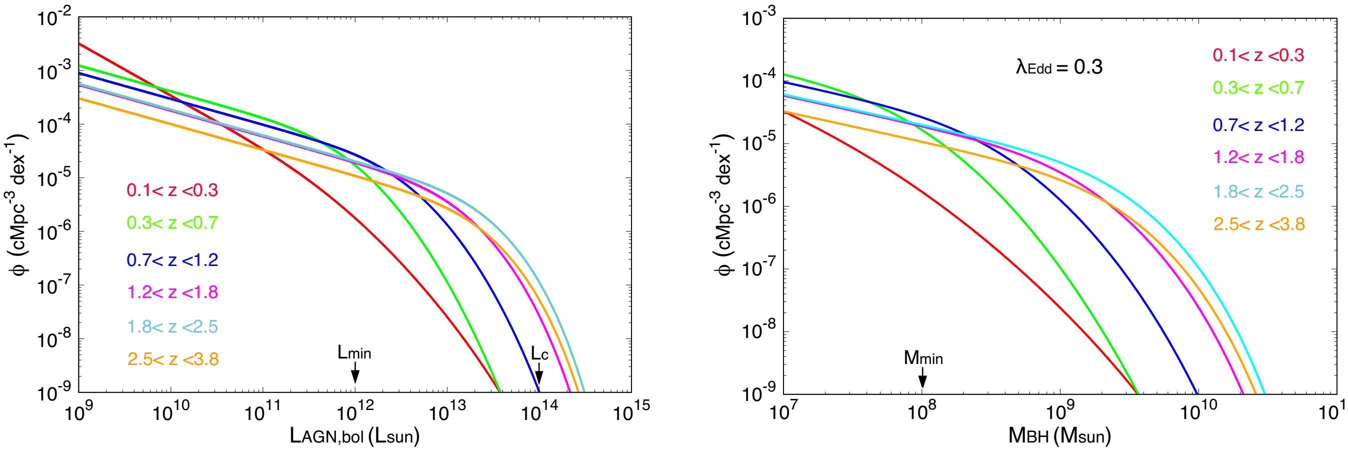

Figure 1. *Left*: bolometric luminosity function of AGNs in IR galaxies at different redshifts ($0.1 < z < 3.8$). The functional form is taken from Delvecchio et al. (2014), which is based on a sample of Herschel-selected galaxies within the GOODS-S and COSMOS fields. *Right*: BH mass function inferred from the luminosity function by assuming a constant Eddington ratio $\lambda_{\rm Edd}(\equiv L_{\rm bol}/L_{\rm Edd}) = 0.3$. Ultra-luminous IR sources with $L_{\rm bol} \gtrsim 10^{12}$ $L_\odot$ (i.e., $M_{\rm BH} \gtrsim 10^8$ $M_\odot$) are considered to be merging galaxies in which coalescing binary SMBHs contribute to the GWB.

a few $\times\, 10^{10}$ $M_\odot$, which is nearly independent of redshift (Netzer 2003; Wu et al. 2015). The radiation luminosity from quasars hosting the most massive BHs is estimated as $L \simeq 10^{15}\lambda_{\rm Edd}$ $L_\odot(M_{\rm BH,max}/3\times10^{10}\ M_\odot)$. Since this luminosity would be $\gtrsim L_{\rm c}$, we obtain $\lambda_{\rm Edd} \gtrsim 0.1(M_{\rm BH,max}/3\times10^{10}\ M_\odot)^{-1}$. Thus, we adopt $\lambda_{\rm Edd} = 0.3$ as our fiducial value. Fig. 1 (right panel) shows the BH mass function in ULIRGs for different redshifts.

Luminous quasars (QSOs) and ULIRGs are much rarer than normal galaxies, which is expected since those luminous phases have a lifetime shorter than a Hubble time. The lifetime is one of the most fundamental quantities for estimating the intrinsic number density of those luminous objects. The QSO lifetime can be observationally constrained by several methods (Martini 2004, and references therein): the clustering effect of dark matter halos that host luminous QSOs (Haiman & Hui 2001), the proximity effect (Bajtlik et al. 1988), and comparison between the local BH population and the space density evolution of QSOs (Yu & Tremaine 2002). Overall, the QSO lifetime lies in the range of 1 Myr $\lesssim t_{\rm life} \lesssim$ 100 Myr. Using galaxy merger simulations, Hopkins et al. (2006) demonstrated that the lifetime tends to decrease with increasing luminosity; namely, $t_{\rm life} \simeq 10-50$ Myr for $L_{\rm bol} > 10^{13}$ $L_\odot$. This shorter lifetime is consistent with 1 Myr $\lesssim t_{\rm life} \lesssim$ 20 Myr obtained from observations of extended Lyα emission near luminous QSOs at $2.5 \lesssim z \lesssim 2.9$ with ultra-violet luminosities of $L_{\rm UV} \sim 10^{14}$ $L_\odot$ (Trainor & Steidel 2013). In this letter, we adopt a conservative value of $t_{\rm life} \simeq 30$ Myr as our fiducial case.

3. GRAVITATIONAL WAVE BACKGROUND

Following Phinney (2001), we estimate the GW energy density per logarithmic frequency interval as

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_{\rm c}c^2}\int \frac{d^2N}{d\mathcal{M}_{\rm c}dz}\,\frac{1}{1+z}\,f_r\frac{dE_{\rm gw}}{df_r}\,d\mathcal{M}_{\rm c}dz, \quad (2)$$

where $\rho_{\rm c}$ is the critical mass density of the Universe at $z = 0$, f_r is the GW frequency in the source's cosmic rest frame, $f = f_r/(1+z)$ is the observed GW frequency, z is the redshift when the GWs are produced, $d^2N/d\mathcal{M}_{\rm c}dz$ is the comoving number density of GW events with chirp masses of $[\mathcal{M}_{\rm c}, \mathcal{M}_{\rm c}+d\mathcal{M}_{\rm c}]$ which occurs at cosmic times corresponding to the redshift range between z and $z+dz$,

$$\frac{d^2N}{d\mathcal{M}_{\rm c}dz}\,d\mathcal{M}_{\rm c}dz = \frac{f_{\rm m,gal}}{f_{\rm duty}}\,\frac{d\phi(L,z)}{d\log L}\,d\log L\;dz, \quad (3)$$

where $f_{\rm m,gal}$ is the merger fraction of galaxies inferred from the morphologies of U/HyLIRGs (we set $f_{\rm m,gal} \simeq 1$; see §2), and $f_{\rm duty} \equiv t_{\rm life}\cdot(dz/dt_r)$ is the duty cycle of ULIRGs. Since a constant $t_{\rm life} \simeq 30$ Myr is adopted, the duty cycle is independent of the luminosity.

The GW emission spectrum from a merging binary in the rest frame is given by

$$\frac{dE_{\rm gw}}{df_r} = \frac{(\pi G)^{2/3}\mathcal{M}_{\rm c}^{5/3}}{3f_r^{1/3}}\,\mathcal{P}(f_r), \quad (4)$$

where $E_{\rm gw}$ is the energy of the GW and $\mathcal{P}(f_r)$ characterizes the inspiral-merger-ringdown waveforms. The functional form of $\mathcal{P}(f_r)$ is taken from Ajith et al. (2008). The chirp mass is written as $\mathcal{M}_{\rm c}^{5/3} \equiv qM_{\rm BH}^{5/3}/(1+q)^{1/3}$, where $M_{\rm BH}$ is the mass of the primary SMBH and $q(< 1)$

Table 1. The relation between the delay time, coalescence fraction and GWB amplitude.

$t_{\rm delay}$ (Gyr)	$\mathcal{F}_{\rm coal}$ (%)	$h_c \times 10^{15}$	$h_{c,{\rm bg}} \times 10^{15}$
0	100	3.31	2.84
1	72	2.81	2.43
3	46	2.25	1.98
5	32	1.88	1.67
7	23	1.57	1.39
9	13	1.20	1.02
11	2.1	0.48	0.36

Note—(1) delay time, (2) coalescence fraction of BHs, (3) total GW amplitude and (4) stochastic GWB amplitude at $f = 10^{-8}$ Hz. We adopt $\lambda_{\rm Edd} = 0.3$ and $t_{\rm life} = 30$ Myr.

is the mass ratio of two SMBHs. We suppose that the primary BH follows the MF in Figure 1. Thus, we implicitly assume that the primary SMBH is located at the center of a ULIRG after the galaxy mergers and is responsible for the ULIRG activity, while the secondary BH is still located off center in a lower-density region. This assumption would be plausible because the number fraction of AGNs that are dual SMBHs is as small as ~ 10 % at $z < 1$ (Comerford et al. 2013).

As discussed in §2, most ULIRGs are triggered by major mergers of galaxies. We here set a minimum value of the BH mass ratio to $q_{\rm min} \simeq 0.1$. The mass-ratio distribution of SMBHs, $\Phi(q)$ at $q_{\rm min} \leq q \leq 1$, is uncertain. However, the chirp mass averaged over q is less uncertain, namely, $\langle \mathcal{M}_{\rm c}^{5/3}\rangle / M_{\rm BH}^{5/3} \simeq 0.47$, 0.34 and 0.3 for $\Phi(q) = $ const., $\Phi(q) \propto 1/q$ and $\Phi(q) \propto \delta(q-1/3)$, respectively. We adopt the last one for a more conservative estimate.

In the course of a galaxy merger embedding two SMBHs, a variety of physical processes affect the binary evolution to the coalescence in a certain timescale (e.g., Begelman et al. 1980; Merritt 2013). Since the delay-time between formation and coalescence of BH binaries is still uncertain, rather than attempting to model this delay, we assume a uniform delay time of $t_{\rm delay}$. To consider the delay effect on BH mergers, we evaluate the LF and duty cycle in Eq. (3) at $\tilde{z} \equiv z + \Delta z$, where Δz is determined by solving $t_{\rm delay} = \int_{z+\Delta z}^{z} \frac{dt_r}{dz} dz$. The delay time tends to be shorter than a Hubble timescale for SMBH binaries with higher total masses ($M_{\rm BH} > 10^8\ {\rm M}_\odot$) and mass ratios ($q > 0.2$) (Khan et al. 2016; Kelley et al. 2017). Within their model uncertainties, the delay time is estimated as $\simeq 0.35 - 6.9$ Gyr (see Table B1 in Kelley et al. 2017).

By using Eqs. (2), (3), and (4), the energy spectrum of the total GW emission due to merging SMBHs in ULIRGs is calculated as

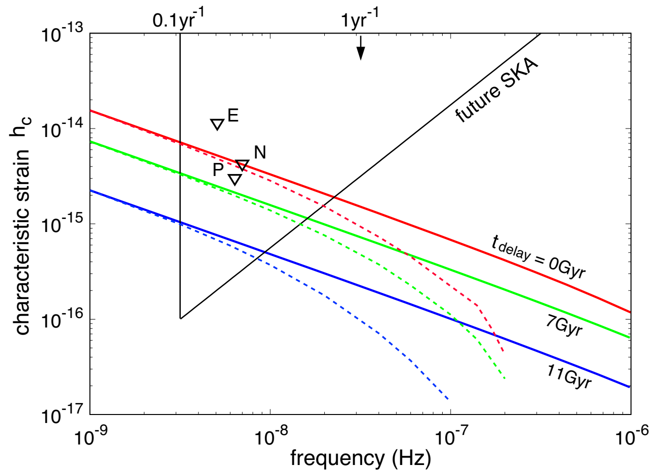

Figure 2. Characteristic amplitude of the GWB signal for different delay timescales for BH mergers ($0 \leq t_{\rm delay} \leq 11$ Gyr). Solid and dashed curves are the predicted total GW amplitudes and the unresolved stochastic GWB signals (i.e., the loudest contributions are subtracted). Triangle symbols show the current upper limits from PTA experiments: the EPTA (E), NANOGrav (N), and PPTA (P). To be consistent with the PTA limits, $t_{\rm delay} \gtrsim 3$ Gyr is required. Black solid line refers to the expected sensitivity by the SKA assuming monitoring of 50 pulsars at 100 ns rms precision over $T_{\rm obs} = 10$ yr with a cadence of 20 yr^{-1}.

$$\Omega_{\rm GW}(f) = 1.53 \times 10^{-9}\ \mathcal{F}_{\rm coal} \times \left(\frac{\lambda_{\rm Edd}}{0.3}\right)^{-5/3} \left(\frac{t_{\rm life}}{30\ {\rm Myr}}\right)^{-1} \left(\frac{f}{10\ {\rm nHz}}\right)^{2/3}, \tag{5}$$

and the characteristic strain is estimated as

$$h_{\rm c}(f) = 3.31 \times 10^{-15}\ \mathcal{F}_{\rm coal}^{1/2} \times \left(\frac{\lambda_{\rm Edd}}{0.3}\right)^{-5/6} \left(\frac{t_{\rm life}}{30\ {\rm Myr}}\right)^{-1/2} \left(\frac{f}{10\ {\rm nHz}}\right)^{-2/3}, \tag{6}$$

where $\mathcal{F}_{\rm coal}$ is the fraction of SMBHs that coalesce and produces GWs within a Hubble time, and directly follows from an assumed value of $t_{\rm delay}$. As shown in Table 1, the coalescence fraction decreases with $t_{\rm delay}$ and sharply drops at $t_{\rm delay} \gtrsim 7$ Gyr. In Figure 2, we plot the total GW spectrum of interest (solid). The upper limits from the PTA are presented by triangle symbols at frequencies where the limit becomes the most stringent; EPA (Lentati et al. 2015), NANOGrav (Arzoumanian et al. 2016) and PPTA (Shannon et al. 2015). Without the delay effect, merging SMBHs in ULIRGs would overproduce a GWB. The GWB has also been overproduced based on the observed (McWilliams et al. 2014) and simulated (Kulier et al. 2015) abundance of massive galaxies, and based on the observed periodic quasar candidates (Sesana et al. 2018), assuming that these objects all host SMBH binary mergers. With these PTA constraints, we obtain an upper limit for $\mathcal{F}_{\rm coal}$ as

$$\mathcal{F}_{\rm coal} \lesssim 0.43 \left(\frac{\lambda_{\rm Edd}}{0.3}\right)^{5/3} \left(\frac{t_{\rm life}}{30\ {\rm Myr}}\right), \tag{7}$$

which corresponds to a uniform delay time of $t_{\rm delay} \gtrsim 3$ Gyr. We also plot the sensitivity that is achievable with the Square Kilometer Array (SKA) with 50 pulsars for a $T_{\rm obs} = 10$ yr observation. If a GWB will not be detected even by such a planned detector, it would imply a strong constraint on $\mathcal{F}_{\rm coal} \ll 1\%$.

We note that the semi-analytical approach with Eq. (2), which assumes a *continuous* distributions of GW sources, allows us to estimate the characteristic amplitude of the total GW signal rather than the unresolved stochastic GWB. As pointed out in previous work (e.g., Jaffe & Backer 2003; Sesana et al. 2008; Kocsis & Sesana 2011), the amplitude of a stochastic GWB is reduced at higher frequencies in the PTA band by taking into account the *discrete* nature of relatively few GW emitters contributing to a single frequency bin. Following Sesana et al. (2008), we calculate the stochastic GW signal that consists of at least one binary in each frequency bin of $[f, f + 1/T_{\rm obs}]$. Sufficiently loud GW signals above the background level would be observed individually (e.g., Sesana et al. 2008; Kocsis & Sesana 2011). As shown in Figure 2 (dashed), the unresolved stochastic amplitude decreases at higher frequencies $\gtrsim 10^{-8}$ Hz, i.e., those GW signals consist of the loudest GW emitters in each frequency bin. In contrast, the GWB amplitudes of interest at $f \lesssim 10^{-8}$ Hz do not change significantly from the total GW signals (solid).

In Figure 3, we present the evolution of the stochastic GWB (black), and those due to SMBHs with $M_{\rm BH} \geq 10^9$ M$_\odot$ (red) and $< 10^9$ M$_\odot$ (blue). Without the delay, half of the stochastic GWB energy is produced by merging SMBHs with $M_{\rm BH} \gtrsim 10^9$ M$_\odot$ at $z > 1.5$, while others are due to less massive ones at $z < 1.5$. This result reflects the shape and redshift-evolution of the LF of ULIRGs and MF of SMBHs. In fact, a GWB from higher-mass BHs dominate at higher redshift. With the delay effect ($t_{\rm delay} = 7$ Gyr), the GWB is mostly produced at $z < 0.5$ and the amplitude is reduced by a factor of five. Our results are *qualitatively* consistent with previous work (e.g., Sesana et al. 2008), concluding that a GBW in the PTA band is dominated by nearby and massive binary SMBHs ($z < 2$ and $M_{\rm BH} > 10^8$ M$_\odot$). However, it is worth emphasizing that coalescing binary SMBHs even in a rare population of high-z ULIRGs associated gas-rich major mergers, which are quite different from multiple dry mergers occurring at low redshift, can produce a GWB close to the present-day upper limit. Since other type of galaxies unlike ULIRGs may have additional SMBH mergers and contribute to the GWBs (see e.g., McWilliams et al. 2014), our result gives a lower limit on the total GWB in the PTA band.

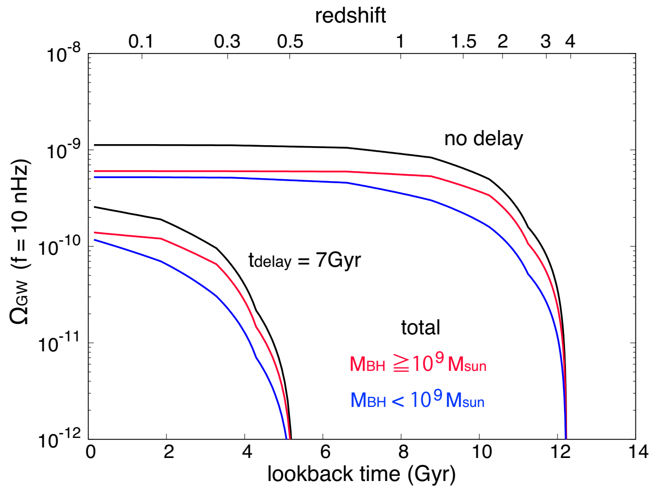

Figure 3. Evolution of the unresolved stochastic GWB produced by coalescing SMBHs in ULIRGs without and with the delay of BH mergers; $t_{\rm delay} = 0$ and 7 Gyr. Black curves show the total GWB, and others present the contribution from SMBHs with masses of $M_{\rm BH} \geq 10^9$ M$_\odot$ (red) and $< 10^9$ M$_\odot$ (blue).

4. DISCUSSION

The growth of SMBHs in galactic nuclei can be constrained by observations of present-day BH remnants. Adopting the LF of ULIRGs and a radiative efficiency ϵ_r, we can estimate the BH mass density accreted during the ULIRG phases, and compare it to that observed in the local universe (Soltan 1982; Yu & Tremaine 2002). The estimated BH mass density is given by

$$\rho_{\rm BH} \simeq 3.5 \times 10^4 \left(\frac{1-\epsilon_r}{\epsilon_r}\right) {\rm M}_\odot\ {\rm cMpc}^{-3}, \tag{8}$$

(Delvecchio et al. 2014). In order not to exceed the value observed in the local universe, $\rho_{\rm BH,obs} \simeq 4.2^{+1.2}_{-1.0} \times 10^5$ M$_\odot$ cMpc^{-3} (e.g., Shankar et al. 2009), the radiative efficiency is required to be $\epsilon_r \gtrsim 0.076^{+0.023}_{-0.018}$. This efficiency is consistent with similar arguments for bright QSOs in the optical and X-ray bands (e.g., Yu & Tremaine 2002; Hopkins et al. 2007; Ueda et al. 2014).

The total present-day energy density in GW radiation (stochastic + individually resolved) is estimated from

$$\mathcal{E}_{\rm GW} \equiv \int_0^\infty \rho_{\rm c} c^2 \Omega_{\rm GW}(f) \frac{df}{f}, \quad (9)$$

and $\mathcal{E}_{\rm GW} \simeq 6.1\ (3.2) \times 10^{-16}$ erg s^{-1} cm^{-3} for $t_{\rm delay} =$ 3 (7) Gyr, $\lambda_{\rm Edd} = 0.3$ and $t_{\rm life} = 30$ Myr. Note that $\mathcal{E}_{\rm GW} \propto \lambda_{\rm Edd}^{-0.98} t_{\rm life}^{-1}$. As a result, the ratio of the total GW energy to the present-day SMBH rest mass energy is estimated as

$$\frac{\mathcal{E}_{\rm GW}}{\rho_{\rm BH} c^2} \lesssim \frac{0.29\ \epsilon_r}{1-\epsilon_r}, \quad (10)$$

because $t_{\rm delay} \gtrsim 3$ Gyr is required from the PTA observations. We note that for unequal-mass binaries, the GW radiative efficiency from a BH with a mass of qM, which is gravitationally captured in a circular orbit by a BH with mass of M, is given by $\epsilon_{gw} \simeq (0.057 + 0.4448\eta + 0.522\eta^2)/(1+q) \simeq 0.1192$, where $\eta = q/(1+q)^2$ and $q = 1/3$ is set (Lousto et al. 2010). Approximating $\epsilon_{gw} \simeq \epsilon_r$, therefore we obtain the interesting constraint that the contribution of BH mergers to the present-day BH mass density is less than $\lesssim 58\%(\langle 1+z\rangle/2)$; see Eq. 7 in Phinney (2001).

The brightest U/HyLIRGs that have experienced active star formation at high redshift would be observed as massive elliptical galaxies in the local universe. An important consequence from Eq. (7) is that $\gtrsim 50\%$ of the binary SMBHs formed in ULIRGs neither coalesce within a Hubble time nor contribute to the GWB. For SMBH binaries with mass ratios of $q > 0.1$, the dynamical friction caused by surrounding stars with velocity dispersion $\sigma_\star$ would quickly carry the binary separation down to

$$a_{\rm h} \sim \frac{12q}{1+q} \left(\frac{M_{\rm BH}}{10^9\ {\rm M}_\odot}\right) \left(\frac{\sigma_\star}{300\ {\rm km\ s}^{-1}}\right)^{-2} \ {\rm pc}, \quad (11)$$

where the binary becomes hard, ejects stars and stalls the orbital decay (e.g., Merritt 2013). Since the host galaxy undergoes multiple mergers (probably gas-poor or minor) within $t_{\rm delay} \sim$ a few Gyrs, the stalled SMBH binary would frequently interact with incoming BHs. The multi-body BH interactions would lead to ejections of some BHs and accelerated mergers of the pre-existing stalled ones (Ryu et al. 2018; Bonetti et al. 2018), possibly also leaving a remnant population of $O(1-10)$ pc binaries at the centers of nearby massive ellipticals. Such a binary with a projected separation of $\simeq 7.3$ pc has been detected in the radio (Rodriguez et al. 2006). Although no such binaries have been detected by PTAs to date, this non-detection has already yielded interesting constraints on their mass ratios (Schutz & Ma 2016) and anisotropy in the GWB (Mingarelli et al. 2017).

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