ВАК 2024 MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES
300 years Russian Academy of Sciences

Primordial intermediate-mass binary black holes in space laser interferometers

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Abstract. Primordial black holes (PBHs) with log-normal mass distributions reaching obtained $\sim 10^4$–10^5 solar masses may form following the quantum chromodynamic (QCD) phase transition in the early Universe, potentially due to modified Affleck–Dine baryogenesis. The expected frequency of detection of binary PBHs with intermediate masses using the TianQin space laser interferometer has been calculated based on the model of binary PBH formation and the assumed parameters of the log-normal distribution of primordial black holes. The obtained results are consistent with the LIGO-Virgo-KAGRA (LVK) data.

Keywords: black hole physics, relativistic processes, gravitational waves; cosmology: dark matter, early universe, primordial nucleosynthesis, observations; instrumentation: detectors

DOI: 10.26119/VAK2024.034

1 Introduction

Currently, there are two primary types of black holes are observed, which differ in mass: stellar-mass black holes (Raidal et al. 2019) and supermassive black holes (SMBHs) (Kormendy & Ho 2013). At the same time, intermediate-mass black holes (IMBHs) with masses around 100–10^5 solar masses remain poorly studied. IMBHs may form from the collapse of very massive Population III stars (Schneider et al. 2002), arise from dynamical evolution in dense star clusters (Fujii et al. 2024; Gonzalez Prieto et al. 2024), or have a primordial origin (Blinnikov et al. 2016). IMBHs located at the centers of galaxies can play a key role in tidal disruption events (Eftekhari et al. 2024), act as templates for the formation of SMBHs (Kovacs et al. 2024; Mezcua 2017), and be an important source of signals for space-based laser gravitational-wave interferometers (Fragione & Loeb 2023).

This paper analyzes the potential for detecting primordial binary IMBH mergers using the TianQin laser space interferometer (Luo et al. 2016; Mei et al. 2021). One of the features of these events could be their origin at high redshifts ($z > 20$), prior to the onset of active star formation, when traditional astrophysical mechanisms typically do not predict the existence of binary IMBHs.

2 Primordial binary black holes

PBHs may form in the early Universe due to primordial density perturbations with their mass equal to the mass inside the cosmological horizon at the moment of PBH formation (Carr 1975; Zeldovich & Novikov 1967) at the stage of radiation dominance. In this work, we use a model of PBHs formation with a log-normal mass spectrum (Dolgov & Silk 1993; Dolgov et al. 2009):

$$\frac{dn}{dM} = \mu^2 \exp\left[-\gamma \ln^2\left(\frac{M}{M_0}\right)\right], \tag{1}$$

where γ is a dimensionless constant, and the parameters μ and M_0 have the dimension of mass. In this model, PBHs are formed due to isocurvature perturbations with a high baryon charge, which are created before the end of the inflationary stage. These perturbations turned into large density perturbations during the QCD phase transition ($T_{\rm QCD} \sim 100$–$150\ MeV$), at which point massless quarks gain mass from the primordial quark-gluon plasma. The QCD phase transition temperature is still undetermined and depends on the chemical potential (density of the substance), possible magnetic fields, etc (Arefeva et al. 2023). Thus, reducing the $T_{\rm QCD}$ with a non-zero chemical potential helps create PBH with a higher central mass.

For a log-normal mass distribution eq. (1), the overall mass function is $\psi(M) = (M/\rho_{\rm pbh})(dn/d\ln M)$ ($\int \psi(M) d\ln M = 1$), where $\rho_{\rm pbh} = f_{\rm pbh}\Omega_{\rm dm}\rho_{\rm cr}$ is the energy density of PBH and $f_{\rm pbh} \leq 1$ represents the fraction of PBH in dark matter and reads:

$$\psi(M) = \sqrt{\frac{\pi}{\gamma}} e^{-1/\gamma} \left(\frac{M}{M_0}\right)^2 e^{-\gamma \ln^2 (M/M_0)}. \tag{2}$$

In what follows, masses will be used in units of the central mass M_0 ($m \equiv M/M_0$). Guided by the results of LVK (Andres-Carcasona et al. 2024; Dolgov et al. 2020; Liu et al. 2023), for the numerical estimates below we will use $M_0 = 10, 17, 25\ M_\odot$ and $\gamma = 1$. We will also use the standard flat cosmological model ΛCDM with $H_0 = 70$ km/s/Mpc, $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$ where necessary. Also, here we use $\hbar = c = k_{\rm B} = 1$ values. The exponentially small tail of this distribution could suggest that the IMBH fraction may not be present. However, integration over volumes of space up to large redshifts detectable by space interferometers, along with the inverse relationship of the merger rate of primordial IMBH binaries to cosmic time $t(z)$, contributes for this and lead to a reasonable probability of detecting such TianQin mergers over several years of observation (Fragione & Loeb 2023).

In this work we use the model of binary black hole formation developed in Raidal et al. (2019):

$$\frac{d\mathcal{R}(z)}{d\ln m_1 d\ln m_2} = \frac{3.2\times 10^6}{\text{Gpc}^3\times\text{yr}} S(m_1, m_2, z) f_{\rm pbh}^{53/57} \left(\frac{t(z)}{t_0}\right)^{-34/37} \times \\ \psi(m_1)\psi(m_2) M^{-32/37} \eta^{-34/37}. \tag{3}$$

Here $S \leq 1$ is the suppression factor which we will set to 1 (Hutsi et al. 2021; Raidal et al. 2019), t_0 is the age of the Universe, $M = (m_1+m_2)/M_\odot$, $\eta = m_1 m_2/(m_1+m_2)^2$. Here we change m_1, m_2 to $\mathcal{M}, q$, where $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$ is the chirp-mass of binary system in units M_0 and $q = m_2/m_1 \leq 1$ is the binary mass ratio. Substituting $m_1 = \mathcal{M}(1+q)^{1/5}/q^{3/5}, m_2 = \mathcal{M}q(1+q)^{1/5}/q^{3/5}$ and the Jacobian $J(\mathcal{M}, q) = \mathcal{M}(1+q)^{2/5}/q^{6/5}$.

After substituting eq. (2) into eq. (3) and performing integration over q in eq. (3) we obtain the specific rate

$$\frac{d\mathcal{R}(z)}{d\mathcal{M}} = A \times \mathcal{M}^{42/37} \mathcal{M} e^{-2\gamma \ln^2 \mathcal{M}} \times \int_0^1 \Phi(q, \mathcal{M}) dq. \tag{4}$$

Here $f_q = (1+q)^{1/5}/q^{3/5}$, also

$$A = \frac{3.2\times 10^6}{\text{Gpc}^3\times\text{yr}} f_{\rm pbh}^{53/57} \left(\frac{t(z)}{t_0}\right)^{-34/37} \frac{\pi}{\gamma} e^{-2/\gamma} \left(\frac{M_\odot}{M_0}\right)^{-32/37}, \tag{5}$$

and

$$\Phi(q,\mathcal{M}) = q^{-3/5}(1+q)^{6/5}e^{-\gamma(\ln^2 f_q+\ln^2 f_q q)}\left(f_q^2 q\right)^{-2\gamma\ln\mathcal{M}}\frac{(1+q)^{2/5}}{q^{6/5}}. \tag{6}$$

The merging rate of binary PBHs $d\mathcal{R}/d\mathcal{M}$ at redshift $z=0$ for various model parameters is presented in Fig. 1a. Integrating $d\mathcal{R}/d\mathcal{M}$ over $\mathcal{M}$ gives the overall merging rate of binary PBHs as a function of z (Fig. 1b). In contrast to the astrophysical binary black hole, in the adopted model the merging rate of binary PBHs increases monotonically with increasing redshift according to the law $\mathcal{R}(z)\sim 1/t(z)$ for all z.

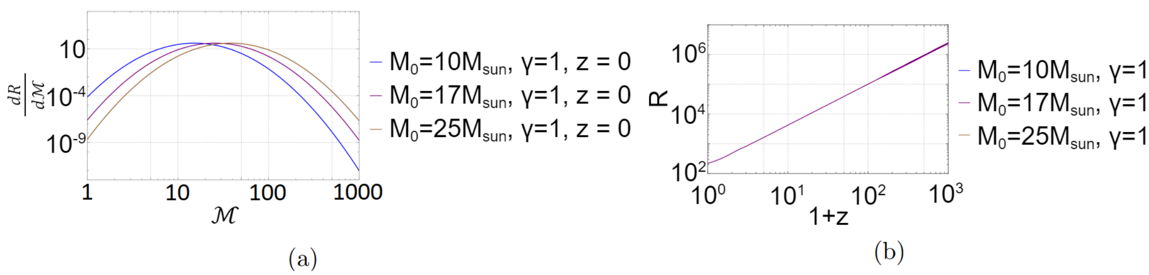

Fig. 1. (a) Expected distribution of the primordial binary IMBH rate over chirp-mass (in solar masses) $d\mathcal{R}/d\mathcal{M}$ [$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$] at $z=0$ for $f_{\rm pbh}=10^{-3}$, $\gamma=1$ and different $M_0=10,17,25M_\odot$. (b) The comoving merging rate of primordial binary PBHs (3) as a function of redshift $\mathcal{R}(z)\sim t(z)^{-34/37}$.

3 Predictions for the detection of merging binary primordial IMBHs at the TianQin detector

The noise sensitivity curve of the detector determines the maximum distance from which a binary system with chirp-mass and mass ratio can be detected at a given signal-to-noise ratio (SNR). We take the sensitivity of TianQin and perform the SNR calculation according to Feng et al. (2019). The limiting redshift $z_{\rm lim}(\mathcal{M})$ with chirp-mass $\mathcal{M}$ for different SNR values is shown in Fig. 2a.

The expected merging rate of binary PBH with taking into account the detector sensitivity is obtained by integrating the rate $d\mathcal{R}/d\mathcal{M}$ in eq. (4) (with eq. (5) and eq. (6)) over redshift up to $z_{\rm lim}(\mathcal{M})$:

$$\frac{dN}{dtd\mathcal{M}} = \int_0^{z_{\rm lim}(\mathcal{M})}\frac{d\mathcal{R}(z)}{d\mathcal{M}}\frac{1}{1+z}\frac{dV(z)}{dz}dz, \tag{7}$$

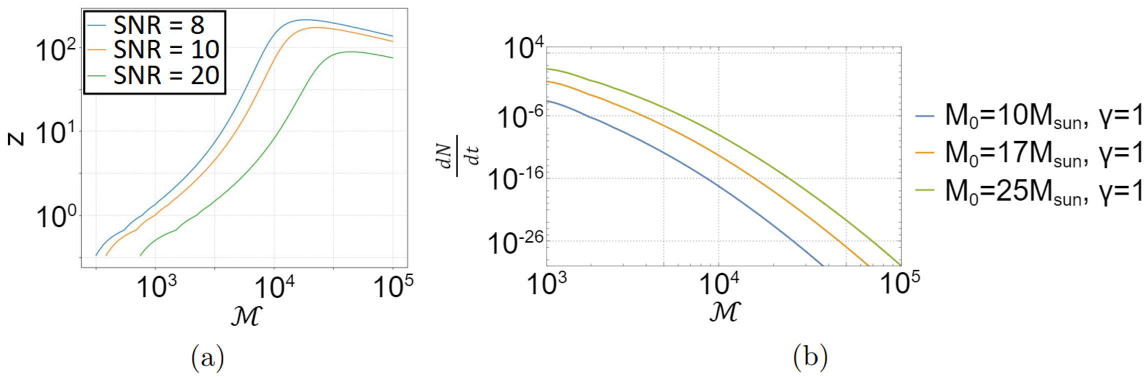

Fig. 2. (a) Limiting redshift $z_{\rm lim}(\mathcal{M})$ (in the source's frame) for detecting of coalescing binary black holes (BHs) with chirp-mass $\mathcal{M}$ (in solar masses) at TianQin threshold $SNR = 8, 10, 20$. (b) The expected cumulative detection rate $\dfrac{dN}{dt}(>\mathcal{M})$ of the primordial binary IMBH with chirp-mass $\mathcal{M}$ (in solar masses) by the TianQin interferometer for $SNR = 8, f_{\rm pbh} = 10^{-3}, \gamma = 1$.

where

$$\frac{dV(z)}{dz} = \frac{1}{H_0}\frac{4\pi D_m^2}{\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda}}. \quad (8)$$

Here, D_m is the metrical distance from the source to the detector. And finally, in eq. (7) according eq. (8) we can obtain a cumulative detection rate:

$$\frac{dN}{dt}(>\mathcal{M}) = \int_{\mathcal{M}}^{\infty} \frac{dN}{dtd\mathcal{M}} d\mathcal{M}. \quad (9)$$

The obtained cumulative detection rate $\dfrac{dN}{dt}(>\mathcal{M})$ in eq. (9) is shown in Fig. 2b. It can be seen that a few primordial binary IMBH mergings can be detected. A feature of such mergers may be zero effective spins and a large redshift $z > 20$, at which nothing but primordial black holes are believed to exist.

4 Conclusions

Using a specific model for the formation of binary PBHs, we calculated the expected rate of detection of such binary BHs using the TianQin interferometer (Fig. 2b). It has been shown that for PBH formation parameters corresponding to the registration rate and distribution of mergers of binary BHs by LVK interferometers ($M_0 \sim 10$–$20\ M_\odot$, $\gamma \sim 1$) and a moderate fraction of PBHs in the dark matter density $f_{\rm pbh} = 10^{-3}$, the expected number of detections of merging IMBHs with a mass

$M \sim 10^3$–10^4 $M_\odot$ can range from several to hundreds of events over several years of observations, depending on the parameters. Thus, we can conclude that space-based laser gravitational-wave interferometers such as TinQin have the potential to provide evidence for the existence of primordial IMBHs.

Acknowledgements. The authors thanks A. Dolgov for discussions.

Funding

The work of N. Mitichkin was supported by the Russian Science Foundation grant 22-12-00103 and the BASIS Foundation grant 22-2-10-2-1. The works of K. Postnov and I. Chekh were supported by the Russian Science Foundation grant 23-42-00055.

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