Coalescing primordial binary black holes with lognormal mass spectrum

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 Submitted January 2021

 Resubmitted January 2021

Primordial black holes created in the early Universe can constitute a substantial fraction of dark matter and serve as seeds for early galaxy formation. Binary primordial black holes with masses of the order of a few dozen solar masses can explain the observed LIGO/Virgo gravitational-wave events. In this Letter, we show that primordial black holes with log-normal mass spectrum centered at $M_0 \approx 15 - 17 M_\odot$ simultaneously explain both the chirp mass distribution of the detected LIGO/Virgo binary black holes and the differential chirp mass distribution of merging binaries as inferred from the LIGO/Virgo observations. The obtained parameters of log-normal mass spectrum of primordial black holes also give the fraction of seeds with distribution of merging binaries as inferred from the LIGO/Virgo observations. The obtained parameters of log-normal mass spectrum of primordial black holes also give the fraction of seeds with

Phase transition stage. Indeed, the temperature at the RD stage is related to the energy density $\rho$ as

$$\rho = \frac{3m_{\text{Pl}}^2}{32\pi t^2} = \frac{\pi^2 g_* T^4}{30}.$$  (2)

Here $g_* \approx 40$ is the number of relativistic species in the primordial plasma above and close to $T_{\text{QCD}}$. Therefore, the mass inside the horizon Eq. (1) can be expressed as

$$M_h \approx 8M_\odot \left( \frac{100 \text{ MeV}}{T_{\text{QCD}}} \right)^2 \left( \frac{40}{g_*} \right)^{1/2}.$$  (3)

where $g_* \approx 40$ is the number of relativistic species in the primordial plasma above and close to $T_{\text{QCD}}$.

Using (1) and (2), the PBH creation condition $R \leq 2M/m_{\text{Pl}}^2$ for the overdensity $\delta \rho$ can be recast into the form

$$\frac{\delta \rho}{\rho} \geq \left( \frac{M_h}{M} \right)^2.$$  (4)

Clearly, this is a rather crude criterion for PBH formation from primordial fluctuations. More detailed calculations for the patches of the horizon collapsing into PBH can be performed by assuming a specific shape and type of the fluctuations (see, e.g., [2] [3] [4]).

In [5], the cosmological inflation has been for the first time employed for PBH formation. It allowed to create PBHs with masses exceeding millions solar masses. PBH creation from adiabatic quantum fluctuations arising at the inflation stage was later considered in [6]. It
was based on Starobinsky’s suggestion \cite{10} on the perturbation generation of the inflaton field in a model with double field inflation. The PBH mass spectrum calculated in ref. \cite{9} has a rather complicated analytical structure and to the best of our knowledge has not been applied to the analysis of observational data.

Depending on the model, PBHs formed at a given epoch can have different mass spectra, including power-law $dn/dM \sim M^{-\alpha}$ \cite{4}, log-normal $dn/dM \sim \exp[-\gamma \ln(M/M_0)^2]$ \cite{5}, or multipeak \cite{11,12} (see recent review \cite{13} for more detail and references).

In the present paper, we will use the log-normal PBH mass spectrum \cite{8,11} that has already been applied to LIGO/Virgo gravitational-wave (GW) events \cite{14} and enabled explanation of the LIGO/Virgo binary black hole chirp mass distribution \cite{15}. Remind that the chirp mass $M$ is the principal parameter that determines the GW waveform of a coalescing binary system with point-like masses $m_1$ and $m_2$ at the inspiralling phase, $M = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$. This parameter is derived from GW observations most accurately.

Cumulative chirp mass distribution of coalescing PBH in LIGO/Virgo observations. As shown in \cite{15}, the cumulative probability $F(>M)$ to observe a population of binary coalescences at a GW detector with given sensitivity is independent of poorly known fraction of PBH as dark matter $f_{\text{PBH}} \lesssim 1$. At the time of writing of ref. \cite{15}, only data on chirp masses of sources from O1-O2 LIGO/Virgo runs were available \cite{16}. Therefore, we have estimated chirp masses of O3 sources from open LIGO/Virgo data by employing the fact the actual sensitivity of LIGO/Virgo detectors is primarily determined by the chirp mass of the coalescing binary and defines the limiting luminosity distance to the source (the detector horizon) $D_h \propto M^{5/6}$.

Here we repeat the analysis of ref. \cite{15} using the published data from both GWTC-1 \cite{15} and GWTC-2 \cite{17} catalogs. The result is presented in Fig. 1. Notably, the best-fit PBH mass spectrum parameters, $M_0 \sim 15 - 17 M_\odot$ and $\gamma \sim 1$, as inferred from the published GW observations, turned out to be similar to those found in our previous analysis \cite{15}. This proves the correctness of our approach to estimate chirp masses from low-latency luminosity distance to the source only.

Chirp mass distribution in the rest frame of coalescing binaries. The GW LIGO/Virgo data enables a Bayesian inference of the intrinsic properties of merging binary BH population. Such an analysis was performed by the LIGO/Virgo team \cite{15} and independently by other authors \cite{19}. Most interesting seems to be the result of ref. \cite{20,21}, which may suggest the emerging evidence for different types of BH populations appeared as BH+BH mergings in distinct mass ranges. Here we draw attention to the high-mass tail of the chirp mass distribution inferred by Bayesian analysis from the LIGO/Virgo data \cite{20,21}. If the PBH model shown in Fig. 1 is correct, then we would expect that the chirp mass distribution of the merging binaries would be constructed from log-normal mass spectrum of each component. The result is presented in Fig. 2. The grey band in Fig. 2 is taken from \cite{20,21} and shows the Bayesian inference (90\% C.L.) of the chirp masses from the published LIGO/Virgo data assuming a power-law mass distribution. The solid green, red and blue curves present the chirp mass distribution for log-normal mass spectrum of the components with $M_0 = 17 M_\odot$ and $\gamma = 0.7, 0.9$ and 1.1, respectively. Clearly, the high-mass tail of the inferred chirp mass distribution can be described by log-normal mass spectrum of the components with parameters close to PBH log-normal mass spectrum shown in Fig. 1 and discussed in detail in ref. \cite{15}. We stress that Fig. 1 and Fig. 2 are totally independent. While Fig. 1 compares the predicted cumulative PBH binary merging chirp mass distribution as observed by the LIGO/Virgo detectors, Fig. 2 shows the chirp mass distribution in the rest-frame of the coalescing binaries. The high-mass tail in Fig. 2 for the best-fit PBH parameters from Fig. 1 (the green curve) lies somewhat higher than the inferred values, but slightly increasing $\gamma$ (red and blue curves) easily ‘puts the tail down’. Note also that here we do not address the problem of the Bayesian inference of parameters of the assumed log-normal mass spectrum of BH-BH components from the published LIGO/Virgo observations, which is a separate task.

High-mass PBHs as seeds of supermassive BH formation. Finally, the obtained PBH mass spectrum parameters $M_0$ and $\gamma$ make it possible to estimate the expected fraction of very heavy PBHs that could be seeds of SMBH observed at $z = 6 - 7$. This problem has been addressed in our previous paper \cite{14}, and here we reappraise this fraction for $M_0 = 17 M_\odot$ and $\gamma = 0.7$. As discussed in ref. \cite{22}, the number density of luminous quasars with $M \sim 10^9 M_\odot$ is $n < 10^{-8}$ Mpc$^{-3}$. The total mass density (both dark matter and baryonic) is $\rho_m \sim 4 \times 10^{10} M_\odot$ Mpc$^{-3}$. This means that if PBHs with log-normal mass spectrum constitute a substantial part of dark matter, the fraction of PBH with masses larger than $\sim 10^4 M_\odot$, that can be seeds for SMBH growth up to $10^9 M_\odot$ at high redshifts should be at least $10^{-9}$. It is easy to check that for $M_0 = 15 - 17 M_\odot$ and $\gamma \sim 1$, this constraint is easily satisfied.
Fig. 1. Cumulative chirp-mass distribution from LIGO/Virgo GWTC-1 and GWTC-2 catalogs (blue histogram) and predicted chirp-mass distribution from binary PBH coalescences with log-normal PBH mass spectrum (solid curves). The red and green curves show the best-fit PBH mass spectrum parameters $M_0$ and $\gamma$ obtained from Kolmogorov-Smirnov and Van den Waerden statistical tests, respectively, at the 95% C.L.

Fig. 2. The chirp-mass distribution as inferred from LIGO/Virgo observations in ref. [20, 21] at 90% C.L. (grey shaded band around curved orange and blue line) and the expected chirp mass distribution of a merging binary PBH with log-normal mass spectrum of the components. Green, red and blue solid lines correspond to $\gamma = 0.7, 0.9, 1.1$, respectively, for $M_0 = 17M_\odot$. 
We conclude that PBHs with log-normal mass spectrum predicted in [8] can provide physical explanation to the population properties of binary BH mergings observed by LIGO/Virgo (the chirp-mass distribution at the detector and in the rest-frame of the coalescing binaries). The central mass of the log-normal PBH mass spectrum is found to be around 15-17 solar masses, close to the predicted PBH mass formed at the QCD phase transition from isocurvature fluctuations suggested by the model [8].

The authors thank the participants of the INR Theory Department New Year-2021 Seminar for constructive criticism and useful discussions. Partial support from RSF grants 19-42-02004 (KP, IS) and 20-42-09010 (AD) is acknowledged. The work of NM is supported by the BASIS foundation.

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