Constraints on primordial black holes and curvature perturbations from the global 21cm signal

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The recent observations of the global 21cm signal by EDGES and gravitational waves by LIGO/VIGO have revived interest in PBHs. Motivated by these observations, many previous works focused on PBHs with lifetimes larger than the present age of the Universe. On one hand, taking into account the radiation from the gas accretion on to PBHs, the influences of the massive PBHs ($M_{\text{PBH}} \sim \mathcal{O}(10^2)M_\odot$) on the evolution of the intergalactic medium (IGM) has been investigated by previous works. On the other hand, considering the Hawking radiation, the similar effects of PBHs on the IGM have also been investigated by previous works for the less massive PBHs ($M_{\text{PBH}} \gtrsim 10^{15}g$). Different from previous works, we investigate the influence of PBHs on the evolution of the IGM for the mass range $6 \times 10^{13}g \lesssim M_{\text{PBH}} \lesssim 3 \times 10^{14}g$. Since the lifetime of these PBHs is smaller than the present age of the Universe, they have evaporated by the present day. Due to Hawking radiation, the heating effects of PBHs on the IGM can suppress the absorption amplitude of the global 21cm signal. In this work, by requiring that the differential brightness temperature of the global 21cm signals in the redshift range of $10 \lesssim z \lesssim 30$, e.g., $\delta T_k \lesssim -100$ mK, we obtain upper limits on the initial mass fraction of PBHs. We find that the strongest upper limit is $\beta_{\text{PBH}} \sim 2 \times 10^{-30}$. Since the formation of PBHs is related to primordial curvature perturbations, by using the constraints on the initial mass fraction of PBHs we obtain the upper limits on the power spectrum of primordial curvature perturbations for the scale range $8.0 \times 10^{15} \lesssim k \lesssim 1.8 \times 10^{16}$ Mpc$^{-1}$, corresponding to the mass range considered here. We find that the strongest upper limit is $P_R(k) \sim 0.0046$. By comparing with previous works, we find that for the mass range (or the scale range) investigated in this work the global 21cm signals or the 21cm power spectrum should give the strongest upper limits on the initial mass fraction of PBHs and on the power spectrum of primordial curvature perturbations.

I. INTRODUCTION

Primordial black holes (PBHs) can form in the early epoch of the Universe if there are large density perturbations. Depending on their mass, PBHs can emit different particles via Hawking radiation\textsuperscript{1,2}, which then interact with other particles in the Universe. The evolution of the intergalactic medium (IGM) is changed due to these interactions, and these changes can influence astrophysical observations, e.g., the global 21cm signal\textsuperscript{3,4}.

The Experiment to Detect the Global Epoch of Reionization Signature (EDGES) has reported the observation of the global 21cm signal, which shows an absorption feature with an amplitude of $T_{21} \sim 500$ mK centered at redshift $z \sim 17$ and is about a factor of 2 larger than expected\textsuperscript{6}. According to the theory, the global 21cm signal is controlled by the evolution of the kinetic temperature ($T_k$), the CMB thermodynamic temperature ($T_{\text{CMB}}$) and the spin temperature ($T_s$). One way to explain the large amplitude observed by the EDGES experiment is to require the IGM to be cooler than expected, which could be caused by, e.g., the interactions between dark matter particles and baryons\textsuperscript{5}. Another way is to enhance the intensity of the radio background at low frequencies, which can be satisfied by possible radio sources\textsuperscript{6,10}. In general, any additional source, e.g., the dark matter annihilation or decay, will heat the IGM and increase the kinetic temperature\textsuperscript{6,14,16}. In order to be consistent with the observational results of the EDGES experiment, the properties of the dark matter particles should be constrained\textsuperscript{6,10,17,21}. As mentioned above, due to Hawking radiation the evolution of the IGM can be influenced by PBHs, and therefore the mass fraction of PBHs can be constrained by the global 21cm signal\textsuperscript{3,6}. In Ref.\textsuperscript{6}, the authors focused on PBHs in the mass range $M_{\text{PBH}} \gtrsim 10^{15}g$ and investigated their influence on the evolution of the IGM. The lifetime of a PBH with a mass $M_{\text{PBH}} \gtrsim 10^{15}g$ is longer than the age of the Universe, and therefore these PBHs have not evaporated by the present day. Taking into account the global 21cm signal, the authors of Ref.\textsuperscript{6} found the upper limits on the present mass fraction of PBHs depending on the masses of PBHs, e.g., $f_{\text{PBH}} \sim 10^{-9}$ for $M_{\text{PBH}} \sim 10^{15}g$. Different from Ref.\textsuperscript{6}, here we focus on PBHs in the mass range $10^{13}g \lesssim M_{\text{PBH}} \lesssim 10^{14}g$, which have evaporated in the redshift range $6 \lesssim z \lesssim 1100$. In Ref.\textsuperscript{22}, the authors investigated the influence of PBHs on the evolution of the IGM for a similar mass range and obtained the upper limits on the initial mass fraction of PBHs using the Planck-2015 data, e.g., $\beta_{\text{PBH}} \sim 10^{-28}$ for $M_{\text{PBH}} \sim 10^{14}g$. For other methods and more detailed discussions on the constraints of initial mass fraction of PBHs see, e.g., Ref.\textsuperscript{1} and references therein.

PBHs can be used to investigate the relevant issues of the early Universe. For example, the initial mass fraction of PBHs is related to primordial curvature pertur-
radiation. The mass loss rate of a black hole can be expressed as 23

$$\frac{dM\text{BH}}{dt} = -5.34 \times 10^{25} f(M\text{BH}) \left( \frac{M\text{BH}}{g} \right)^{-2} g s^{-1}, \quad (2)$$

where $f(M\text{BH})$ measures the number of particle species that are emitted directly. $f(M\text{BH})$ can be calculated exactly 1 and in this work we use the fitted formula used in, e.g., Ref. 13.

$$f(M\text{BH}) = 1.569 + 0.569 e^{-0.6234/T_{\text{BH}}} + 3.414 e^{-0.066/T_{\text{BH}}} + 1.707 e^{-0.117/T_{\text{BH}}} + 0.569 e^{-0.394/T_{\text{BH}}} + 1.707 e^{-0.413/T_{\text{BH}}} + 1.707 e^{-0.222/T_{\text{BH}}} + 0.963 e^{-0.1/T_{\text{BH}}} \quad (3)$$

where $T_{\text{BH}}$ is determined by Eq. (1). For the mass range considered here, $f(M\text{BH})$ is in the range 2.5 \( \lesssim f(M\text{BH}) \lesssim 6.1, \) corresponding to the temperature range \( 33 \text{ MeV} \lesssim T_{\text{PBH}} \lesssim 167 \text{ MeV}. \) For this range, pions, muons, quarks (up, down, and strange), and gluons will be emitted 22, 44, and hadrons will be produced after the emission of quarks and gluons through the process of fragmentation. In this work, we will investigate the influence of PBHs on the evolution of the IGM. Based on previous works, it has been found that the main influence of PBHs on the IGM is due to electrons, positrons, and photons 5, 12. Therefore, following previous works, we consider electrons, positrons, and photons that are emitted directly by PBHs or produced indirectly through the decay of, e.g., muons, pions, and other hadrons 1, 3, 6, 44.

The lifetime of a PBH with a fixed mass, $\tau_{\text{PBH}}$, can be obtained by integrating Eq. (2). One good approximation of the lifetime can be written as 23

$$\tau_{\text{PBH}} \approx 3 \times 10^{14} \left( \frac{M_{\text{PBH}}}{10^{14} g} \right)^3 f(M_{\text{PBH}})^{-1} s. \quad (4)$$

According to Eq. (4), the lifetime of a PBH with mass of $M_{\text{PBH}} \sim 5 \times 10^{14} g$ is equal to the age of the Universe, $t \sim 13.7 \text{ Gyr}$ 45. Therefore, for masses of $M_{\text{PBH}} < 5 \times 10^{14} g$, PBHs have evaporated by the present day. The final stages of PBHs, e.g., a stable Planck mass relic or a connection to extra dimensions, have been discussed in previous works 11, 12. Following Ref. 1, in this work we assume that the Hawking evaporation stops at the final stages.

II. THE INFLUENCE OF PBHS ON THE EVOLUTION OF THE IGM

A. The basic properties of PBHs

In this section we briefly review the basic properties of PBHs. For more detailed discussions, one can refer to, e.g., Refs. 1, 4, 23, and references therein.

In the early epoch of the Universe, PBHs can form if there are large density perturbations. The needed amplitude of large density perturbation is generally of $\delta \rho/\rho \gtrsim 0.3$ 42. According to the theory, a PBH can radiate thermally with temperature 1, 4, 23

$$T_{\text{PBH}} = \frac{1}{8\pi G M_{\text{PBH}}} \approx \left( \frac{M_{\text{PBH}}}{10^{14} g} \right)^{-1} \text{GeV}. \quad (1)$$

The mass of a PBH changes with time due to Hawking

$$\frac{dM_{\text{PBH}}}{dt} = -5.34 \times 10^{25} f(M_{\text{PBH}}) \left( \frac{M_{\text{PBH}}}{g} \right)^{-2} g s^{-1}, \quad (2)$$

where $f(M_{\text{PBH}})$ measures the number of particle species that are emitted directly. $f(M_{\text{PBH}})$ can be calculated exactly 1 and in this work we use the fitted formula used in, e.g., Ref. 13.

$$f(M_{\text{PBH}}) = 1.569 + 0.569 e^{-0.6234/T_{\text{PBH}}} + 3.414 e^{-0.066/T_{\text{PBH}}} + 1.707 e^{-0.117/T_{\text{PBH}}} + 0.569 e^{-0.394/T_{\text{PBH}}} + 1.707 e^{-0.413/T_{\text{PBH}}} + 1.707 e^{-0.222/T_{\text{PBH}}} + 0.963 e^{-0.1/T_{\text{PBH}}} \quad (3)$$

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The lifetime of a PBH with a fixed mass, $\tau_{\text{PBH}}$, can be obtained by integrating Eq. (2). One good approximation of the lifetime can be written as 23

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According to Eq. (4), the lifetime of a PBH with mass of $M_{\text{PBH}} \sim 5 \times 10^{14} g$ is equal to the age of the Universe, $t \sim 13.7 \text{ Gyr}$ 45. Therefore, for masses of $M_{\text{PBH}} < 5 \times 10^{14} g$, PBHs have evaporated by the present day. The final stages of PBHs, e.g., a stable Planck mass relic or a connection to extra dimensions, have been discussed in previous works 11, 12. Following Ref. 1, in this work we assume that the Hawking evaporation stops at the final stages.

B. The evolution of the IGM including PBHs

There are interactions between the particles emitted from PBHs and that existed in the Universe. Due to these interactions the evolution of the IGM is changed.
The main influence of the interactions on the IGM are heating, ionization and excitation \[6, 10, 13, 22, 49\]. For our purposes, the ionization fraction \(x_e\) and the temperature of the IGM \(T_k\) are mainly used to study the evolution of the IGM. The evolutions of \(x_e\) and \(T_k\) with the redshift can be written as \[11, 13, 22\]

\[
(1 + z)\frac{dx_e}{dz} = \frac{1}{H(z)} \left[ R_s(z) - I_s(z) - I_{add}(z) \right], \quad (5)
\]

\[
(1 + z)\frac{dT_k}{dz} = 8\sigma T a_R T_{CMB}^4 \frac{x_e}{3m_e c H(z)} \left[ 1 + f_{He} + x_e \right] (T_k - T_{CMB}), \quad (6)
\]

\[
- \frac{2}{3k_B H(z)} \frac{K_{add}}{1 + f_{He} + x_e} + T_k,
\]

where \(R_s(z)\) is the recombination rate, \(I_s(z)\) is the ionization rate caused by the standard sources. \(I_{add}\) and \(K_{add}\) are the ionization rate and heating rate caused by the additional sources. For our purposes, \(I_{add}\) and \(K_{add}\) are caused by PBHs, i.e. \(I_{add} = I_{PBH}\) and \(K_{add} = K_{PBH}\), and they can be written as \[4, 11, 13, 22\].

\[
I_{PBH} = \chi_i f \frac{1}{n_b} \frac{1}{E_0} \times \frac{dE}{dV dt}|_{PBH} \quad (7)
\]

\[
K_{PBH} = \chi_h f \frac{1}{n_b} \frac{1}{E_0} \times \frac{dE}{dV dt}|_{PBH} \quad (8)
\]

The energy injection rate per unit volume due to PBHs can be written as

\[
\frac{dE}{dV dt}|_{PBH} = \frac{1}{M_{PBH}} \frac{dM_{PBH}}{dt} n_{PBH}(z), \quad (9)
\]

where \(n_{PBH}(z)\) is the number density of PBHs at redshift \(z\). The initial mass fraction of PBHs, \(\beta_{PBH}\), can be written as \[23\]

\[
\beta_{PBH} = \frac{\rho_{PBH}}{\rho_{crit}} = \frac{\rho_{eq}^{PBH}}{\rho_{crit}^{eq}} \left( \frac{a_i}{a_{eq}} \right), \quad (10)
\]

where \(a_i = 1/(1 + z)\) is the scale factor, \(\rho_{PBH}^{eq}\) and \(\rho_{crit}^{eq}\) are the mass density of PBHs and the critical density of the Universe at the time of PBH formation (matter-radiation equality), respectively. The scale factor is related to the horizon mass \(M_H\) as \[23\]

\[
ar_i = \left( \frac{g_{eq}^*}{g_i^*} \right)^{1/12} \left( \frac{M_H}{M_{eq}} \right)^{1/2}, \quad (11)
\]

where \(g_{eq}^* \approx 3\) and \(g_i^* \approx 100\) are the total number of effectively massless degrees of freedom at the epoch of matter-radiation equality and PBH formation, respectively. With the above equations, the number density of PBHs can be written as

\[
n_{PBH}(z) = \beta_{PBH} \left( \frac{1 + z}{1 + z_{eq}} \right)^3 \frac{\rho_{crit}^{eq}}{M_{PBH}^{eq}} \left( \frac{g_i^*}{g_{eq}^*} \right)^{3/2} \left( \frac{M_{eq}^{PBH}}{M_H} \right)^{3/2} \quad (12)
\]

where \(M_{PBH}\) is the mass of PBH at the formation time and we have used the relations and values, \(M_{eq}^{PBH} = 1.3 \times 10^{49} (\Omega_m h^2)^{-2} g\), \(M_{PBH}^{eq} = f_M M_H\) with \(f_M = (1/3)3/2\), \(\rho_{crit}^{eq} = 1.88 \times 10^{-29} h^2 g\ cm^{-3}\) and \(z_{eq} = 3403\) \[23\].

In Eqs. \(7\) and \(8\), \(f\) stands for the energy fraction injected into the IGM due to Hawking radiation and it is a function of redshift \[14, 16, 50, 52\]. In general, the energy that can be injected into the IGM is mainly caused by electrons and photons \[5, 12\]. \(\chi_{i(h)}\) are the fractions of the energy deposited into the IGM for ionization (heating) \[5, 11, 12, 52\]. According to theories on structure formation, the first stars could be formed after the redshift of \(z \sim 30\). These stars became the main sources for ionization, and in this work we adopt the model used in Refs. \[10, 50\]. We have modified the public code RECFAST in CAMB\[2\] to include the influence of PBHs. The evolutions of \(x_e\) and \(T_k\) are shown in Fig. \[1\].

For this figure, we have set the initial mass fraction of PBHs as \(\beta_{PBH} = 10^{-29}\). Due to the influence of PBHs, in general, \(x_e\) and \(T_k\) are larger than that for the case with no PBH, which can be seen clearly in Fig. \[1\] especially after the redshift \(z \sim 600\). The details of the evolutions of \(x_e\) and \(T_k\) are different depending on the mass of PBHs. Since we have assumed that PBHs stop evaporating at the final stage, therefore, there are inflections in Fig. \[1\] for the mass range \(0.6 \times 10^{14} g \lesssim M_{PBH} \lesssim 10^{14} g\), PBHs evaporate in the redshift range \(30 \lesssim z \lesssim 300\). The \(x_e\) and \(T_k\) reach their largest values at redshift \(z'\) (inflections in Fig. \[1\]) corresponding to the lifetime of PBHs. After the redshift \(z'\), the evolutions of \(x_e\) and \(T_k\) tend to follow the cases without PBHs. Similar evolutions can be found for the mass range \(10^{14} g \lesssim M_{PBH} \lesssim 3 \times 10^{14} g\), in which PBHs evaporate in the redshift range \(6 \lesssim z \lesssim 30\).

### III. THE INFLUENCE OF PBHS ON THE GLOBAL 21CM SIGNAL

In the early epoch, the Universe is in the ionized phase and the temperature of the IGM is very high. With the expansion of the Universe, the temperature decreases\[1\].

Here we assume a monochromatic mass fraction for PBHs, and we will investigate the extended mass spectrum for PBHs in detail in future work.

\[2\] https://camb.info/
and the hydrogen atoms form due to the combination of protons and electrons at redshift $z \sim 1100$. The 21cm line is related to the transition between the triplet and singlet levels of the ground state of the hydrogen atom. The transition energy $E$ between the two levels is $E = 5.9 \times 10^{-6}$ eV, corresponding to the wavelength of photon $\lambda = 21$ cm. The spin temperature, $T_s$, which is used to describe the transition, is defined as 

$$T_s = \frac{n_1}{n_0} = 3 \exp \left( -\frac{T_s}{T_s} \right),$$

(13)

where $n_0$ and $n_1$ are the number densities of hydrogen atoms in triplet and singlet states, $T_s = 0.068$ K is the temperature corresponding to the transition energy. The spin temperature $T_s$ is mainly affected by (i) background photons; (ii) collisions between the hydrogen atoms and other particles; (iii) resonant scattering of Lyα photons named Wouthuysen-Field effect $^{53, 54}$. Considering the cosmic microwave background as the main part of the background photons, the spin temperature can be written as $^{50, 51}$

$$T_s = \frac{T_{\text{CMB}} + (y_\alpha + y_e) T_k}{1 + y_\alpha + y_e},$$

(14)

where $y_\alpha$ corresponds to the Wouthuysen-Field effect and we adopt the form used in e.g. Refs. $^{22, 51, 55}$,

$$y_\alpha = \frac{P_{10} T_s}{A_{10} T_k} e^{-3.3 (1 + z)^{0.5} T_k^{-2/3} (1 + \frac{T_k}{T_{\text{CMB}}})^{-1}},$$

(15)

where $A_{10} = 2.85 \times 10^{-15}$ s$^{-1}$ is the Einstein coefficient of the hyperfine spontaneous transition. $P_{10}$ is the de-excitation rate of the hyperfine triplet state due to Lyα scattering $^{53, 54}$. $y_e$ corresponds to the collisions between hydrogen atoms and other particles $^{10, 50, 55}$,

$$y_e = \frac{(C_{\text{HH}} + C_{\text{eH}} + C_{\text{PBH}}) T_s}{A_{10} T_k},$$

(16)

where $C_{\text{HH}}, C_{\text{eH}}, C_{\text{PBH}}$ are the de-excitation rate and we adopt the forms used in Refs. $^{10, 53, 57}$.

In general, the differential brightness temperature, $\delta T_b$, is used to describe the global 21cm signals, which can be written as $^{10, 51, 55}$

$$\delta T_b = 26 (1 - x_e) \left( \frac{\Omega_b h}{0.02} \right) \left\{ \frac{1 + z}{10 \times \frac{\Omega_m}{\Omega_b}} \right\}^{1/2} \times \left( 1 - \frac{T_{\text{CMB}}}{T_s} \right) \text{mK},$$

(17)

Using the above equations, in Fig. 2 we display the evolutions of $\delta T_b$ in the redshift range $10 \lesssim z \lesssim 300$ for different PBH masses. For comparison, the case with no PBHs is also shown (thin black solid line). From Fig. 2 it can be seen that due to the influence of PBHs the absorption amplitude of the global 21cm signal is suppressed, which is caused mainly by the heating effects of PBHs on the IGM. Similar results can also be found in e.g. Refs. $^{5, 6, 10, 50}$. Depending on the different PBH masses, the global 21cm signal exhibits different features and there are also inflections in the plots. For lower mass, e.g. $M_{\text{PBH}} = 0.6 \times 10^{14}$ g (red solid line), PBHs evaporate at the redshift $z \sim 200$. For the redshifts $z \lesssim 200$, the evolutions of $x_e$ and $T_k$ (Fig. 1) tend
to follow the case with no PBHs but are still larger than that case (thin black solid line). As a result, the amplitude of $\delta T_b$ becomes smaller than that for the case with no PBHs. For larger mass, e.g., $M_{PBH} = 1.68 \times 10^{14}$ g (black dot-dashed line), PBHs evaporate in the redshift range $10 \lesssim z \lesssim 30$. For this case, the absorption amplitude of the global 21cm signal is strongly suppressed, and the absorption trough tends to become an emission peak. As shown in Fig. 3 there are two absorption features in the global 21cm signal. One is in the redshift range $30 \lesssim z \lesssim 300$ and another one appears in the redshift range $10 \lesssim z \lesssim 30$. For the mass range considered by us, PBHs have effects on the global 21cm signals in both redshift ranges. Specifically, the main effects are in the higher (lower) redshift range for the smaller (larger) PBHs depending on their lifetime. For our purposes, inspired by the observational results of the EDGES experiment, we have focused on the redshift range $10 \lesssim z \lesssim 30$. As shown in Fig. 2 for this redshift range, larger PBHs have stronger effects on the global 21cm signal compared with that in the redshift range $30 \lesssim z \lesssim 300$. For the plots, we have set the initial mass fraction of PBHs as $\beta_{PBH} = 10^{-29}$, and PBHs with larger initial mass fractions (fixed mass) should have stronger effects on the global 21cm signal. Therefore, in view of the observational results of the EDGES experiment, the initial mass fraction of PBHs should have upper bounds, and this issue will be discussed in the following section.

IV. CONSTRAINTS ON PBHS AND CURVATURE PERTURBATIONS

A. Constraints on the initial mass fraction of PBHs

As the discussed above, PBHs with different masses have a different significant influence on the global 21cm signal. As shown in Fig. 2 the main influence is a suppression of the amplitude of the absorption trough. Moreover, the absorption trough could disappear or become an emission peak due to the effects of PBHs with large initial mass fractions. Therefore, the global 21cm signal can be used to investigate the abundance of PBHs. Recently, the global 21cm signal with a large absorption trough was observed by the EDGES experiment at the redshift $z \sim 17$. Following previous works [5, 17], we obtain the upper limits on the initial mass fraction of PBHs, $\beta_{PBH}$, by requiring the differential brightness temperature of the global 21cm signals to be $\delta T_b \lesssim -100$ mK. In Fig. 3 we display the upper limits on $\beta_{PBH}$ for the mass range $6 \times 10^{13}$ g $\lesssim M_{PBH} \lesssim 3 \times 10^{14}$ g (red solid line). From this plot, it can be seen that the strongest upper limit on the initial mass fraction of PBHs is $\beta_{PBH} \sim 2 \times 10^{-30}$. Because we have considered the effects of PBHs on the global 21cm signal in the redshift range $10 \lesssim z \lesssim 30$, the strongest upper limit appears for larger masses (longer lifetime) in the mass range considered here.

In Ref. [3], using the expected 21cm power spectrum observed by SKA, the authors obtained the potential upper limits on $\beta_{PBH}$ and the strongest upper limit is $\beta_{PBH} \sim 2 \times 10^{-31}$, which is also displayed in Fig. 3 (black dashed-dotted line). Different from this work, the authors of Ref. [3] focused on the influence of PBHs on the 21cm signal in the redshift range $30 \lesssim z \lesssim 300$. Therefore, as shown in Fig. 3 for the mass range considered here the constraints on $\beta_{PBH}$ are stronger for smaller masses (shorter lifetime) than those for larger masses (longer lifetime).

The influence of PBHs on the IGM can also affect the anisotropy of the CMB. Therefore, CMB observations can also be used to investigate the initial mass fraction of PBHs. Utilizing the Planck-2015 data, the authors of Ref. [22] obtained the upper limits on $\beta_{PBH}$ for the mass range $2.8 \times 10^{13}$ g $\lesssim M_{PBH} \lesssim 2.5 \times 10^{14}$ g, and they found that the strongest limit is $\beta_{PBH} \sim 4 \times 10^{-29}$ (black dotted line in Fig. 3). Since the constraints on $\beta_{PBH}$ from the CMB data are mainly from the high redshift range, the strongest upper limit on $\beta_{PBH}$ appears for smaller masses, which can be seen in Fig. 3 and is similar to that of the 21cm power spectrum.

PBHs with masses $M_{PBH} \lesssim 6 \times 10^{13}$ g evaporate before the recombination. Therefore, for this mass range the constraints on the initial mass fraction of PBHs are mainly from the BBN and CMB distortions [1, 13], and the strongest upper limit is about $\beta_{PBH} \sim 10^{-24}$. For large masses $M_{PBH} \gtrsim 6 \times 10^{15}$ g, the constraints on $\beta_{PBH}$ are mainly from the lensing effect [1]. The radiation from the accretion onto PBHs can also affect the evolution of the IGM, and the CMB data can also be used to obtain the upper limits on $\beta_{PBH}$ [59, 62]. The recent observations of gravitational waves provide an important way to constrain the initial mass fraction of PBHs for $M_{PBH} \sim O(10^5) M_{\odot}$ [63, 64]. For other methods and more detailed discussions about the constraints on the initial mass fraction of PBHs, one can refer to e.g. Refs. [1, 23, 65–72] and references therein. As discussed above, the upper limits of the initial mass fraction of PBHs are different for the different astrophysical observations. Since the main influence of PBHs on the CMB are on the higher redshifts, the upper limit on the initial mass fraction of PBH with lower mass (shorter lifetime) is stronger than that of PBHs with larger mass. Compared with the smaller mass, as shown in Fig. 2 PBHs with larger mass have a significant influence on the global 21cm signal observed by the EDGES experiment at the redshift $z \sim 17$. Therefore, different from the constraints from the CMB, the upper limit on the initial mass fraction of PBHs with larger mass (longer lifetime) is stronger than that of PBHs with smaller mass. In particular, PBHs with mass $M_{PBH} \lesssim 10^{13.7}$ g evaporate before recombination (z $\sim 1000$). Therefore, as shown in Fig. 3 there is a cut on the masses of PBHs.

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3 PBHs with smaller masses evaporate before recombination ($z \sim 1000$). Therefore, as shown in Fig. 3 there is a cut on the masses of PBHs.
ororate at redshift $z > 30$. Therefore, the observational results of the EDGES experiment cannot give stringent upper limits on the initial mass fraction of PBHs. On the other hand, since the lifetime of PBHs with mass $M_{\text{PBH}} \gtrsim 10^{14.4} \, \text{g}$ is larger than the present age of the Universe, the observational results of the EDGES experiment also cannot give stringent upper limits on the initial mass fraction of PBHs. From Fig. 3 it can be seen that the strongest upper limits correspond to the intermediate mass range, in which PBHs evaporate in the redshift range $10 \lesssim z \lesssim 30$.

Moreover, for the mass range $6 \times 10^{13} \, \text{g} \lesssim M_{\text{PBH}} \lesssim 3 \times 10^{14} \, \text{g}$, comparing with other constraints, the strongest upper limit on the initial mass fraction of PBHs comes from the observations of the global 21cm signal or the future 21cm power spectrum. In this mass range, constraints can also be obtained through studies of the extragalactic photon background, extragalactic antiprotons and neutrinos \cite{21, 29}, but the constraints are weaker than the 21cm constraints \cite{11, 13}.

B. Constraints on primordial curvature perturbations

PBHs can form via the collapse of the large density perturbations present in the early epoch of the Universe. The density perturbations can be Gaussian or non-Gaussian \cite{73}. In this work, we have considered Gaussian perturbations, and in this case, in light of the Press-Schechter theory \cite{80}, the initial mass fraction $\beta_{\text{PBH}}$ can be written as \cite{23}

$$\beta_{\text{PBH}} = \frac{2 M_{\text{PBH}}}{M_{\text{H}}} \int_{\delta_c}^{1} p(\delta_R(R)) d\delta_R(R) \quad (18)$$

where $M_{\text{PBH}} = f_{\text{PBH}} M_{\text{H}}$. $M_{\text{H}}$ is the horizon mass at the formation time of PBHs, $f_{\text{PBH}}$ is the fraction of the horizon mass that collapses into PBHs. $\delta_c = \delta / \rho$ is the critical value of the density perturbation that can form PBHs and here we set $\delta_c = 1/3$ \cite{39}. $\delta_R(R)$ is the smoothed density contrast at horizon crossing with $R = (aH)^{-1}$. $p(\delta_R(R))$ is the probability distribution of the smoothed density contrast. For the Gaussian perturbations, $p(\delta_R(R))$ can be written as

$$p(\delta_R(R)) = \frac{1}{\sqrt{2\pi \sigma_R(R)}} \exp \left( - \frac{\delta_R^2(R)}{2\sigma_R^2(R)} \right), \quad (19)$$

where $\sigma_R(R)$ is the mass variance in the form of

$$\sigma_R^2(R) = \int_{0}^{\infty} W^2(kR) P_R(k) \frac{dk}{k}, \quad (20)$$

where $W(kR)$ is the Fourier transform of the window function. $P_R(k)$ is the power spectrum of the primordial density perturbations, and it is related to the power spectrum of primordial curvature perturbations, $P_R(k)$ as \cite{23, 81, 82}

$$P_R(k) = \frac{16}{3} \left( \frac{k}{aH} \right)^2 j_1^2(k/\sqrt{5aH}) P_R(k), \quad (21)$$

where $j_1$ is a spherical Bessel function. Different inflation models predict different forms of $P_R(k)$. For the general slow-roll inflation models, $P_R(k)$ can be written as \cite{23, 22, 32, 33}

$$P_R(k) = P_R(k_0) \left( \frac{k}{k_0} \right)^{n(k_0) - 1}. \quad (22)$$

We use this form for our calculations and for more detailed discussions one can refer to e.g. Refs. \cite{22, 32, 33}.

Using the above equations and the constraints on the initial mass fraction of PBHs, in Fig. 4 we display the upper limits on the power spectrum of primordial curvature perturbations for the scale range $8.0 \times 10^{15} \lesssim k \lesssim 1.8 \times 10^{16}$, corresponding to the mass range considered here. The strongest upper limit is $P_R(k) \sim 0.0046$. For comparison, in Fig. 4 we also display the constraints from the Planck-2015 and 21cm power spectrum, corresponding to the constraints on $\beta_{\text{PBH}}$ shown in Fig. 3. Similar to the discussions about the constraints on $\beta_{\text{PBH}}$ in the previous section, for the scale range considered here, since we have focused on the effects of PBHs on the IGM in the redshift range $10 \lesssim z \lesssim 30$, the strongest upper limit appears at the smaller value of
\[ k \sim 1.1 \times 10^{16} \text{ Mpc}^{-1} \] with \( \mathcal{P}_R(k) \sim 0.0046 \), corresponding to a larger PBH mass. For the potential constraints from the 21cm power spectrum, since the authors focused on the redshift range \( 30 \lesssim z \lesssim 300 \), the strongest upper limit appears at the larger value of \( k \sim 1.7 \times 10^{16} \text{ Mpc}^{-1} \) with \( \mathcal{P}_R(k) \sim 0.0044 \), which corresponds to a smaller PBH mass. The constraints on \( \mathcal{P}_R(k) \) from the CMB are mainly from higher redshifts, and the strongest upper limit appears at the larger value of \( k \sim 2.8 \times 10^{16} \text{ Mpc}^{-1} \) with \( \mathcal{P}_R(k) \sim 0.0048 \), corresponding to a smaller PBH mass.

**V. CONCLUSIONS**

We have investigated the influence of PBHs on the IGM due to Hawking radiation for the mass range \( 6 \times 10^{13} \text{ g} \lesssim M_{\text{PBH}} \lesssim 3 \times 10^{14} \text{ g} \). Particles emitted by PBHs interact with those that exist in the Universe. Due to these interactions, the degree of ionization and the temperature of the IGM are enhanced after a redshift \( z \sim 1100 \). The changes of the evolution of the IGM have an influence on the astrophysical observations such as the global 21cm signal. Inspired by the recent observations on the global 21cm signal in the redshift range \( 10 \lesssim z \lesssim 30 \) by EDGES, we have investigated the effects of PBHs on the global 21cm signal. We have found that the main effect is to suppress the absorption amplitude of the global 21cm signal, which is consistent with previous works. By requiring that the differential brightness temperature of the global 21cm signal be \( \delta T_b \lesssim -100 \text{ mK} \), we obtained the upper limits on the initial mass fraction of PBHs depending on their mass. The strongest upper limit is \( \beta_{\text{PBH}} \sim 2 \times 10^{-30} \). In previous works, for the same mass range of PBHs, the constraints on \( \beta_{\text{PBH}} \) can also be obtained using the CMB data, the extragalactic photon background and the potential 21cm power spectrum. By comparing these constraints, we found that for the mass range of PBHs considered here the global 21cm signal or the 21cm power spectrum could give the strongest upper limit. Since the formation of PBHs is related to the primordial curvature perturbations, using the constraints on the initial mass fraction of PBHs we obtained the upper limits on the power spectrum of primordial curvature perturbations for the scale range \( 8.0 \times 10^{15} \lesssim k \lesssim 1.8 \times 10^{16} \text{ Mpc}^{-1} \), corresponding to the mass range of PBHs considered here. The strongest upper limit is \( \mathcal{P}_R(k) \sim 0.0046 \).

Previous works (e.g., Ref. [5]) also investigated the limits on PBHs by requiring \( \delta T_b \lesssim -50 \text{ mK} \). The constraints on the abundance of PBHs are about a factor of 3 weaker for \( \delta T_b \lesssim -50 \text{ mK} \) than that of \( \delta T_b \lesssim -100 \text{ mK} \). These differences should have a slight influences on the constraints of primordial curvature perturbations. In this work, inspired by the observational results of EDGES, we focused on the global 21cm signal in the redshift range \( 10 \lesssim z \lesssim 30 \). As shown in Fig. 4 there are also global 21cm signals in the redshift range \( 30 \lesssim z \lesssim 300 \), and observing these global 21cm signals is very difficult. Future experiments that could be run, e.g., on the Moon would detect these global 21cm signals. As discussed in the above sections and motivated by the work of Ref. [3], the expected 21cm power spectrum in the redshift range \( 10 \lesssim z \lesssim 30 \) should give stronger upper limits on \( \beta_{\text{PBH}} \) or \( \mathcal{P}_R(k) \) than that of global 21cm signal. For the redshift range considered here, the global 21cm signal can also be influenced significantly by other astrophysical factors, such as the star formation efficiency, the collapse fraction of the halos and so on. We will investigate these issues in future work.

In summary, we investigated the influence of PBHs on the global 21cm signal at the redshift \( z \sim 17 \) due to Hawking radiation. Compared with previous works, the new features of this work are as follows:

- We have extended the mass range of PBHs to \( 6 \times 10^{13} \text{ g} \lesssim M_{\text{PBH}} \lesssim 3 \times 10^{14} \text{ g} \). PBHs with masses in this range evaporate in the redshift range \( 10 \lesssim z \lesssim 30 \), and they are expected to have significant effects on the global 21cm signal depending on their initial mass fraction \( \beta_{\text{PBH}} \). Inspired by the observational results of the EDGES experiment, by requiring the differential brightness temperature of the global 21cm signal to be \( \delta T_b \lesssim -100 \text{ mK} \), we have found that the strongest upper limit of the initial mass fraction of PBHs is \( \beta_{\text{PBH}} \sim 2 \times 10^{-30} \), and as far as we know this is currently the strongest upper limit for the mass range considered here.

\[ ^4 \text{As shown in Fig. 4, the upper limits from the future expected} \]
Based on the constraints on the initial mass fraction of PBHs, we obtained the upper limits on the power spectrum of primordial curvature perturbations for the scale range $8.0 \times 10^{15} \lesssim k \lesssim 1.8 \times 10^{16}$ Mpc$^{-1}$. The strongest upper limit is $P_{R}(k) \sim 0.0046$, and this (as far as we know) is currently the best upper limit.

For the mass range considered in this work, and after comparing with other works, we found that the observations and studies on the global 21cm signal or the power spectrum of the 21cm signal could give the strongest upper limits on the initial mass fraction of PBHs and the power spectrum of primordial curvature perturbations. Moreover, since the astrophysical influence on the 21cm signals are very weak in the redshift range $30 \lesssim z \lesssim 300$, future observations of the 21cm signals in this redshift range (e.g., experiment on the Moon) are very useful for the researches on PBHs.

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