The recently proposed trans-Planckian censorship conjecture (TCC) imposes a strong constraint on the inflationary Hubble scale, of which the upper bound could be largely relaxed by considering a non-instantaneous reheating history. In this letter we will show that, if the primordial black holes (PBHs) are collapsed at reentry in the radiation-dominated era from the enhanced curvature perturbations at small scales, the TCC would impose a lower bound on the PBH mass $M_{\text{PBH}} > \gamma (H_{\text{end}}/10^9 \text{GeV})^2 M_\odot$ regardless of the detail for reheating history, where $\gamma$ is the collapse efficiency factor and $H_{\text{end}}$ is the Hubble scale at the end of inflation. In particular, the current open window for PBHs to make up all the cold dark matter could be totally ruled out if the inflationary Hubble scale is larger than 10 TeV. For the case of PBHs formed in an early matter-dominated era, an upper mass bound is obtained.

I. INTRODUCTION

Perhaps the most astonishing insight on cosmology is that, the phenomena at the largest scale like those of cosmic microwave background (CMB) [1,2] and large scale structure (LSS) could be emerged from the phenomena of quantum fluctuations at the smallest scale, which could be traced back to an accelerating expansion phase in the early universe with shrinking comoving Hubble horizon $1/(aH)$ in the inflationary cosmology [4-8] as well as some alternative scenarios (see e.g. [9] for a review). Such an early inflationary phase, if lasts long enough, would eventually stretch even the smallest quantum fluctuations of Planck size out of the Hubble horizon, after which they become classical and frozen until the reentry to be observed today. This imposes the well-known inflationary trans-Planckian problem [10-14], since, in a consistent theory of quantum gravity, these trans-Planckian quantum fluctuations should remain quantum so as not to jeopardize the effective field theory (EFT) treatment on inflation. This leads to a recent claim [15] of trans-Planckian mode should ever exit the Hubble horizon that would otherwise belongs to the swampland.

TCC puts a strong constraint on the duration of an early inflationary phase by

$$\frac{a_i}{a_f} < \frac{M_{\text{Pl}}}{H_f}, \quad (1)$$

where $a_i,f$ are the scale factors at the beginning/end of that inflating phase, and $H_i,f$ are the corresponding Hubble scales. Working with the approximation of a constant inflationary Hubble scale $H_i \approx H_f \approx H_{\text{inf}}$, (1) could be translated into an upper bound on the inflationary e-folding number $N_{\text{inf}}$ (the e-folding number at the end of inflation is fixed to be zero throughout the letter),

$$e^{N_{\text{inf}}} \leq \frac{M_{\text{Pl}}}{H_{\text{inf}}}, \quad (2)$$

which serves as a stronger bound compared to an early estimation $N_{\text{inf}} < M_{\text{Pl}}/H_{\text{inf}}^2$ from quantum gravity [10]. If such an early inflationary phase is directly connected to the phase of standard big bang expansion with instantaneous reheating history, it could be quickly observed [17] from (2) that $N_{\text{inf}} = 46.2$, leading to a strong constraint on the inflationary Hubble scale and tensor-to-scalar ratio,

$$\frac{H_{\text{inf}}}{M_{\text{Pl}}} < e^{-N_{\text{inf}}} = 8.4 \times 10^{-21}, \quad (3)$$

$$r \equiv \frac{2}{\pi^2 P_R} \left( \frac{H_{\text{inf}}}{M_{\text{Pl}}} \right)^2 < 6.8 \times 10^{-33}, \quad (4)$$

where $P_R \approx 2.1 \times 10^{-9}$ is used from Planck 2018 [3]. However, the upper bound [1] is so strong for slow-roll inflation models that would cause a severe fine tuning of initial conditions.

Fortunately, the upper bound [4] could be largely relaxed by considering a non-instantaneous reheating history [18] (See also [19, 20] for non-thermal/non-standard post-inflationary history). Starting with the observation that the current comoving Hubble horizon should be originated from the comoving Hubble horizon at the beginning of the inflation, $1/(a_0 H_0) \lesssim 1/(a_i H_i)$, one arrives at

$$\frac{H_i}{M_{\text{Pl}}} < \frac{a_0 H_0}{a_i H_f}, \quad (5)$$

after appreciating the TCC bound [1]. To further evaluate the denominator $a_i H_f$ at the end of inflation in
terms of a general reheating history characterized by an e-folding number \(N_{\text{reh}}\) and an equation-of-state (EoS) parameter \(w_{\text{reh}}\), one could use following relations

\[
a_{\text{reh}} = e^{-N_{\text{reh}}}, \quad a_{\text{reh}} = \left( \frac{43}{11} \right)^{\frac{1}{3}} \frac{T_0}{T_{\text{reh}}}, \quad a_{\text{reh}} = \left( \frac{43}{11} \right)^{\frac{1}{3}} \frac{T_0}{T_{\text{reh}}},
\]

\[
3M_{\text{Pl}}^2 H_i^2 e^{-3N_{\text{reh}}(1+w_{\text{reh}})} = \frac{\pi^2}{30} g_{\text{reh}} T_{\text{reh}}^4,
\]

where \(T_{\text{reh}}, g_{\text{reh}}\), and \(a_{\text{reh}}\) are the reheating temperature, the degrees of freedom of relativistic species and the scale factor at the end of reheating, respectively. The inflationary Hubble scale is therefore bounded from above by

\[
\frac{H_i}{M_{\text{Pl}}} < e^{-\frac{N_{\text{reh}}(1+3w_{\text{reh}})}{43}} \left( \frac{11}{43} \right)^{\frac{1}{3}} \frac{1}{6} \frac{H_0 M_{\text{Pl}}}{(\pi^2/90)^{1/2} g_{\text{reh}}} \frac{T_0}{T_{\text{reh}}},
\]

\[
\lesssim \frac{H_0 M_{\text{Pl}}}{T_0 T_{\text{reh}}} \approx 66 \frac{T_0}{T_{\text{reh}}} = 1.5 \times 10^{-8} \left( \frac{\text{1 MeV}}{T_{\text{reh}}} \right)
\]

where the first inequality in the second line is taken for a near-critical expansion after inflation with EoS parameter \(w_{\text{reh}} \gtrsim -1/3\) to achieve the maximum relaxation on the tensor-to-scalar ratio

\[
r \lesssim 2.3 \times 10^{-8} \left( \frac{1 \text{ MeV}}{T_{\text{reh}}} \right)^2.
\]

Now the upper bound [10] with reheating temperature down to the lowest possible temperature required by big bang nucleosynthesis (BBN) could be realized in some supergravity- or string-inspired inflation models. On the other hand, the reheating temperature cannot be too large, otherwise the inflationary energy density bounded by [8] could be smaller than the reheating energy density. Therefore, by requiring \(3M_{\text{Pl}}^2 H_i^2 \gtrsim \frac{\pi^2}{30} g_{\text{reh}} T_{\text{reh}}^4\) for [8], one obtains

\[
(T_{\text{reh}} M_{\text{Pl}})^6 \lesssim \left( \frac{90 H_0^2}{\pi^2 T_0^2} \right)^6,
\]

namely, \(T_{\text{reh}} \lesssim 6.5 \times 10^8 \text{ GeV}\). See [21] [24] for other discussions on TCC from the viewpoints of initial state, dark matter and warm inflation.

In this letter, we will discuss the TCC implication on the mass bound for the primordial black holes (PBHs) formed in the radiation-dominated era (Sec. II A) and an early matter-dominated era (Sec. II B), assuming that the PBH formation at reentry comes from large curvature perturbations at small scales. We conclude in the last section. It is worth noting that, the derived PBH mass bounds would not be applicable to other scenarios of PBH production from curvaton [25] [26], scalar lumps [27] [28], cosmic strings [29] [30], domain walls [31] [32], primordial bubbles [33], bubble collisions [34] [35], and preheating instability [36], to name just a few.

II. MASS BOUND FOR PBH FROM TCC

The only existing lower bound on the PBH mass, \(M_{\text{PBH}} \gtrsim 10^{15} \text{ g}\), comes from the observation of absence of extragalactic photon [37] [38] during PBH evaporation [39] [40]. Here we will derive the mass bound for PBH from a theoretical perspective of TCC irrespective of detail reference to the reheating history.

### A. PBHs formed in the radiation-dominated era

For PBHs collapsed from the horizon mass with efficiency factor \(\gamma \approx 0.2\) [49], the PBH mass is estimated by

\[
M_{\text{PBH}} = \gamma \frac{4 \pi^2 M_{\text{Pl}}^2}{H_{\text{form}}^3} = \frac{4 \pi^2 M_{\text{Pl}}^2}{H_{\text{form}}^3}.
\]

For PBHs formed in the radiation-dominated era (as shown in the left panel of Fig. 1), the Hubble scale at PBH formation \(H_{\text{form}}\) could be related to the Hubble scale \(H_{\text{PBH}}\) at the exit of the corresponding curvature perturbations via the comoving relation \(\delta_{\text{form}} H_{\text{form}} = \delta_{\text{PBH}} H_{\text{PBH}}\) and the scaling relation \(H \propto a^{-3(1+w)/2}\), namely,

\[
H_{\text{form}} = \gamma \frac{4 \pi^2 M_{\text{Pl}}^2}{H_{\text{PBH}}^3} = \gamma \frac{4 \pi^2 M_{\text{Pl}}^2}{H_{\text{PBH}}^3}.
\]

Note that the exponential factor in above equation could be rearranged in such a way that all dependence on the reheating history could be totally removed away [50],

\[
H_{\text{form}} = e^{-2(N_0 - N_{\text{PBH}}) \frac{1}{2} \left[ \left( \frac{43}{11} \right)^{1/3} \left( \frac{11}{43} \right)^{1/2} g_{\text{reh}} \right] - \frac{1}{2} \ln \left( \frac{2 \pi r_{\text{CMB}}}{9} \right)}.
\]

where \(N_{\text{PBH}} \equiv N_{\text{CMB}} - N_{\text{PBH}}\) is the difference in the e-folding number at the exit of CMB pivot scale \(k_{\text{CMB}} = 0.002 \text{ Mpc}^{-1}\) with respect to the exit of curvature perturbations that collapse into PBHs at reentry, and \(N_{\text{tot}}\) is an abbreviation for the combination

\[
N_{\text{tot}} \equiv \ln \left[ \frac{T_0}{k_{\text{CMB}}} \left( \frac{\pi^2/90}{\frac{43}{11}} \right)^{1/2} g_{\text{reh}} \right] - \frac{1}{2} \ln \left( \frac{2 \pi r_{\text{CMB}}}{9} \right)
\]

\[
\approx 64.99 + \frac{1}{4} \ln(r_{\text{CMB}}) \approx 65 + \frac{1}{4} \ln \left( \frac{2 H_{\text{CMB}}}{\pi^2 M_{\text{Pl}}^2} \right).
\]

Now the PBH mass could be expressed as

\[
M_{\text{PBH}} = 4 \sqrt{2 \gamma} \left( \frac{H_{\text{CMB}}}{H_{\text{PBH}}} \right)^2 e^{2(65-\Delta_{\text{PBH}}) M_{\text{Pl}}},
\]

which, after using \(H_{\text{CMB}} \gtrsim H_{\text{PBH}}\) and the TCC bound \(\Delta_{\text{PBH}} < N_{\text{inf}} < \ln(M_{\text{Pl}}/H_{\text{end}})\), gives rise to a lower bound as

\[
M_{\text{PBH}} > \gamma \left( \frac{H_{\text{end}}}{1.3 \times 10^9 \text{ GeV}} \right)^2 M_{\odot},
\]

which is independent from specific configurations of reheating history. It is easy to see that, if there is a lower bound on the inflationary Hubble scale, then there would
be a corresponding lower bound on the PBH mass, below which there are no PBHs as shown by the excluded gray regions in the right panel of Fig. 1. On the other hand, the PBH abundance in cold dark matter (DM) cannot be constrained by TCC, since it is exponentially sensitive to the small-scale enhancement in curvature perturbations. Several implications from above bound are as follows: First, the observational lower bound $M_{\text{PBH}} \gtrsim 10^{-18} M_\odot$ could always be fulfilled as long as the inflationary scale $H_{\text{end}} \lesssim \gamma^{-1/2} \text{GeV}$. Second, no PBH with mass smaller than $10^2 M_\odot$ is allowed if the inflationary Hubble scale is larger than $10^{10} \gamma^{-1/2} \text{GeV}$. Fortunately, such LIGO-type PBHs could be allowed by TCC, because the reheating-assisted TCC bound on inflationary Hubble scale forbids any inflationary scale larger than $10^{10} \gamma^{-1/2} \text{GeV}$.

B. PBHs formed in an early matter-dominated era

To minimally extend previous discussion on mass bound for PBH to other production channels, one could also consider PBH formation in an early matter-dominated era right after inflation but before the reheating era [53,54], which is shown by the gray region in the left panel of Fig. 2. After simple manipulations with the comoving relation $a_{\text{form}} H_{\text{form}} = a_{\text{PBH}} H_{\text{PBH}}$ and the scaling relation $H \propto a^{-3(1+w)/2}$, one could express the Hubble scale at PBH formation in terms of the Hubble scale at the exit of the enhanced small-scale fluctuations directly by

$$\frac{H_{\text{form}}}{H_{\text{PBH}}} = \frac{a_{\text{PBH}}}{a_{\text{form}}} = \frac{a_{\text{end}}^3}{a_{\text{form}}^3} \frac{H_{\text{PBH}}^2}{H_{\text{end}}^2} = e^{-3 N_{\text{PBH}}} \frac{H_{\text{end}}^2}{H_{\text{PBH}}^2}$$

(18)

without referring to the reheating era. Hence the PBH mass becomes

$$M_{\text{PBH}} = 4 \pi \gamma \frac{M_{\text{Pl}}^2 H_{\text{end}}^2 e^{3 N_{\text{PBH}}}}{H_{\text{PBH}}^3} < 4 \pi \gamma \frac{M_{\text{Pl}}^2 H_{\text{end}}^2}{H_{\text{BPB}}^3} e^{3 N_{\text{inf}}}$$

(19)

where we have used $N_{\text{PBH}} \ll N_{\text{inf}} \ll \ln(M_{\text{Pl}}/H_{\text{end}})$ and $H_{\text{PBH}} \gtrsim H_{\text{end}}$. Now the PBH mass formed in an early matter-dominated era has an upper bound as

$$M_{\text{PBH}} < \gamma \left( \frac{9.9 \times 10^8 \text{GeV}}{H_{\text{end}}} \right)^4 M_\odot,$$

(20)

above which is excluded in gray as shown in the right panel of Fig. 2 if the inflationary scale is larger than certain value. Several implications from above bound are in
order: First, no PBH with mass larger than $10^{-18} M_\odot$ is allowed if the inflationary Hubble scale is larger than $10^{14}$ GeV. Second, LIGO-type PBH could not fit the upper bound (20) if the inflationary Hubble scale is larger than $10^9$ GeV. Third, PBHs formed in an early matter-dominated era with mass larger than $10^4 M_\odot$ is not allowed if the inflationary Hubble scale is larger than $10^8$ GeV.

III. CONCLUSION

In this letter, using only the recently proposed TCC bound on the inflationary e-folding number, we derive the mass bounds for PBHs formed in the radiation-dominated and an early matter-dominated eras from the enhanced curvature perturbations at small-scales in the inflationary cosmology. The explicit dependence on the detail configurations of reheating history are carefully removed. The resulting mass bounds for PBH therefore only rely on the inflationary Hubble scale. In particular, for PBHs formed in the radiation-dominated era, the asteroid-mass PBHs observationally allowed to make up all the cold DM cannot exist if the inflationary Hubble scale is higher than 10 TeV scale.

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