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Full Text

Preamble

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Supermassive Primordial Black Holes for Nano-Hertz Gravitational Waves and High-redshift JWST Galaxies

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Abstract

Recently, observational hints for supermassive black holes have been accumulating, prompting the question: Can primordial black holes (PBHs) be supermassive, particularly with masses $M \gtrsim 10^9 M_\odot$? A supercritical bubble, containing an inflating baby universe, that nucleated during inflation can evolve into a PBH in our observable universe. We find that when the inflaton slowly transitions past a neighboring vacuum, the nucleation rate of supercritical bubbles inevitably peaks, leading to a mass distribution of multiverse PBHs with a peak mass up to $M \gtrsim 10^{11} M_\odot$. Thus, our mechanism naturally provides a primordial origin for supermassive black holes.

Key words: (cosmology:) early universe – (cosmology:) inflation – (galaxies:) quasars: supermassive black holes

1. Introduction

In recent years, the cosmological implications of primordial black holes (PBHs) (Zel'dovich & Novikov 1967; Hawking 1971; Carr & Hawking 1974), which might be responsible for dark matter and LIGO-Virgo gravitational wave (GW) events (Bird et al. 2016; Sasaki et al. 2016; Clesse & García-Bellido 2017), have been intensively studied (e.g., Sasaki et al. 2018; Carr et al. 2021a, 2024). However, an intriguing question remains: Can PBHs be supermassive? In particular, can their masses reach $M \gtrsim 10^9 M_\odot$ (Carr et al. 2021b)?

The origin of supermassive PBHs likely requires a connection to inflation, since only inflation can stretch sub-horizon inhomogeneities to the scales needed for supermassive PBHs. It has been widely thought that massive PBHs can be sourced by very large inflationary perturbations (Carr & Lidsey 1993; Ivanov et al. 1994; García-Bellido et al. 1996; Kawasaki et al. 1998; Yokoyama 1998), with $\delta\rho/\rho \gtrsim 0.1$. However, current cosmic microwave background (CMB) spectral

distortion observations have ruled out such significant enhancement of primordial perturbation amplitudes (if Gaussian) on scales $k \lesssim 10^4 \text{Mpc}^{-1}$, and hence PBHs with masses $M > 10^4 M_\odot$ (Nakama et al. 2018; see also De Luca et al. 2021, 2023; Franciolini et al. 2023).

It seems that scenarios with highly non-Gaussian primordial perturbations are needed to create supermassive PBHs (e.g., Nakama et al. 2016; Hasegawa & Kawasaki 2018; Kawasaki & Murai 2019; Kitajima & Takahashi 2020; Atal et al. 2021; see also Shinohara et al. 2021, 2023).

It is also well-known that a supercritical bubble (containing an inflating baby universe inside) that nucleated during inflation can develop into a PBH in our observable universe (Garriga et al. 2016). In the corresponding multiverse scenario, after inflation ends, the supercritical bubble connects to our universe through a wormhole, and we would eventually observe a PBH after the wormhole pinches off (see also Deng et al. 2017; Deng & Vilenkin 2017; Deng 2020; Wang et al. 2019; He et al. 2024 for further investigations). However, the mass distribution of such multiverse PBHs is heavily suppressed at large masses (Garriga et al. 2016; Deng & Vilenkin 2017), making it negligible in the supermassive band $M \gtrsim 10^9 M_\odot$ (see also Kusenko et al. 2020).

Recently, observational hints for supermassive black holes (BHs) have been accumulating. Evidence for a nano-Hertz stochastic GW background has been found with pulsar timing arrays (PTAs) (Agazie et al. 2023b; EPTA Collaboration et al. 2023; Reardon et al. 2023; Xu et al. 2023), which might be interpreted as arising from a population of supermassive BH binaries with $M \gtrsim 10^9 M_\odot$ (Agazie et al. 2023a; see also Ellis et al. 2024). An alternative explanation might be an inflationary primordial GW (Vagnozzi 2021, 2023; Benetti et al. 2022; Afzal et al. 2023; Jiang et al. 2024a), which can be implemented by null energy condition violation (e.g., Piao & Zhang 2004; Liu et al. 2011; Cai & Piao 2021, 2022; see also Papanikolaou & Gourgouliaos 2023; Ashoorioon et al. 2022; Sakharov et al. 2021; Bian et al. 2022).

Supermassive BHs with $M \sim 10^8\text{--}10^{10} M_\odot$ are believed to reside at the centers of galaxies observed at redshifts $z \gtrsim 6$, which still represents a challenge for standard astrophysical accretion models (Volonteri 2010; Volonteri et al. 2021). James Webb Space Telescope (JWST) observations have also discovered numerous early supermassive galaxies ($M \gtrsim 10^{10} M_\odot$) at higher redshifts $z \sim 10$, which are discordant with the ΛCDM model (Boylan-Kolchin 2023) but might be explained with ΛCDM +supermassive BHs (Liu & Bromm 2022; Hütsi et al. 2023). Currently, there is consensus that supermassive BHs can either originate from seed-like PBHs as massive as $\sim 10^3 M_\odot$ (Düchting 2004; Serpico et al. 2020), which must then acquire sufficient accretion, or be supermassive PBHs by birth, which might be most natural.

However, it remains unclear how supermassive PBHs can form. In this work, we present such a mechanism. We find that in a slow-roll inflation model with multiple neighboring metastable vacua, the mass distribution of multiverse PBHs

formed by supercritical bubbles that nucleated during inflation inevitably exhibits a multi-peak spectrum, with the peak mass reaching $M \gtrsim 10^{11} M_\odot$. Thus, our multiverse PBHs can naturally serve as the supermassive BHs needed to explain nano-Hertz GWs and supermassive JWST galaxies.

2. Our Multiverse PBH Model

In our phenomenological model (see Figure 1 for $V(\phi_1, \phi_2)$), the inflaton ϕ_1 slowly rolls along its potential $V_{\text{inf}}(\phi_1)$ at $\phi_2 = 0$, while a neighboring vacuum with $V = V_b$ exists at $\phi_2 = \phi_{2,F}$ and $\phi_1 = \phi_{1,*}$. It is expected that bubble nucleation with $V = V_b$ is maximized only when ϕ_1 rolls to the vicinity of $\phi_{1,*}$.

In the thin-wall regime, the bubble nucleation rate per Hubble spacetime volume in the inflating background is given by (Garriga et al. 2016)

$$\lambda \sim H^4 e^{-S_E},$$

where $S_E = 27\pi^2 \sigma^4 / (2\epsilon^2)$ is the Euclidean action, with σ being the wall tension and $\epsilon = V_{\text{inf}}(\phi_1) - V_b$ representing the energy difference between vacua. The “path” represents the “least-action” path (Ahlqvist et al. 2011). Here, we will not calculate σ exactly, but consider an approximation that highlights how λ is affected by the inflaton’s roll: when the inflaton passes through $\phi_{1,*}$, we have $d\phi_1 \sim \Delta\phi_1 = \phi_1 - \phi_{1,*}$ and $d\phi_2 \sim \phi_{2,F}$, thus

$$\sigma \simeq \sqrt{(\Delta\phi_1)^2 + \phi_{2,F}^2}.$$

According to this approximation, we have

$$S_E \simeq \frac{27\pi^2}{2} \frac{[(\Delta\phi_1)^2 + \phi_{2,F}^2]^2}{\epsilon^2},$$

where the effect of the rolling velocity of the inflaton on λ is imprinted in $\Delta\phi_1$, with N being the e-folding number before inflation ended.

After nucleation, the bubble expands rapidly. Inflation ends at $t = t_i$, at which time the number density of bubbles is $n \sim \lambda/H^3$ (where r_i is the bubble radius at t_i), and the energy of the inflaton is rapidly converted to radiation, so $V \sim 0$ outside the bubble and is completely negligible.

In Figure 2, we present the full Penrose diagram for the supercritical bubble evolving into a PBH. In the corresponding spacetime, the supercritical bubble contains a baby inflating universe, which is connected to the exterior through a wormhole that eventually closes. A PBH will ultimately form in our observable universe. By causality, the region affected by the PBH’s Schwarzschild radius cannot exceed the Hubble radius of the parent universe $1/H \sim t_H$. During the radiation era, the bubble expands comovingly with $a(t)$ until its physical radius

$r = a(t_H)r_i \sim t_H$ (so $t_H \sim r_i$), after which the bubble will be hidden behind the horizon of a PBH with mass

$$M \sim \frac{t_H}{G} \sim \frac{r_i}{G} \sim \frac{H^{-1}e^{-N}}{G} \sim M_{\text{Pl}}^2 H^{-1} e^{-N}.$$

The dark matter density is $\Omega_{\text{PBH}} = \rho_{\text{PBH}}/\rho_c$, where $\rho_{\text{PBH}} \sim Mn$ and $\rho_c \sim H^2 M_{\text{Pl}}^2$. Thus the mass distribution of such PBHs is (Garriga et al. 2016; Deng & Vilenkin 2017)

$$f(M) \equiv \frac{M}{\rho_{\text{PBH}}} \frac{d\rho_{\text{PBH}}}{dM} \sim \frac{M^2 n(M)}{\int Mn(M)dM}.$$

According to this expression, $f(M)$ is maximized at $\phi_1 = \phi_{1,*}$ (equivalently at $M = M_{\text{peak}}$). It is significant to examine the resulting $f(M)$ in different slow-roll inflation models. As a simple example, we consider $V_{\text{inf}}(\phi_1) \sim \phi_1^p$. In the large- N limit,

$$\Delta\phi_1 \sim \phi_{1,*} e^{-pN},$$

where $p = 2$ corresponds to chaotic inflation (Linde 1983; Kaloper & Sorbo 2009), and $p = 2/3, 1, 4/3$ correspond to monodromy inflation (Silverstein & Westphal 2008; McAllister et al. 2010). Thus with the mass distribution formula, we have

$$M_{\text{peak}} \sim M_{\text{Pl}}^2 H^{-1} \exp \left[-N - \frac{2}{p} \ln \left(\frac{\phi_{1,*}}{\phi_{2,F}} \right) \right].$$

In KKLТ brane inflation models, $V(\phi_1) \sim \phi_1^{-p}$ (Kachru et al. 2003a; Kallosh et al. 2019), where $p = 1, 2, 3, 4$. In such models, for $\mu = M_{\text{Pl}}$, we have

$$M_{\text{peak}} \sim M_{\text{Pl}}^2 H^{-1} \exp \left[-N + \frac{2}{p} \ln \left(\frac{\phi_{1,*}}{\phi_{2,F}} \right) \right].$$

The corresponding results are shown in Figure 3. Different values of p and $\phi_{2,F}$ (the “shortest paths” to a neighboring vacuum) result in different profiles of $f(M)$.

In our multiverse PBH model, we can have $\epsilon \sim 0.01$ on all scales (outside the bubbles) for $p \sim 2$ inflation. However, it must be mentioned that in primordial-perturbation-sourced PBH models, a large amplitude $\delta\rho/\rho \gtrsim 0.1$ of primordial scalar perturbations requires breaking the standard slow-roll evolution ($\epsilon \sim 0.01$) of the inflaton on corresponding PBH scales, as in so-called ultra-slow-roll scenarios. It is also interesting to consider Kachru-Kallosh-Linde-Trivedi

(KKLT) brane inflation, where $V(\phi_1) \sim \phi_1^{-p}$. The corresponding results are also displayed in Figure 3.

3. Discussion

In this work, we found that if the inflaton passes by a neighboring vacuum, the mass spectrum of multiverse PBHs formed by supercritical bubbles that nucleated during inflation develops a peak. It is usually expected that inflation occurred at $V \sim (10^{16}\text{GeV})^4$ and lasted for $N \sim 50\text{--}60$ e-folds. Thus, if bubbles nucleated at $N \sim 40$, the mass peak will be at

$$M_{\text{peak}} \sim 10^{11} M_{\odot} \left(\frac{H}{10^{14}\text{GeV}} \right)^{-1} \exp \left[-40 + \frac{2}{p} \ln \left(\frac{\phi_{1,*}}{\phi_{2,F}} \right) \right].$$

In Liu & Bromm (2022), it was shown that early supermassive galaxies observed by JWST can be explained by supermassive BHs ($M \gtrsim 10^9 M_{\odot}$) comprising a small fraction ($\sim 10^{-3}$) of dark matter. According to our results, multiverse PBHs can be supermassive, reaching up to $10^{11} M_{\odot}$, and thus can naturally serve as such supermassive BHs.

The nano-Hertz stochastic GW background recently detected might be interpreted as arising from a population of supermassive BH binaries with $M \gtrsim 10^9 M_{\odot}$, though this explanation appears to have mild tension with North American Nanohertz Observatory for Gravitational Waves (NANOGrav) 15-year data (Agazie et al. 2023a; Ellis et al. 2024). However, the interpretation actually depends on the origin and evolution mechanism of supermassive BHs. In this sense, the current tension might simply reflect the primordial origin of supermassive BHs.

Generally, the number density of supermassive PBHs is very low, so their merger rate is non-negligibly affected by the Hubble expansion of the background. Taking into account the effect of cosmic expansion on the comoving distance of PBH pairs, as well as torques from all PBHs and linear density perturbations, we calculated the merger rate of supermassive PBHs with any extended mass distribution (Huang et al. 2024). It was found in Huang & Piao (2023) that the merging of clustered supermassive PBHs can explain the recent NANOGrav stochastic gravitational wave background (SGWB) (see also Rubin et al. 2001; Khlopov et al. 2005; Belotsky et al. 2019; Guo et al. 2023).

Though we have presented a mechanism for the origin of supermassive PBHs, it can also be expected that in a string theory landscape, the slow-roll path of the inflaton would be accompanied by more than one neighboring vacuum, so that our multiverse PBHs would have a multi-peak mass spectrum. This might simultaneously account for current LIGO-Virgo GW events (e.g., He et al. 2024), supermassive BHs ($M \sim 10^9 M_{\odot}$), and other observations hinting at PBHs (Carr et al. 2024), as shown in Figure 4. Thus, it is interesting to further

study the implications of recent observations at corresponding mass scales—such as LIGO-Virgo-KAGRA Gravitational-wave Transient Catalog (GWTC) events and early supermassive JWST galaxies—on our multiverse PBHs.

It is significantly noted that the multi-peak mass spectrum of our multiverse PBHs encodes information not only about slow-roll inflation but also about string vacua (Susskind 2003; Kachru et al. 2003b), which might provide a potential probe of relevant issues worthy of exploration. It is also interesting to ask whether such multiverse PBHs help resolve the information paradox of eternally inflating spacetime (Arkani-Hamed et al. 2007; see also Piao 2023). Though our simplified calculation might capture the essentials of how the nucleation rate is affected by the inflaton’s roll, it is necessary to perform calculations in a well-motivated string theory landscape, which requires further investigation to better understand the origin of supermassive PBHs.

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