Phys. Lett. B 849 (2024) 138465

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Super-slow phase transition catalyzed by BHs and the birth of baby BHs

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ARTICLE INFO

Editor: R. Gregory

ABSTRACT

We discuss the unique phenomenology of first-order phase transitions catalyzed by primordial black holes (BHs). If the number of BHs within one Hubble volume is smaller than unity at the time of bubble nucleation, each bubble catalyzed around them can expand to the Hubble size, and the universe is eventually filled with true vacuum much after nucleation. This super-slow transition predicts enhanced gravitational wave signals from bubble collisions and can be tested in future observations. Moreover, the remaining rare false vacuum patches give birth to baby BHs, which can account for the abundance of dark matter in our universe.

1. Introduction

Scalar fields are ubiquitous in physics beyond the Standard Model (SM) and may have a nontrivial vacuum structure. It is expected that the Universe has experienced several phase transitions during its thermal history. However, the vacuum nucleation rate can be comparable or smaller than the present age of the Universe. For example, in the SM, the lifetime of the electroweak vacuum is slightly longer than the present age of the Universe [1–15] (see, e.g., Ref. [16]). In such a case, vacuum nucleation is expected to be triggered if the tunneling action is reduced by a factor of $\mathcal{O}(1\text{-}10)$. This can occur around compact objects such as black holes (BHs).

Several studies have been conducted on the enhancement of vacuum nucleation rate around a BH [17–43]. Although it is under debate how to properly treat the thermal effect of Hawking radiation, it is still reasonable to expect that the vacuum nucleation rate around BHs is strongly enhanced by the strong gravitational field, at least for bubbles whose radii are comparable to those of the BHs. Moreover, such an enhancement can be even stronger for compact objects without a horizon because the Bekenstein entropy is absent in these cases [44].

In this letter, we consider a unique phenomenology of vacuum nucleation triggered around primordial black holes (PBHs), assuming that the false-true vacuum structure of the scalar potential is maintained in the course of evolution. If the average number of PBHs within one Hubble volume is lower than unity at the bubble nucleation, bubbles can expand to the Hubble size. The Hubble patches that contain BHs can transition to the true vacuum, whereas the remainder of the Hubble patches remain in the false vacuum (left panel of Fig. 1). The phase transition is eventually completed only after the average number of BHs within one Hubble volume is of the order of unity. This super-slow phase transition scenario provides a unique signal in the gravitational waves (GWs) from bubble collisions [45–51].

Moreover, even though the phase transition is successfully completed, some rare regions remain in the false vacuum and inflate forever (the red region in the left panel of Fig. 1). These regions result in baby universes that are connected to our (parent) universe by wormholes and are eventually seen as BHs by an outside observer [52–55]. (See also Refs. [56–59] for wormhole formation from collapsing domain walls or vacuum bubbles and Refs. [52,60–63] for that after a first-order phase transition (FOPT) in different contexts.) We describe the causal structure of this phenomenon using the Penrose diagram shown in the right panel of Fig. 1, assuming spherical symmetry around the center of the inflating region for simplicity. The purple curve represents the vacuum bubble front that sweeps toward the center of the coordinate system (corresponding to the left most part), while our universe is in the true vacuum region. A baby universe is created because of inflation in the false vacuum region and eventually becomes disconnected from our universe by the event horizons (dotted lines) of the baby BH.

This provides a unique scenario for the generation of large baby PBHs from the phase transition triggered by the original PBHs. Simi-

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https://doi.org/10.1016/j.physletb.2024.138465
Received 13 November 2023; Received in revised form 26 December 2023; Accepted 13 January 2024
Available online 19 January 2024

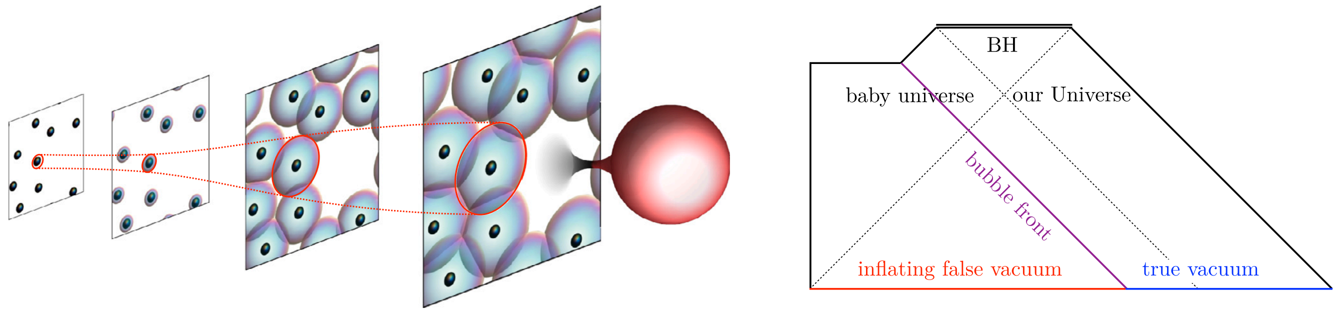

Fig. 1. (Left) Schematic of cosmological evolution in our scenario. The black dots represent BHs, while the spheres surrounding them represent true vacuum regions. The red circles on each sheet connected by dotted lines represent the Horizon scale at each cosmic time. The red sphere represents an inflating region that is connected to our universe by a wormhole. (Right) Penrose diagram starting from $t \sim H_{\rm eq}^{-1}$, when the vacuum energy dominates in the false vacuum region.

lar but different scenarios for PBH formation during a FOPT have been previously considered [64–83]. In these studies, the authors considered the collapse of overdense regions following the collision of the bubbles. Their mechanism may depend on the details of the phenomenology of the bubbles and surrounding plasma as well as the assumption of spherical symmetry, whereas in our case, BHs appear in regions where bubble collision is not complete. In the mechanism we propose, inflation naturally occurs in the false vacuum regions larger than the Hubble horizon, even if they are not spherically symmetric. Furthermore, our argument does not rely on the complicated and nontrivial dynamics of the collapse of overdense regions, and thus we believe the present letter offers a rather robust discussion on PBH formation.

2. Super-slow phase transition catalyzed by PBHs

In this letter, we consider PBHs as the catalysts of a first-order phase transition. As mentioned above, the nucleation rate can be drastically enhanced around the BH if the radius of BH is comparable to the bubble radius for vacuum nucleation. For a sector undergoing the catalyzed transition, we assume a scalar field satisfying the following conditions: i) The scalar potential develops a meta-stable vacuum and true vacuum before the time of catalyzed nucleation, and our Universe is trapped in the former. This vacuum structure is maintained until the transition is completed. ii) The vacuum nucleation rate in a homogeneous background is too small for the transition to occur, but it is sufficiently enhanced around the PBHs so that bubbles can nucleate. iii) The cosmological constant is vanishingly small in the true vacuum. Note that i) is a rather nontrivial assumption, especially for the case of a thermal transition. As a possible and simple realization, we may envision a "dark" scalar with the zero-temperature potential possessing a false-true vacuum structure, so that its potential is (almost) unaffected by the thermal history of the Universe.[1]

Under these assumptions, we arrive at a situation where the true vacuum bubbles nucleate only around the PBHs. For simplicity, we take the initial mass of PBHs, $M_{\rm PBH,i}$, to be monochromatic so that the bubbles nucleate simultaneously around all PBHs. We denote the time of PBH formation and bubble nucleation respectively as t_* and $t_{\rm nuc}$ ($\geq t_*$), and the PBH number density as $n(t)$ ($\propto a^{-3}(t)$). Let us define ϵ as the average number of PBHs within one Hubble volume at $t = t_{\rm nuc}$:

$$\epsilon \equiv \frac{4\pi n(t_{\rm nuc})}{3H^3(t_{\rm nuc})}. \tag{1}$$

The case $\epsilon < 1$ is the focus of this study. In this case, the true vacuum bubbles do not fill the universe within one Hubble time after $t = t_{\rm nuc}$. The bubbles expand with velocity v_b (~ 1), and their radii become of the order of the Hubble length. Subsequently, these Hubble-sized bubbles collide with each other, and the true vacuum slowly fills the universe.

Note that ϵ is related to the energy fraction of the universe $\beta_{\rm PBH}$, which collapses into a PBH at the temperature T_*, as described below:

$$\epsilon = \frac{\beta_{\rm PBH}}{\gamma}\left(\frac{T_*}{T_{\rm nuc}}\right)^3, \tag{2}$$

where γ is the ratio of the PBH mass to the horizon mass. Here, for simplicity, we assume that the initial mass of the PBH is $M_{\rm PBH,i} \simeq 4\pi\gamma M_{\rm Pl}^2/H_*$, which holds for PBH formation from the collapse of overdense regions in a radiation-dominated epoch. Hereafter, we consider the fiducial value of γ as 0.2 [84]. Our scenario can be applied to other PBH formation mechanisms with some trivial corrections.

We quantitatively discuss our scenario according to the percolation theory. The probability of finding a spatial point in false vacuum at time t is given by $P(t) = e^{-I(t)}$, where

$$I(t) = \frac{4\pi}{3}\int_0^t dt'\Gamma(t')a^3(t')r_{\rm bubble}^3(t,t'), \tag{3}$$

$$r_{\rm bubble}(t,t') = v_b\int_{t'}^{t}\frac{dt''}{a(t'')}. \tag{4}$$

Here, $\Gamma(t)$ denotes the bubble nucleation rate per unit time and volume. We assume $v_b = \text{const.}$ for simplicity. In our case, bubble nucleation occurs at $t = t_{\rm nuc}$ around the BHs such that

$$\Gamma(t') = \delta(t' - t_{\rm nuc})n(t_{\rm nuc}). \tag{5}$$

Using the above expressions, the time $t_{\rm col}$ of the bubble collision and thus the completion of the phase transition can be defined as $I(t_{\rm col}) = 1$.

If the energy density of the false vacuum region is dominated by the false vacuum energy by the time $t = t_{\rm col}$, that region experiences eternal inflation, and the entire universe is never filled with true vacuum bubbles. Instead, we assume that the false vacuum region is dominated by the radiation energy until $t = t_{\rm col}$. This condition can be represented as follows:

$$\alpha_{\rm col} \equiv \left.\frac{\rho_{\rm vac}}{\rho_{\rm rad}}\right|_{t=t_{\rm col}} \ll 1, \tag{6}$$

where $\rho_{\rm vac}$ is the false vacuum energy in the transition sector and $\rho_{\rm rad}$ is the radiation energy in the SM sector. In this case, the true vacuum bubbles eventually collide with other bubbles, and the phase transition can be completed within a finite time.

Under the assumption of radiation domination, $I(t)$ is evaluated as

$$I(t) = \epsilon v_b^3\left\{\left(\frac{t}{t_{\rm nuc}}\right)^{1/2} - 1\right\}^3. \tag{7}$$

[1] One can also consider a hot dark sector, where the false vacuum is stabilized by thermal effect at a high temperature. The phase transition can happen around PBHs once the temperature decreases enough to make the false vacuum metastable.

Thus, we obtain

$$t_{\rm col} = \left(1 + \frac{1}{\epsilon^{1/3} v_b}\right)^2 t_{\rm nuc}. \tag{8}$$

The growth rate of the true vacuum fraction can be quantified as

$$\beta_P(t) \equiv -\frac{d\ln P}{dt} = \dot{I} = \frac{3I(t)v_b}{a(t)r_{\rm bubble}(t,t_{\rm nuc})}. \tag{9}$$

Because $a(t)r_{\rm bubble}(t,t_{\rm nuc}) = 2v_b t(1-(t_{\rm nuc}/t)^{1/2})$, we obtain $\beta_P/H \simeq 3I(t) \propto t^{3/2}$ during the radiation-dominated era. In particular, we obtain

$$\beta_P(t_{\rm col}) = 3H(t_{\rm col})\left(1+\epsilon^{1/3}v_b\right), \tag{10}$$

which can be regarded as the inverse duration of the phase transition in this scenario. One sees that $\epsilon \to 0$ gives $\beta_P(t_{\rm col})/H(t_{\rm col}) = 3$, and also that $\epsilon = 0.1$ already gives $\beta_P(t_{\rm col})/H(t_{\rm col}) \simeq 4.4$, only $\simeq 50\%$ different from the $\epsilon \to 0$ limit. Our following discussion will be valid as long as such a small value of $\beta_P(t_{\rm col})/H(t_{\rm col})$ is realized.

Notably, $\beta_P/H_{\rm col} \simeq 3$ ($\epsilon \ll 1$) is actually the lowest allowed value for β_P because the volume of the false vacuum region continues to decrease only if

$$\frac{d}{dt}\left(a^3(t)P(t)\right) < 0 \quad \leftrightarrow \quad \frac{\beta_P(t)}{H(t)} > 3. \tag{11}$$

The feature $\beta_P/H_{\rm col} \simeq 3$ quantitatively represents the slowness of the phase transition. Such a small value of $\beta_P/H_{\rm col}$ is difficult to realize in standard scenarios without fine-tuning but is sometimes motivated from a phenomenological point of view (see, e.g., [85–92]).

3. Birth of baby BHs

Despite the successful completion of the phase transition, some rare regions could remain in a false vacuum and inflate forever. These regions are seen as BHs by outside observers [56,58,93]. Thus, we arrive at the scenario of "the birth of baby BHs from vacuum decay catalyzed by parent BHs".

The number density of baby PBHs is estimated as follows: A false vacuum region can inflate if it is as large as the Hubble horizon for the false vacuum $H_{\rm fv}^{-1}$ at $t \gtrsim t_{\rm eq}$, where $t_{\rm eq}$ is the time at which the vacuum energy begins to dominate, and is defined by $\rho_{\rm rad}(t_{\rm eq}) = \rho_{\rm vac}$. The average number of parent PBHs within a volume of $(4\pi/3)H_{\rm fv}^{-3}$ is given by

$$N_{\rm PBH}(t_{\rm eq}) \simeq \epsilon\left(\frac{a_{\rm eq}}{a_{\rm nuc}}\right)^3 \simeq v_b^{-3}\alpha_{\rm col}^{-3/4}, \tag{12}$$

meaning that the value of ϵ can be traded for $\alpha_{\rm col}$ and $t_{\rm nuc}$, the latter being implicitly in $a_{\rm nuc}$. Assuming that the number of PBHs within the region follows a Poisson distribution, we estimate the probability that no true vacuum bubble forms within the same volume as $P \simeq e^{-N_{\rm PBH}(t_{\rm eq})}$. The number density of the baby PBHs is then given by $P/((4\pi/3)H_{\rm fv}^{-3})$. The inflating false vacuum region can eventually be perceived as a BH by distant observers. Its mass is estimated as

$$M_{\rm baby} \simeq \frac{4\pi}{3}H_{\rm fv}^{-3}\cdot 3M_{\rm Pl}^2H_{\rm fv}^2 \simeq 2.8\times10^{-7}M_\odot\left(\frac{\rm TeV^4}{\rho_{\rm vac}}\right)^{1/2}. \tag{13}$$

The abundance of baby BHs is also subject to observational constraints that depend on their masses. In particular, for $10^{-15}M_\odot \lesssim M_{\rm baby} \lesssim 10^{-10}M_\odot$, baby BHs are allowed to constitute the entire dark matter (DM) of our universe. For comparison with the strongest observational bounds for a monochromatic PBH mass, as shown in Fig. 18 of Ref. [94], it is convenient to introduce a parameter $\beta_{\rm bBH}$, which characterizes the fraction of energy in the universe occupied by baby BHs during their formation

$$\beta_{\rm bBH} \equiv \frac{\rho_{\rm bBH}}{3M_{\rm Pl}^2H_{\rm fv}^2} = P = \exp\left(-v_b^{-3}\alpha_{\rm col}^{-3/4}\right), \tag{14}$$

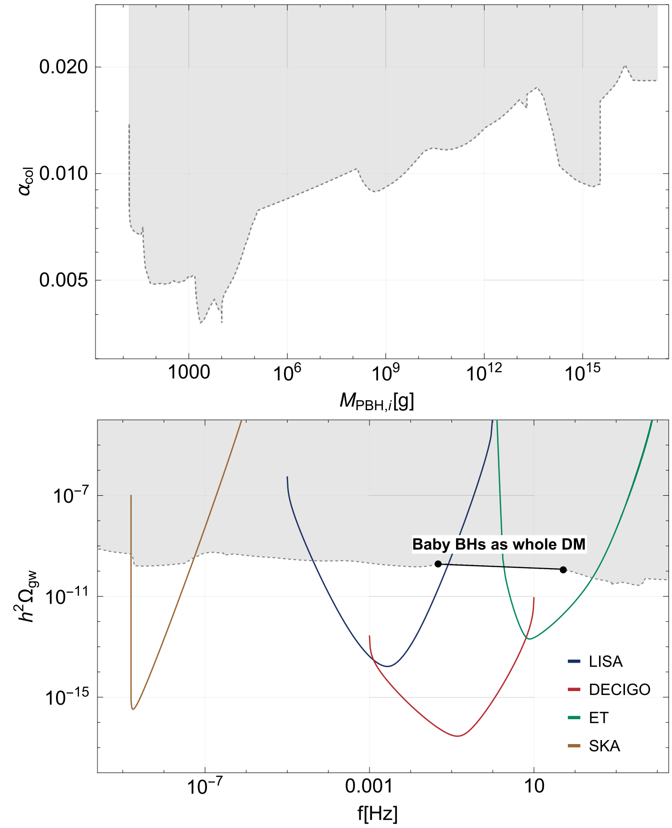

Fig. 2. (*Top panel*) Upper bound on $\alpha_{\rm col}$ derived from the observational constraints imposed on $\beta_{\rm bBH}$ based on Eqs. (14) and (20). (*Bottom panel*) Projection of the maximally allowed value of $\alpha_{\rm col}$ for each $M_{\rm PBH,i}$ onto the $(f, \Omega_{\rm gw})$ plane. For both plots, the upper shaded region is excluded in our scenario.

where $M_{\rm Pl} \equiv (8\pi G)^{-1/2}$ is the reduced Planck mass with G being the Newtonian constant. For example, when $\rho_{\rm vac} \sim (10^5{\rm TeV})^4$, the baby BH mass is $M_{\rm baby} \sim 10^{10}$ g, and the constraint from Big-Bang nucleosynthesis (BBN) $\beta_{\rm bBH} \lesssim 10^{-24}$ yields $v_b^4\alpha_{\rm col} \lesssim 5\times10^{-3}$. Constraints on PBH abundance typically result in $\alpha_{\rm col} < \mathcal{O}(10^{-2})$. Detailed values of the upper bound will be provided shortly (see Fig. 2).

Note that the largest allowed value of $\alpha_{\rm col}$ can be increased by lowering the wall velocity v_b, which may be achieved by the friction between the wall and fluid. In most realistic cases, however, we expect the velocity to eventually reach $v_b \sim 1$ as any radiation coupled to the transition sector must be extremely dilute from the beginning in our setup so as not to spoil the metastable vacuum structure. Therefore, we use $v_b = 1$ as the fiducial value.

4. GW signals

A stochastic gravitational wave background (SGWB) is produced by complicated dynamics during the cosmological phase transition, which is typically classified into contributions from bubble collisions, sound waves, and turbulence. In our scenario, in which the Hubble-sized bubbles collide over the Hubble time, the dominant source of SGWB is expected to be the collision of the bubble walls [45–51].[2] The amplitude and characteristic frequency of the SGWB generated by bubble collisions can be roughly estimated as [95]

[2] Depending on the model, the fluid contribution could be comparable to Eq. (15). In other words, our estimate of SGWB is relatively conservative because it is based solely on bubble collisions.

$$\Omega_{\rm gw}h^2 \sim 1.6\times10^{-5}\left(\frac{100}{g_*(T_{\rm col})}\right)^{1/3}\left(\frac{H_{\rm col}}{\beta_P}\right)^2\left(\frac{\kappa_\phi\alpha_{\rm col}}{1+\alpha_{\rm col}}\right)^2, \tag{15}$$

$$f \sim 1.6\times10^{-3}{\rm Hz}\left(\frac{g_*(T_{\rm col})}{100}\right)^{1/6}\frac{\beta_P}{H_{\rm col}}\frac{T_{\rm col}}{10\,{\rm TeV}}, \tag{16}$$

where κ_ϕ represents the fraction of energy transferred from vacuum energy to the scalar kinetics and gradient. In contrast to the standard scenario of cosmological FOPT, the super-slow phase transition scenario predicts $\beta_P/H_{\rm col} \simeq 3 = \mathcal{O}(1)$. Therefore, the amplitude of the SGWB from bubble collision can be within the reach of future observation of the Pulsar Timing Arrays (PTAs) [96–100] and planned detectors, such as the Einstein Telescope [101,102], Cosmic Explorer [103,104], LISA [105,106], and DECIGO [107,108].

Based on Eq. (8), the temperature at the bubble collision $T_{\rm col}$ can be expressed via the PBH parameters by using Eq. (2) and representing T_* in terms of $M_{\rm PBH,i}$ as

$$\begin{aligned} T_{\rm col} &\simeq \gamma^{1/6}v_b\beta_{\rm PBH}^{1/3}\sqrt{\frac{4\pi M_{\rm Pl}^3}{M_{\rm PBH,i}}}\left(\frac{90}{\pi^2 g_*(T_*)}\right)^{1/4} \\ &\simeq 23\,{\rm TeV}\left(\frac{g_*(T_*)}{100}\right)^{-1/4}\left(\frac{\beta_{\rm PBH}}{10^{-21}}\right)^{1/3}\left(\frac{M_{\rm PBH,i}}{10^9\,{\rm g}}\right)^{-1/2}, \end{aligned} \tag{17}$$

for $\epsilon \ll 1$. Using this expression, the peak frequency Eq. (16) can be expressed in terms of the PBH parameters, whereas the strength of the phase transition $\alpha_{\rm col} = \rho_{\rm vac}/\rho_{\rm rad}(T_{\rm col})$ depends on the details of the scalar sector and requires an additional assumption, which we will specify shortly.

4.1. Predictions and existing constraints

During the bubble nucleation catalyzed by the PBHs, the radius of the vacuum bubbles should be comparable to the BH radius $M_{\rm PBH}/M_{\rm Pl}^2$. Although the relationship between the radius of the vacuum bubble and vacuum energy $\rho_{\rm vac}$ depends on the model details, we simply assume the following relationship:

$$\rho_{\rm vac}^{1/4} \sim M_{\rm Pl}^2/M_{\rm PBH}, \tag{18}$$

which should be sufficient for an order-of-magnitude estimate. From Eq. (13), the mass of the baby BHs is expressed as $M_{\rm baby} \simeq 5.0\times10^{24}{\rm g}\left(M_{\rm PBH}/(10^9\,{\rm g})\right)^2$.

If we further assume $T_{\rm nuc} \gg T_{\rm ev}$, where $T_{\rm ev}$ is the evaporation temperature of the PBH, $M_{\rm PBH}$ is approximately equal to $M_{\rm PBH,i}$. Therefore, once $(M_{\rm PBH,i}, \beta_{\rm PBH})$ are given, $T_{\rm col}$ and $\alpha_{\rm col}$ are fixed such that

$$\begin{aligned} \alpha_{\rm col} &\sim \frac{1}{3}\left(\frac{g_*(T_*)}{g_*(T_{\rm col})}\right)v_b^{-4}\beta_{\rm PBH}^{-4/3}\frac{1}{(4\pi\gamma^{1/3})^2}\left(\frac{M_{\rm Pl}}{M_{\rm PBH,i}}\right)^2 \\ &\sim 10^{-3}\left(\frac{g_*(T_*)}{g_*(T_{\rm col})}\right)\left(\frac{\beta_{\rm PBH}}{10^{-21}}\right)^{-4/3}\left(\frac{M_{\rm PBH,i}}{10^9\,{\rm g}}\right)^{-2}. \end{aligned} \tag{19}$$

Now we consider the upper bound on $\alpha_{\rm col}$, which originates from the constraints imposed on the abundance of baby BHs. The mass of the baby BHs is given by

$$M_{\rm baby} \simeq 5.0\times10^{24}{\rm g}\left(\frac{M_{\rm PBH,i}}{10^9{\rm g}}\right)^2, \tag{20}$$

under the assumptions described by Eq. (18) and $T_{\rm nuc} \gg T_{\rm ev}$. Using $\beta_{\rm bBH}$ defined in Eq. (14) for the abundance of baby BHs, the constraints as provided in Ref. [94] yields an upper bound on $\alpha_{\rm col}$ for a given $M_{\rm PBH,i}$.

The excluded region (derived from $v_b = 1$) is shown in the top panel of Fig. 2 over the mass range relevant to the SGWB observations. If the mass of the baby PBHs is less than about $10^{-15}M_\odot$, they evaporate by the present epoch. In this case, BBN [109], anisotropies of cosmic microwave background (CMB) [110], the galactic and extragalactic γ-ray (GGB [111] and EGB [109]), and cosmic ray backgrounds [112]

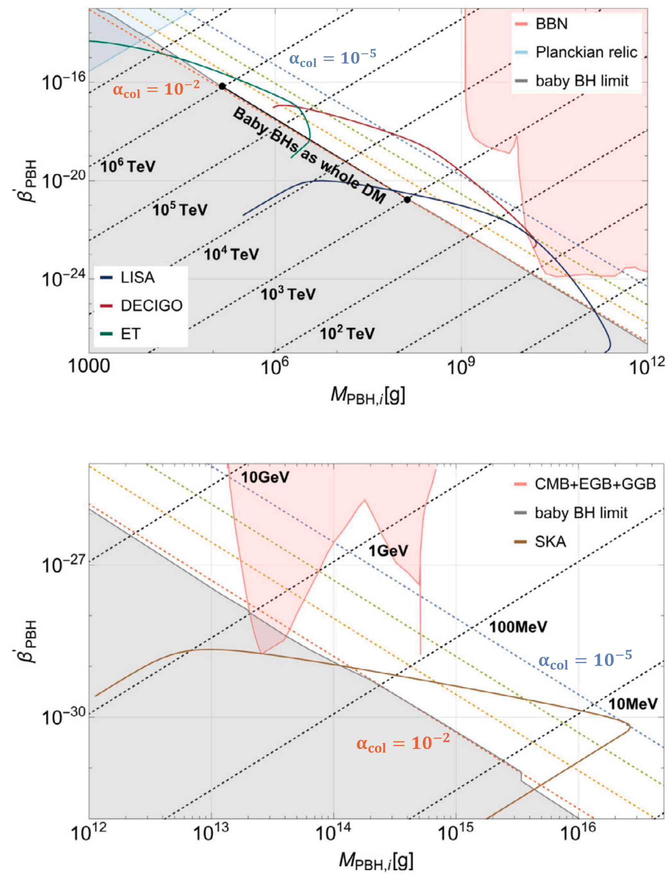

Fig. 3. Contours of $\alpha_{\rm col}$ (color-dashed) and $T_{\rm col}$ (black-dashed) drawn in the PBH parameter space $(M_{\rm PBH,i}, \beta'_{\rm PBH})$. Red and light-blue shaded regions are the constraints on the (parent) PBHs from BBN [109] and Planckian relics [122], respectively. The left-bottom gray-shaded region is excluded in our scenario by the constraints on baby BHs. The solid-colored lines are the projection of the power-law integrated sensitivity curves of the future GW observations. The bottom panel shows the results in the PTA band, where $g_*(T_{\rm col})/g_*(T_*) = 1/10$ and the $\alpha_{\rm col}$ contours are slightly shifted above.

attain the tightest bounds on their abundance at formation. However, baby BHs survive to the present if they are heavier than $10^{-18}M_\odot$. The tightest (and relatively secure) bound on their abundance comes from gravitational lensing [113–117], dynamical friction and its influence on large-scale structures [118], accretion [119,120], and gravitational waves [121]. In particular, for $10^{-15}M_\odot \lesssim M_{\rm baby} \lesssim 10^{-10}M_\odot$, baby BHs are allowed to constitute the entire DM of our universe. The maximally allowed value of $\alpha_{\rm col}$ is approximately $\mathcal{O}(10^{-2})$ for all the masses described here.

Under our assumptions (Eq. (18) and $T_{\rm nuc} \gg T_{\rm ev}$), the peak frequency and amplitude of SGWB can be determined using Eqs. (15) and (16). With the parameters fixed at $\gamma = 0.2$, $g_*(T_*) = g_*(T_{\rm col}) = 100$ and $\beta/H_p = 3$, the largest amplitudes of $\Omega_{\rm gw}$ in our scenario are derived from the upper bound of $\alpha_{\rm col}$ for a given $M_{\rm PBH,i}$. (To be precise, $g_*(T_{\rm col}) \sim 10$ is expected for the PTA band, although this difference is only slight.) As shown in the bottom panel of Fig. 2, the amplitudes are compared with the power-law integrated sensitivity curves of the future SGWB observations. As the window of the baby-BH DM is described by $10^5{\rm g} \lesssim M_{\rm PBH,i} \lesssim 10^8{\rm g}$, a particular scenario exists, where the baby PBHs can explain the abundance of DM in the universe while the SGWB from the bubble collisions can be observed in the laser interferometer band.

In Fig. 3, we summarize how the (seed) PBH parameters $M_{\rm PBH,i}$ and $\beta'_{\rm PBH} \equiv \gamma^{1/2}\beta_{\rm PBH}$ in our scenario can be constrained by future SGWB observations in combination with the other observational constraints discussed in Ref [94]. To show the accessible parameter region, we first plot the contours of $T_{\rm col}$ (black-dashed lines with $T_{\rm col} = 10^0, 10^1, \cdots, 10^7$ TeV from bottom-right to top-left) and $\alpha_{\rm col}$ (color-dashed lines with $\alpha_{\rm col} = 10^{-2}, 10^{-3}, 10^{-4}$ and 10^{-5} from bottom-left to top-right) using Eqs. (17) and (19), respectively. Subsequently, using Eq. (15), where $\beta_P/H_{\rm col} = 3$, $\kappa_\phi = 1$ and $g_*(T_{\rm col}) = 100$ (10) for the top panel (bottom panel) of Fig. 3, the power-law integrated sensitivity curves of the detectors (acquired from Ref. [123]) are projected onto the $(M_{\rm PBH,i}, \beta'_{\rm PBH})$ plane. That is, the lower-left side of these projected curves is the region that can be probed by the SGWB observations.

The gray (red and light-blue) shaded region is excluded because of the overproduction of baby (parent) BHs. The black line connected by the black dots represents the region in which the DM can be explained by the baby BHs. This is within the sensitivity curves of the planned laser interferometers.

Finally, we should check if the condition $\epsilon < 1$ is consistently satisfied in the parameter space of our interest. The condition is translated into an upper bound on $\beta'_{\rm PBH}$ by using Eq. (2) as

$$\beta'_{\rm PBH} < \gamma^{3/2} \left(\frac{T_{\rm nuc}}{T_*} \right)^3 . \tag{21}$$

As long as the transition temperature $T_{\rm nuc}$ is not significantly lower than the PBH formation temperature T_*, this condition can be met in the entire region plotted in Fig. 3.[3]

5. Discussion

We have discussed the phenomenology of a first-order phase transition triggered around PBHs with a small number density. This provides a novel scenario of a super-slow phase transition in which the bubbles grow to the Hubble size and collide over a time significantly longer than the Hubble time at nucleation. We expect two distinct features in relation to the standard scenario of FOPT. The first is the approximate delta-function feature of the effective nucleation rate Eq. (5). The GW spectrum in this case is expected to be more sharply peaked than that with the ordinary exponential nucleation rate, reflecting the uniform bubble-size distribution [124]. Second, the duration of the phase transition is longer than one Hubble time for a small number density of parent BHs, which implies that the expansion of the universe affects the spectrum of GWs. From these results, we expect that our scenario is distinguishable from the standard scenario with a precise determination of the GW spectrum. We leave the precise GW spectrum for future research.

Throughout this letter, we specifically consider PBHs [56,58, 84,125–132] as catalysts; however, other compact objects including monopoles [133], Q-balls [134–143], oscillons [144–154], boson stars (including axion stars) [155–170], gravastars [171,172] (see also Ref. [173]), neutron stars, and BH remnants [174,175] should function similarly if their gravitational potential is sufficiently strong [21,44,176].[4]

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jun'ya Kume reports financial support, JSPS Overseas Research Fellowships, was provided by Japan Society for the Promotion of Science (JSPS). Ryusuke Jinno, Masaki Yamada reports financial support, JSPS KAKENHI Grant Numbers 23K19048 (RJ), 20H05851 (MY) and 23K13092 (MY), was provided by JSPS. Masaki Yamada reports financial support, MEXT Leading Initiative for Excellent Young Researchers, was provided by Government of Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors are thankful to Simone Blasi for helpful comments. JK is supported by the JSPS Overseas Research Fellowships. JK and MY acknowledge the hospitality at Jeonbuk National University where this work was initiated during "Korea - Japan joint workshop on Particle Physics, Cosmology, and Gravity". This work was supported by JSPS KAKENHI Grant Numbers 23K19048 (RJ), 20H05851 (MY) and 23K13092 (MY). MY was supported by MEXT Leading Initiative for Excellent Young Researchers.

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