

Asteroid-mass primordial black holes as dark matter from supersymmetry

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We study the formation of asteroid-mass primordial black holes (PBHs) as a dark matter candidate in supersymmetric extensions of the Standard Model. We show that the presence of heavy particles predicted in the minimal supersymmetric Standard Model (MSSM) can lead to a transient softening of the equation of state of the Universe during their nonrelativistic transition, enhancing PBH formation. We compute the effective equation of state for different realizations of the MSSM mass spectrum, parametrized by three characteristic mass scales. Assuming a broad and approximately scale-invariant primordial curvature power spectrum, we evaluate the resulting PBH mass functions and compare them with current observational constraints. We find that, for supersymmetric masses above $\sim 10^5$ GeV, the PBH mass function is significantly enhanced in the asteroid-mass window, allowing PBHs to account for the total dark matter abundance without violating existing bounds. In contrast, within the Standard Model the same configurations lead to PBH mass functions that are observationally excluded. For lighter supersymmetric mass spectra, PBH production is shifted toward masses above $\sim 10^{22}$ g, which are strongly constrained by microlensing searches, thereby reducing their allowed contribution to the dark matter density.

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I. INTRODUCTION

Multiple independent cosmological and astrophysical observations provide compelling evidence for a cold, nonbaryonic component of the Universe, commonly referred to as dark matter (DM). Yet, despite decades of theoretical and experimental efforts, its fundamental nature remains unknown and constitutes one of the most pressing open questions in modern physics. A wide range of well-motivated particle candidates, like weakly interacting massive particles [1,2] and axionlike particles [3,4], has been proposed, however, no conclusive evidence has emerged from collider searches, direct detection experiments, or indirect probes. This situation motivates the investigation of alternative, nonparticle explanations for dark matter. Primordial black holes (PBHs) emerge as a particularly well-motivated alternative.

First proposed by Zel'dovich [5], Hawking [6], and Carr [7], PBHs can form in the early Universe, shortly after inflation, e.g. through the gravitational collapse of large primordial density fluctuations. Unlike astrophysical black

holes, whose origin is tied to stellar evolution, PBHs would arise from purely cosmological processes and could therefore span an extremely wide mass range, determined by the horizon mass at the time of formation. If sufficiently massive to survive Hawking evaporation [8] until the present epoch, they would behave as a cold, nonbaryonic component of the matter density, thus constituting a viable DM candidate [9–12]. Observationally, black holes are known to exist over a broad range of masses. Stellar-mass black holes are well established as the end products of massive star evolution, while supermassive black holes, with masses ranging from millions to billions of solar masses, are known to reside at the centers of most galaxies. More recently, gravitational-wave observations by LIGO/Virgo Collaborations [13] have revealed merging black holes with masses $M \gtrsim 30M_\odot$, further stimulating interest in the possible cosmological origin of some of these objects [14–17]. Over the years, an extensive body of work on PBH phenomenology has placed increasingly stringent constraints on their cosmological abundance across a wide range of observational probes. Current bounds rule out PBHs as the dominant DM component over most of the parameter space. However, a viable window remains in the asteroid-to-planetary mass range, $10^{18} \text{ g} \lesssim M_{\text{PBH}} \lesssim 10^{22} \text{ g}$. This region is bounded at lower masses by evaporation constraints [18–31] and at higher masses by microlensing observations [32–40]. Recent studies have pointed out that quantum effects, referred to as “memory burden” [41,42], may slow down black hole evaporation, allowing much

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lighter PBHs to survive until today and account for the totality of the dark matter [43–51]. We do not consider this scenario here.

If PBHs form through gravitational collapse in the early Universe, their abundance is primarily controlled by two key ingredients: the primordial curvature power spectrum $\mathcal{P}_\zeta$ and the equation of state (EoS) of the primordial plasma at the time of horizon reentry. The former is dictated by the inflationary dynamics and may exhibit enhanced features on the small scales relevant for PBH formation. The latter, instead, is determined by the thermal history of the Universe and ultimately by its underlying particle content. In particular, cosmological phase transitions or the decoupling of particle species from the thermal bath can induce a temporary softening of the EoS from its value $w = p/\rho = 1/3$ in radiation domination, lowering the collapse threshold and exponentially enhancing the PBH production at masses corresponding to the horizon mass at that epoch. Several works [52–60] have shown that the EoS softening during the QCD phase transition can enhance near-solar mass PBH formation by orders of magnitude, given sufficient power spectrum amplitude at the relevant scales. Similar effects on different mass ranges can be achieved by considering the softening of the EoS due to electroweak phase transition or electron-positron annihilation [61,62]. Moreover, several studies [63–68] have also explored scenarios in which PBHs form during an early matter-dominated phase, characterized by an EoS parameter $w \simeq 0$, leading to a significant enhancement of PBH production by several orders of magnitude.

In this work, we investigate the impact on the equation of state induced by a particle sector characterized by a large number of degrees of freedom, becoming nonrelativistic at temperatures above the electroweak scale, as motivated by beyond-the-Standard-Model scenarios. In particular, we focus on the minimal supersymmetric Standard Model (MSSM), which predicts a superpartner for each Standard Model (SM) particle [69–72]. We show that the resulting temporary softening of the equation of state at temperatures $T \gtrsim 1$ TeV can significantly enhance the PBH abundance at formation within a mass range compatible with the so-called asteroid-mass window. Similar modifications of the thermal history above the electroweak scale have been considered in previous studies, along with their implications for the PBH formation [73,74] and for the production of gravitational waves from cosmic string networks [75,76].

We here adopt a self-consistent treatment of PBH formation, explicitly incorporating the dependence of the collapse threshold on the equation of state across the relevant temperature range and analyzing the resulting extended mass functions in light of current observational constraints. Differently from Ref. [74], which focuses on a single supersymmetric breaking scale, we consider a more general MSSM setup characterized by three independent mass scales: a single mass scale m_f governing the fermionic

superpartners, a single mass scale m_b governing the bosonic superpartners, and a separate scale m_h for the second Higgs doublet required in the MSSM. This multiscale approach enables a systematic exploration of the parameter space and allows us to identify the regions where departures from the SM thermal history can lead to PBH mass functions that remain compatible with existing bounds.

The paper is organized as follows. In Sec. II, we outline the computation of the EoS parameter for a general particle content and introduce the MSSM setup considered in this work. In Sec. III, we review the basics of the PBH formation via critical collapse and describe the procedure adopted to confront extended mass functions with the monochromatic observational constraints. In Sec. IV, we present our results and compare them with the ones obtained within the SM. Finally, in Sec. V, we summarize our findings and discuss their implications.

II. UNIVERSE'S EQUATION OF STATE WITHIN THE MSSM

The thermal history of the Universe is fully determined by the particle content in equilibrium with the primordial plasma. Following the reheating epoch, the Universe is into a state characterized by a hot, thermalized plasma composed of ultrarelativistic species. In this regime, both energy density $\rho(T)$ and pressure $p(T)$ evolve according to the radiation-dominated scaling, and the equation of the state of the Universe is equal to the one of a relativistic fluid. This behavior persists until the cosmic temperature falls below the rest-mass threshold of individual particle species, at which point each species undergoes a relativistic-to-nonrelativistic transition. This induces changes in the equation of state of the plasma, leaving possible observable imprints on several cosmological processes.

Let us first describe the general methodology to compute the equation of state as a function of the temperature T of the thermal bath. The EoS parameter can be written as

$$w(T) = \frac{p(T)}{\rho(T)} = \frac{4}{3} \frac{g_s(T)}{g_*(T)} - 1, \quad (1)$$

where $g_s(T)$ and $g_*(T)$ are the effective degrees of freedom associated to entropy and energy density, respectively. The effective degrees of freedom control the expansion rate through the Friedmann equation and determine the relation between temperature and cosmic time. When all particle species are ultrarelativistic and in thermal equilibrium, one has $g_s(T) = g_*(T)$ and therefore $w = 1/3$. Deviations occur when species become nonrelativistic or when different sectors have different temperatures, as during annihilations, decouplings, or phase transitions. In the standard cosmological scenario, this occurs several times during the history of the Universe according to the SM particle content. The biggest drop in w is expected during the QCD phase transition due to the entropy being redistributed

among the high number of hadrons that become available when the temperature of the thermal bath drops below $T_{\text{QCD}} \sim 200$ MeV [77,78].

The effective degrees of freedom can be computed from the energy, pressure, and entropy densities of a relativistic fluid composed of multiple particle species with masses m_j in thermal equilibrium at temperature T . Introducing the auxiliary variables $u = E/T$ and $z_j = m_j/T$, one obtains the corresponding expressions for the effective degrees of freedom associated with energy, pressure, and entropy [79]

$$\begin{aligned} g_*(T) &= \sum_j \frac{15}{\pi^4} g_j \int_{z_j}^{\infty} \frac{u^2 \sqrt{u^2 - z_j^2}}{e^u \pm 1} du, \\ g_p(T) &= \sum_j \frac{15}{\pi^4} g_j \int_{z_j}^{\infty} \frac{(u^2 - z_j^2)^{3/2}}{e^u \pm 1} du, \\ g_s(T) &= \frac{3g_*(T) + g_p(T)}{4}, \end{aligned} \quad (2)$$

where g_j are the internal degrees of freedom of each particle species and the $\pm$ sign in the denominator accounts for Pauli blocking (plus sign for fermions) and Bose enhancement (minus sign for bosons), with the sum being performed over all particle species. The integrals in Eqs. (2) can be evaluated numerically as a function of temperature for each particle species. Then, Eq. (1) can be used to obtain the EoS parameter for any beyond-the-Standard-Model scenario.

In the MSSM, each SM particle has a superpartner with the same quantum numbers but with spin differing by one-half. Moreover, a second Higgs doublet is introduced because the superpotential must be holomorphic, preventing the use of the conjugate Higgs field to generate masses for both up- and down-type quarks. A second Higgs doublet is also required to cancel gauge anomalies introduced by the Higgsino fermions. Hence, at very high temperatures, when all particles are in thermal equilibrium, the MSSM has $g_* = 228.75$ relativistic degrees of freedom, i.e. nearly twice the SM value of $g_* = 106.75$. In general, it is assumed that all the supersymmetric particles share a common mass scale. This is however a simplifying assumption, as the soft supersymmetric breaking (SSB) parameters responsible for breaking supersymmetry down to the SM generically arise from different terms in the Lagrangian, naturally leading to a nondegenerate mass spectrum. These soft parameters can be divided into three classes (see e.g. Ref. [80]): the F -terms, which give masses of the order $\mathcal{O}(M_F)$ to the fermions including the Majorana gaugino masses; the D -terms, which give masses of the order $\mathcal{O}(M_D)$ to the bosons including the squarks, the sleptons, and the Higgses; and the so-called μ -term, which determines the Higgsino masses and contributes to the masses of the two Higgs doublets. Embedding the MSSM in the framework of a grand unified theory (GUT) imposes additional

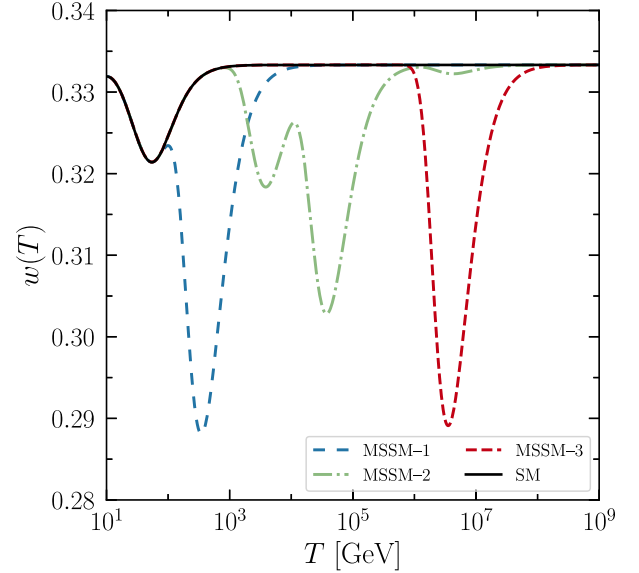


FIG. 1. Equation of state parameter as a function of temperature for three supersymmetric scenarios: a degenerate mass spectrum at low (long-dashed blue line) and high (short-dashed red line) scales, and a nondegenerate spectrum with intermediate mass splitting (dot-dashed green line). Also shown is the equation of state for the SM scenario (solid black line).

constraints on the MSSM mass spectrum [80–84]. Indeed, GUT unification requires all gaugino masses to be equal at the GUT scale, and an analogous mass unification can be assumed for squarks and sleptons belonging to the same GUT multiplet. The mass differences observed among gluinos and neutralinos, or among squarks and sleptons, therefore arise purely from renormalization group running, which generically leads to order-one modifications of the MSSM masses [74,80,85].

In the present work, rather than focusing on a specific realization of the MSSM, we consider a phenomenological scenario characterized by three distinct mass scales for the MSSM particles: a common mass scale $m_f \sim \mathcal{O}(M_F)$ for the fermionic superpartners, a common mass scale $m_b \sim \mathcal{O}(M_D)$ for the bosonic superpartners, and a mass scale m_h for the second decoupled Higgs doublet. The mass scale m_h indeed arises from a combination of all the three SSB parameters, which together define the full mass matrix of the two Higgs doublets. This simplified framework, which emerges in some concrete supersymmetric realizations (see e.g. Refs. [86,87]), allows us to perform a systematic exploration of the modifications to the EoS parameter and, consequently, to the PBH mass function arising from a nondegenerate MSSM mass spectrum.

In Fig. 1 we show the EoS parameter as a function of temperature for the following different MSSM benchmark realizations:

- (i) *low-scale degenerate spectrum (MSSM-1)* with $m_f = m_b = m_h = 10^3$ GeV;

- (ii) *hierarchical spectrum (MSSM-2)* with $m_f = 10^4$ GeV, $m_b = 10^5$ GeV, and $m_h = 10^7$ GeV;
- (iii) *high-scale degenerate spectrum (MSSM-3)* with $m_f = m_b = m_h = 10^7$ GeV.

We find that the most significant deviation from the radiation-dominated value $w = 1/3$ occurs in the case of degenerate MSSM masses, where $w \simeq 0.289$. In contrast, a nondegenerate spectrum leads to a series of smaller departures from $w = 1/3$, each associated with a distinct feature in the PBH mass function, as will be discussed in the following sections. In this scenario, the largest deviation arises around $T \sim m_b$, corresponding to the mass scale at which the number of additional MSSM degrees of freedom is maximized. Quantitatively, we observe a reduction of approximately $\sim 10\%$, $\sim 5\%$, and $\lesssim 1\%$ at m_b , m_f , and m_h , respectively. We also show the EoS parameter for the SM scenario (black solid line), where the electroweak sector induces $w < 1/3$ at temperatures $T \simeq 100$ GeV.

III. PRIMORDIAL BLACK HOLES FORMATION AND MASS FUNCTION

PBH formation has been widely discussed and many mechanisms have been proposed throughout the years [88]. Here we briefly review the formation through direct gravitational collapse of density anisotropies in the early Universe within the threshold statistics formalism [89–91].

Given the primordial curvature power spectrum $\mathcal{P}_\zeta(k)$ resulting from inflation, the corresponding power spectrum of the primordial density contrast, $\delta = \delta\rho/\rho$, can be derived as [92]

$$\mathcal{P}_\delta(k) = \left(\frac{4}{9}\right)^2 (kR)^4 \tilde{W}^2(kR) T^2(kR) \mathcal{P}_\zeta(k), \quad (3)$$

where

$$\tilde{W}(kR) = 3 \frac{\sin(kR) - (kR) \cos(kR)}{(kR)^3} \quad (4)$$

is the Fourier transform of the real-space top-hat window function used to smooth the density contrast over the comoving scale $R = r_m/(aH)$, with $r_m = 3.4$ being a phenomenological parameter fixed following Refs. [55,93–95], and

$$T(kR) = 3 \frac{\sin(kR/\sqrt{3}) - (kR/\sqrt{3}) \cos(kR/\sqrt{3})}{(kR/\sqrt{3})^3} \quad (5)$$

is the radiation transfer function [96]. When the density perturbations δ reenter the horizon after inflation, they may collapse to form a black hole if their amplitude exceeds a critical threshold δ_c . This threshold depends on the details of the collapse, including the shape of the perturbation and the equation of state of the background fluid, and is typically determined through numerical hydrodynamical

simulations [93,94,97–100]. If the amplitude of the primordial perturbation δ is close to the threshold value, the relation between the PBH mass and the horizon mass at the time of formation is given by [97,101,102]

$$M_{\text{PBH}}(T) = \kappa(\delta - \delta_c)^\gamma M_H(T), \quad (6)$$

where $\kappa = 3.3$ and $\gamma = 0.36$ are numerically estimated parameters encoding the details of the collapse. Here, we assume that only the collapse threshold $\delta_c(\omega(T))$ depends on the EoS parameter, taking the numerical results for $\delta_c(\omega(T))$ from Ref. [98]. The relation between the horizon mass M_H and the temperature of the thermal bath in a radiation dominated universe is [103–105]

$$M_H(T) = 12 \left(\frac{10}{g_*(T)} \right)^{1/2} \frac{M_P}{T^2}, \quad (7)$$

with M_P being the reduced Planck mass. Relying on the one-to-one correspondence given by Eq. (7), throughout this section we will use interchangeably the horizon mass M_H and the corresponding temperature $T_H \equiv T(M_H)$. Using the relation between the wave number k at horizon reentry and the horizon mass [103]

$$\frac{k}{k^*} \simeq 83.5 \left(\frac{g_*(T_H)}{106.75} \right)^{1/4} \left(\frac{g_s(T_H)}{106.75} \right)^{1/3} \left(\frac{10^{20} \text{ g}}{M_H} \right)^{1/2}, \quad (8)$$

with $k^* = 10^{10} \text{ Mpc}^{-1}$, we can directly compute the fraction of dark matter in the form of PBHs of mass M_{PBH} .

Assuming Gaussian statistics, the probability distribution of the density contrast is given by

$$P(\delta) = \frac{1}{\sqrt{2\pi\sigma^2(M_H)}} \exp\left(-\frac{\delta^2}{2\sigma^2(M_H)}\right), \quad (9)$$

where the variance $\sigma^2(M_H)$ is obtained from the power spectrum as [106]

$$\sigma^2(M_H) = \int_0^\infty \mathcal{P}_\delta(k) d \ln k. \quad (10)$$

Primordial non-Gaussianities may also be considered and can significantly affect the resulting PBH mass function [90,107–113]. While we do not include such primordial non-Gaussianities in this work, we do account for the unavoidable nonlinear effects discussed in [114,115]. Following [115], we compute the fraction of dark matter in the form of PBHs of mass M_{PBH} as

$$\mathcal{F}(M_{\text{PBH}}) = \frac{1}{\Omega_{\text{DM}}} \int_{M_{\text{min}}}^\infty \frac{dM_H}{M_H} \sqrt{\frac{M_{\text{eq}}}{M_H}} \frac{\kappa}{\gamma} \mu^{\frac{1+\gamma}{\gamma}} \times \frac{1}{\sqrt{2\pi\sigma^2\Lambda}} \exp\left[-\frac{8(1-\sqrt{\Lambda})^2}{9\sigma^2}\right], \quad (11)$$

with $\mu = M_{\text{PBH}}/\kappa M_{\text{H}}$, $M_{\text{eq}} \simeq 2.8 \times 10^{17} M_{\odot}$ the horizon mass at matter-radiation equality, $\Omega_{\text{DM}} = 0.26$ the present-day DM density fraction [116], and

$$\Lambda = 1 - \left(\delta_c(M_{\text{H}}) - \frac{3}{2} \mu^{1/\gamma} \right). \quad (12)$$

The lower limit of the integral is set by the condition $\Lambda > 0$. The total contribution of PBHs to today's energy budget is then given by

$$\Omega_{\text{PBH}} = \Omega_{\text{DM}} \int \mathcal{F}(M_{\text{PBH}}) d \ln M_{\text{PBH}}. \quad (13)$$

Equation (11) clearly highlights the exponential dependence of the mass function on the collapse threshold $\delta_c(M_{\text{H}})$, implying that even small variations in this parameter can lead to significant changes in the resulting PBH mass function. The collapse threshold depends on the equation of state of the Universe at the time of formation. This dependence is typically determined through numerical simulations, whose results are sensitive to the details of the collapse dynamics. Nevertheless, the threshold is found to increase monotonically with the EoS parameter in the range of w considered here [98]. As a consequence, when the EoS parameter $w = p/\rho$ drops below $1/3$, the corresponding decrease of the threshold δ_c enhances the PBH formation, leading to a resonant production of PBHs with masses comparable to the horizon mass at that time. For instance, in the case of degenerate MSSM masses (MSSM-1 and MSSM-3 in Fig. 1), the EoS softening results in a reduction of δ_c by about 5%, which in turn translates into an enhancement of the PBH abundance by more than one order of magnitude. These results also depend on the collapse dynamics and on the shape of the primordial perturbations [59], which is kept fixed in this analysis.

For our purposes, we need a primordial curvature power spectrum which is broad and nearly flat, so that our resulting mass function is sensible to different MSSM scales from 10^3 to 10^7 GeV. According to Eq. (7), these particle mass scales roughly correspond to a horizon mass $M_{\text{H}} \sim 10^{26}$ g and $M_{\text{H}} \sim 10^{18}$ g, respectively. A power spectrum with these characteristics can be obtained in multifield inflationary models [117–119]. We adopt a truncated power-law parametrization at the small scales relevant for PBH formation, defined as

$$P_{\zeta}(k) = \begin{cases} A_* \left(\frac{k}{k^*} \right)^{n_s-1} & k_1 \leq k \leq k_2, \\ 0 & \text{otherwise} \end{cases}, \quad (14)$$

where $k_1 = 10^7 \text{ Mpc}^{-1}$ and $k_2 = 10^{13} \text{ Mpc}^{-1}$ [see Eq. (8)], while n_s denotes the spectral index. For simplicity, we neglect the running of the spectral index, $\alpha_s = dn_s/d \ln k$, instead we vary n_s from 0.980 to 0.995. The parameter A_* is

treated as a free normalization, setting the amplitude of the spectrum at the pivot scale k^* , corresponding to a characteristic PBH mass of $\mathcal{O}(10^{23} \text{ g})$.

The amplitude A_* can be fixed by requiring that PBHs account for the total DM abundance, namely

$$f_{\text{PBH}} \equiv \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} = \int \mathcal{F}(M_{\text{PBH}}) d \ln M_{\text{PBH}} \simeq 1. \quad (15)$$

Imposing this condition, we find $A_* \sim \mathcal{O}(10^{-3})$ for all the values of n_s considered. This result indicates that the amplitude of the primordial curvature perturbations must be enhanced by several orders of magnitude with respect to its value at CMB scales [116], to produce a sizeable amount of PBHs. We also find that the value of A_* required to account for the total DM abundance is largely insensitive to n_s , due to the exponential dependence of the PBH abundance on the variance of the density fluctuations.

At this stage, we must compare our results with various constraints on PBHs as DM candidates available in the literature [11,120]. These bounds arise from different observational probes, depending on the PBH mass, and are typically derived under the assumption of a monochromatic PBH mass function. To extend them to a general mass distribution, we follow the prescription of Ref. [121] and define the maximum observationally allowed PBH fraction in DM as

$$f_{\text{PBH}}^{\text{max}} = \left[\sum_i \left(\int \frac{\mathcal{F}(M_{\text{PBH}})}{\mathcal{F}_i^{\text{max}}(M_{\text{PBH}})} \frac{dM_{\text{PBH}}}{M_{\text{PBH}}} \right)^2 \right]^{-1/2}, \quad (16)$$

where $\mathcal{F}_i^{\text{max}}(M_{\text{PBH}})$ denotes the maximum PBH dark matter fraction allowed by monochromatic constraints for the i th observable. The quantity $f_{\text{PBH}}^{\text{max}}$ directly quantifies the degree to which a given extended mass function is compatible with the observational bounds: values $f_{\text{PBH}}^{\text{max}} \geq 1$ indicate that PBHs can account for all dark matter, while $f_{\text{PBH}}^{\text{max}} < 1$ indicate that PBHs can contribute at most a fraction $f_{\text{PBH}}^{\text{max}}$ of the total DM abundance. This procedure is valid when PBHs of different masses contribute approximately independently to a given observable, so that the total signal can be expressed as a linear superposition over the mass function. This condition is well satisfied for microlensing constraints which are the most relevant for our analysis and, to a good approximation, for evaporation bounds.

In Fig. 2 we show the PBH mass functions corresponding to the benchmark scenarios introduced in Sec. II. The left panel corresponds to the case where we assume $f_{\text{PBH}} = 1$, with the mass functions for the MSSM scenarios peaking at $M_{\text{PBH}} \sim M_{\text{H}}(T = m_i)$ with $i = b, f, h$, as expected. The right panel shows the same mass functions rescaled by $f_{\text{PBH}} = \min\{f_{\text{PBH}}^{\text{max}}, 1\}$, where the minimum ensures that unphysical cases with $f_{\text{PBH}} > 1$ are excluded. For the displayed cases, PBHs in the SM, MSSM-1, and

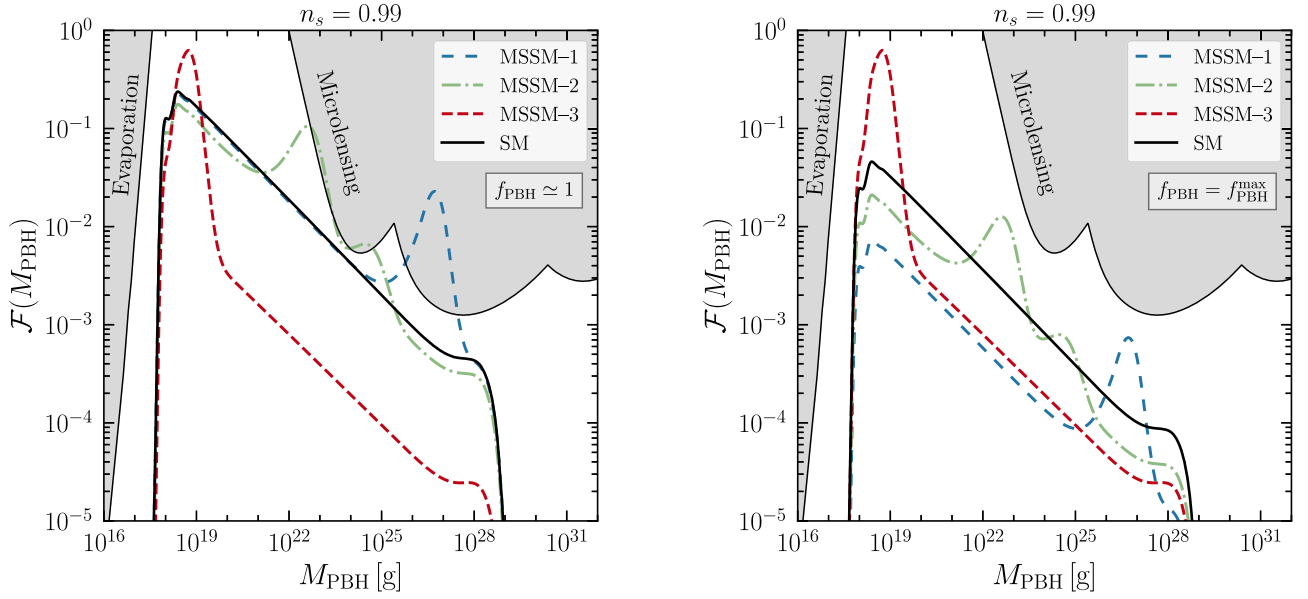


FIG. 2. Primordial black hole mass fraction $\mathcal{F}(M_{\text{PBH}})$ as a function of the PBH mass assuming $n_s = 0.99$. The colored curves correspond to the MSSM benchmark realizations listed in Sec. II, while the black curve shows the mass fraction computed assuming the SM equation of state. In the left panel, PBHs account for the total DM abundance, while in the right panel the mass functions satisfy $f_{\text{PBH}} = f_{\text{PBH}}^{\text{max}}$ to be consistent with current observational constraints. Also displayed are the monochromatic evaporation [18–25,27–31] and microlensing [32–40] constraints, compiled using the repository [122].

MSSM–2 scenarios cannot account for the entirety of the dark matter, with their relative abundance constrained to be below $\sim 10\%$, and the most stringent bound applying to MSSM–1, which is limited to $\sim 5\%$ of the total DM abundance. The only exception is the MSSM–3 mass function, which features a narrow peak at $M_{\text{PBH}} \sim 10^{19}$ g and remains consistent with current observational constraints.

IV. RESULTS

We compute the equation of state by varying the three mass scales (m_f, m_b, m_h) from 10^3 GeV to 10^7 GeV in order to assess the impact on PBH formation due to the variations of the EoS parameter in the MSSM. For each mass configuration, we first evaluate the resulting PBH mass function by fixing the spectral index n_s and adjusting the amplitude of the primordial power spectrum so as to obtain $f_{\text{PBH}} \simeq 1$. We quantify the enhancement in PBH production through the ratio $\mathcal{F}_{\text{MSSM}}(M_{\text{PBH}})/\mathcal{F}_{\text{SM}}(M_{\text{PBH}})$, where $\mathcal{F}_{\text{SM}}(M_{\text{PBH}})$ is obtained using the SM equation of state.

In Fig. 3 we show the maximum value

$$\mathcal{R}_{\text{max}} \equiv \max_{M_{\text{PBH}}} \left[\frac{\mathcal{F}_{\text{MSSM}}(M_{\text{PBH}})}{\mathcal{F}_{\text{SM}}(M_{\text{PBH}})} \right] \quad (17)$$

in the (m_f, m_b) plane, fixing $m_h = 10^3$ GeV. This choice is motivated by the relatively small number of degrees of freedom associated with the heavy Higgs, which leads to a milder modification of the EoS compared to the fermionic

and bosonic superpartners. A clear enhancement of the PBH abundance appears along the $m_f = m_b$ direction. This behavior is expected as the drop in the EoS is maximized when multiple species decouple simultaneously, i.e. for nearly degenerate masses. We find the maximum value for the ratio to be $\mathcal{R}_{\text{max}} \simeq 40$ for $m_b = m_f \simeq 3.7 \times 10^3$ GeV

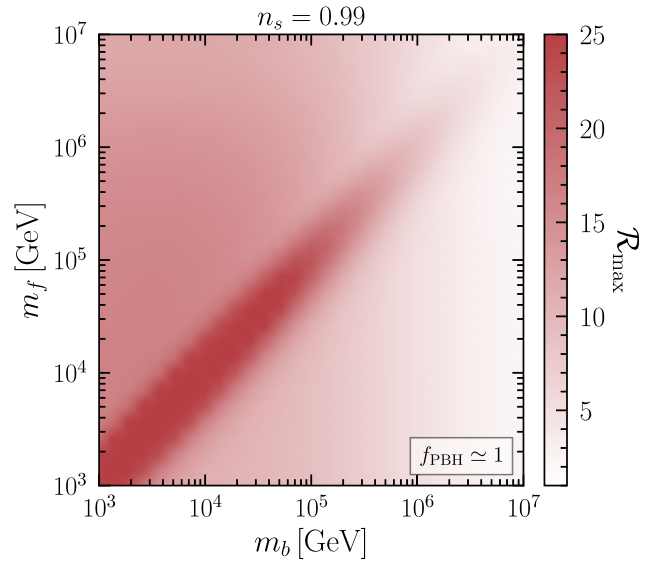


FIG. 3. Maximum enhancement of the PBH mass fraction in the MSSM relative to the SM case, $\mathcal{R}_{\text{max}}$ [see Eq. (17)], shown in the (m_f, m_b) plane for fixed $m_h = 10^3$ GeV and $n_s = 0.99$. For each scenario, we here consider $f_{\text{PBH}} \simeq 1$.

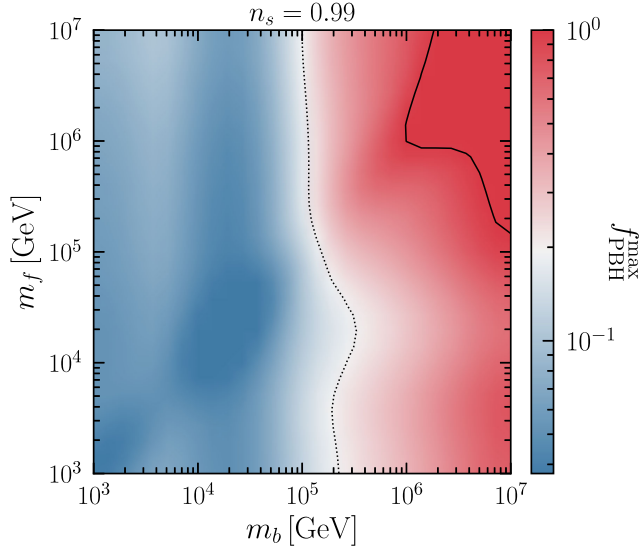


FIG. 4. Maximum allowed fraction of DM in the form of PBHs, $f_{\text{PBH}}^{\text{max}}$, in the (m_b, m_f) parameter space with $m_h = 10^3$ GeV and $n_s = 0.99$. The color scale is chosen such that the white region marks where the SM and MSSM scenarios predict the same value of $f_{\text{PBH}}^{\text{max}}$, i.e. where the effect of observational constraints is unchanged. The dotted black curve further outlines this region, while the solid contour encloses the parameter space in which PBHs can account for all of the DM abundance. To the right (left) of the dotted curve, the allowed DM fraction in PBHs is larger (smaller) than in the SM case.

and $n_s = 0.995$. A complementary feature of our results is that the peak of the PBH mass function is largely set by m_b , reflecting the dominant contribution of bosonic degrees of freedom. In most cases, the peak mass is well approximated by

$$M_{\text{PBH}}^{\text{peak}} \simeq 5 \times 10^{22} \left(\frac{10^5 \text{ GeV}}{m_b} \right)^2 \text{ g}, \quad (18)$$

with only a weak dependence on m_f and m_h .

We then confront the resulting mass functions with existing observational constraints in Fig. 4, where for each scenario we show the quantity $f_{\text{PBH}}^{\text{max}}$ given in Eq. (16). In the SM case, PBHs cannot account for the total DM abundance for any of the n_s values considered, as the corresponding mass functions are excluded by evaporation and microlensing bounds. The white region in the plot denotes the subset of parameter space in which the MSSM and SM scenarios yield identical values of $f_{\text{PBH}}^{\text{max}}$.

Several MSSM realizations shift and enhance the peaks of the mass function toward regions of parameter space that are currently weakly constrained, the asteroid-mass window. Remarkably, we find that, for specific combinations of (n_s, m_f, m_b, m_h) , the resulting mass function is compatible with primordial black holes accounting for the entirety of dark matter. For all the scenarios considered, this

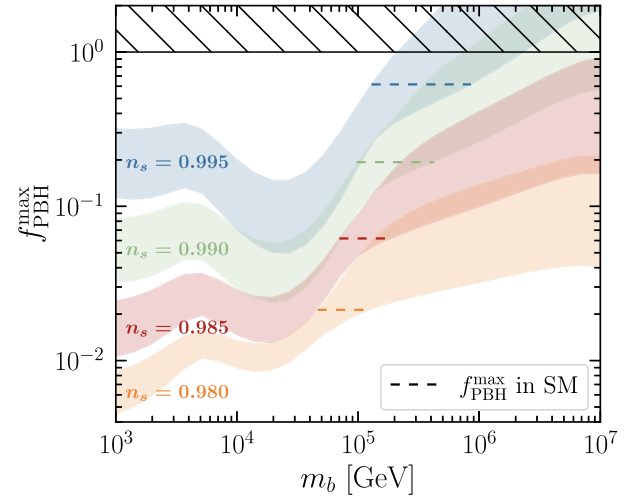


FIG. 5. Maximum allowed DM fraction in PBHs, $f_{\text{PBH}}^{\text{max}}$, as a function of m_b for different values of the spectral index n_s . Shaded bands are obtained by varying m_f and m_h , with their edges corresponding to the minimum and maximum values of $f_{\text{PBH}}^{\text{max}}$. Dashed lines show the SM value of $f_{\text{PBH}}^{\text{max}}$.

improvement in compatibility with monochromatic constraints occurs for $m_b \gtrsim 10^5$ GeV, while for smaller values the resulting mass functions are more strongly excluded than in the SM case. According to Eq. (18), $m_b \gtrsim 10^5$ GeV corresponds to a peak mass $M_{\text{PBH}}^{\text{peak}} \lesssim 10^{22}$ g, which lies within the asteroid-mass window where monochromatic constraints are comparatively weaker or absent.

In Fig. 5 we present the maximum allowed PBH dark matter fraction, $f_{\text{PBH}}^{\text{max}}$, as a function of m_b for different values of the spectral index n_s . For each n_s , the shaded bands illustrate the range of the allowed values obtained by varying m_f and m_h over the parameter space considered. The extent of these bands highlights the sensitivity of the constraints on the PBH abundance to the underlying mass spectrum, with larger widths indicating a stronger dependence on the fermionic and Higgs mass scales. The horizontal dashed segments indicate the corresponding $f_{\text{PBH}}^{\text{max}}$ in the SM scenario. The features induced by the MSSM equation of state in the PBH mass function are largely insensitive to the spectral index, as the varying n_s primarily produces an overall vertical shift of the curves.

We find that, for our choice of parameters, a nearly scale-invariant power spectrum leads to a mass function that is in better overall agreement with current observational constraints. Indeed, only for spectral index values close to unity ($n_s = 0.990$ and $n_s = 0.995$ in our analysis), the features induced by the MSSM equation of state significantly improve the compatibility with monochromatic bounds, allowing PBHs to constitute the entirety of dark matter. For smaller spectral index values, the mass function develops a high-mass tail that is constrained by the absence of microlensing events in observations.

V. CONCLUSIONS

In this work, we have investigated a scenario in which a heavy supersymmetric sector becomes nonrelativistic at temperatures $T \gtrsim 1$ TeV, inducing a temporary softening of the equation of state and enhancing the PBH production in the asteroid-mass range. We computed the equation-of-state parameter for different MSSM realizations, parametrized by the masses of the fermionic, bosonic, and heavy Higgs sectors, which we assumed to be degenerate within each sector for simplicity. We then derive the resulting PBH mass functions within the critical collapse framework, adopting a minimal phenomenological parametrization of the primordial curvature power spectrum. We quantified the enhancement in PBH formation by comparing the MSSM and SM predictions, finding that the dominant peaks in the mass function are associated with the mass scale of the bosonic superpartners.

We showed that, for all the spectral index values considered, PBHs cannot account for the entirety of dark matter in the SM scenario, as the corresponding mass functions are excluded by current monochromatic constraints. In contrast, we found that specific MSSM equations of state can both enhance and shift the PBH mass function toward regions of parameter space that remain weakly constrained, in particular within the asteroid-mass window. For suitable combinations of supersymmetric mass scales, PBHs can consistently account for the full DM abundance. Interestingly, this occurs in regions of parameter space where the relative enhancement of the mass function is moderate, rather than maximal.

Overall, our results demonstrate that modifications of the high-energy particle content above the electroweak scale can leave observable imprints on small-scale structure formation through their impact on PBH production. A more complete assessment would require embedding the primordial power spectrum within a concrete inflationary framework, which we leave for future work.

Finally, we emphasize that our analysis has implications for particle DM searches, as supersymmetric models naturally predict additional DM candidates that freeze out and contribute to the relic abundance. In scenarios where PBHs account for the entirety of the dark matter, the contribution from particle DM must necessarily be negligible or absent, implying strong constraints on the underlying particle physics framework. The interplay between PBH and particle DM components has not been addressed here and will be the subject of future investigations.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] G. Jungman, M. Kamionkowski, and K. Griest, Supersymmetric dark matter, *Phys. Rep.* **267**, 195 (1996).
 - [2] G. Bertone, D. Hooper, and J. Silk, Particle dark matter: Evidence, candidates and constraints, *Phys. Rep.* **405**, 279 (2005).
 - [3] D. J. E. Marsh, Axion cosmology, *Phys. Rep.* **643**, 1 (2016).
 - [4] K. Choi, S. H. Im, and C. Sub Shin, Recent progress in the physics of axions and axion-like particles, *Annu. Rev. Nucl. Part. Sci.* **71**, 225 (2021).
 - [5] Y. B. Zel'dovich and I. D. Novikov, The hypothesis of cores retarded during expansion and the hot cosmological model, *Sov. Astron.* **10**, 602 (1967).
 - [6] S. Hawking, Gravitationally collapsed objects of very low mass, *Mon. Not. R. Astron. Soc.* **152**, 75 (1971).
 - [7] B. J. Carr and S. W. Hawking, Black holes in the early universe, *Mon. Not. R. Astron. Soc.* **168**, 399 (1974).
 - [8] S. W. Hawking, Particle creation by black holes, *Commun. Math. Phys.* **43**, 199 (1975); **46**, 206(E) (1976).
 - [9] B. J. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, New cosmological constraints on primordial black holes, *Phys. Rev. D* **81**, 104019 (2010).
 - [10] B. Carr, F. Kuhnel, and M. Sandstad, Primordial black holes as dark matter, *Phys. Rev. D* **94**, 083504 (2016).
 - [11] A. M. Green and B. J. Kavanagh, Primordial black holes as a dark matter candidate, *J. Phys. G* **48**, 043001 (2021).
 - [12] B. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, Constraints on primordial black holes, *Rep. Prog. Phys.* **84**, 116902 (2021).
 - [13] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GW151226: Observation of gravitational waves from a 22-solar-mass binary black hole coalescence, *Phys. Rev. Lett.* **116**, 241103 (2016).
 - [14] S. Bird, I. Cholis, J. B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E. D. Kovetz, A. Raccanelli, and A. G. Riess, Did LIGO detect dark matter?, *Phys. Rev. Lett.* **116**, 201301 (2016).

- [15] J. García-Bellido, Massive primordial black holes as dark matter and their detection with gravitational waves, *J. Phys. Conf. Ser.* **840**, 012032 (2017).
- [16] M. Sasaki, T. Suyama, T. Tanaka, and S. Yokoyama, Primordial black holes—perspectives in gravitational wave astronomy, *Classical Quantum Gravity* **35**, 063001 (2018).
- [17] N. Bartolo, V. De Luca, G. Franciolini, A. Lewis, M. Peloso, and A. Riotto, Primordial black hole dark matter: LISA serendipity, *Phys. Rev. Lett.* **122**, 211301 (2019).
- [18] B. V. Lehmann, S. Profumo, and J. Yant, The maximal-density mass function for primordial black hole dark matter, *J. Cosmol. Astropart. Phys.* **04** (2018) 007.
- [19] R. Laha, Primordial black holes as a dark matter candidate are severely constrained by the galactic center 511 keV γ -ray line, *Phys. Rev. Lett.* **123**, 251101 (2019).
- [20] M. Boudaud and M. Cirelli, Voyager 1 $e^\pm$ further constrain primordial black holes as dark matter, *Phys. Rev. Lett.* **122**, 041104 (2019).
- [21] S. Clark, B. Dutta, Y. Gao, L. E. Strigari, and S. Watson, Planck constraint on relic primordial black holes, *Phys. Rev. D* **95**, 083006 (2017).
- [22] B. Dasgupta, R. Laha, and A. Ray, Neutrino and positron constraints on spinning primordial black hole dark matter, *Phys. Rev. Lett.* **125**, 101101 (2020).
- [23] R. Laha, J. B. Muñoz, and T. R. Slatyer, INTEGRAL constraints on primordial black holes and particle dark matter, *Phys. Rev. D* **101**, 123514 (2020).
- [24] A. Coogan, L. Morrison, and S. Profumo, Direct detection of Hawking radiation from asteroid-mass primordial black holes, *Phys. Rev. Lett.* **126**, 171101 (2021).
- [25] H. Kim, A constraint on light primordial black holes from the interstellar medium temperature, *Mon. Not. R. Astron. Soc.* **504**, 5475 (2021).
- [26] R. Calabrese, D. F. G. Fiorillo, G. Miele, S. Morisi, and A. Palazzo, Primordial black hole dark matter evaporating on the neutrino floor, *Phys. Lett. B* **829**, 137050 (2022).
- [27] S. Mittal, A. Ray, G. Kulkarni, and B. Dasgupta, Constraining primordial black holes as dark matter using the global 21-cm signal with X-ray heating and excess radio background, *J. Cosmol. Astropart. Phys.* **03** (2021) 030.
- [28] B.-Y. Su, X. Pan, G.-S. Wang, L. Zu, Y. Yang, and L. Feng, Constraining primordial black holes as dark matter using AMS-02 data, *Eur. Phys. J. C* **84**, 606 (2024); **84**, 768(E) (2024).
- [29] X.-h. Tan and J.-q. Xia, Revisiting bounds on primordial black hole as dark matter with X-ray background, *J. Cosmol. Astropart. Phys.* **09** (2024) 022.
- [30] P. De la Torre Luque, J. Koechler, and S. Balaji, Refining galactic primordial black hole evaporation constraints, *Phys. Rev. D* **110**, 123022 (2024); **112**, 109904(E) (2025).
- [31] N. K. Khan, A. Ray, G. Kulkarni, and B. Dasgupta, Stronger constraints on primordial black holes as dark matter derived from the thermal evolution of the intergalactic medium over the last twelve billion years, *Phys. Rev. D* **112**, 123019 (2025).
- [32] R. A. Allsman *et al.* (Macho Collaboration), MACHO project limits on black hole dark matter in the 1-30 solar mass range, *Astrophys. J. Lett.* **550**, L169 (2001).
- [33] P. Tisserand *et al.* (EROS-2 Collaboration), Limits on the Macho content of the galactic halo from the EROS-2 survey of the magellanic clouds, *Astron. Astrophys.* **469**, 387 (2007).
- [34] J. Garcia-Bellido, S. Clesse, and P. Fleury, Primordial black holes survive SN lensing constraints, *Phys. Dark Universe* **20**, 95 (2018).
- [35] M. Oguri, J. M. Diego, N. Kaiser, P. L. Kelly, and T. Broadhurst, Understanding caustic crossings in giant arcs: Characteristic scales, event rates, and constraints on compact dark matter, *Phys. Rev. D* **97**, 023518 (2018).
- [36] D. Croon, D. McKeen, N. Raj, and Z. Wang, Subaru-HSC through a different lens: Microlensing by extended dark matter structures, *Phys. Rev. D* **102**, 083021 (2020).
- [37] T. Blaineau *et al.*, New limits from microlensing on Galactic black holes in the mass range $10 M_\odot < M < 1000 M_\odot$, *Astron. Astrophys.* **664**, A106 (2022).
- [38] C. Leung *et al.*, Constraining primordial black holes using fast radio burst gravitational-lens interferometry with CHIME/FRB, *Phys. Rev. D* **106**, 043017 (2022).
- [39] A. Esteban-Gutiérrez, E. Mediavilla, J. Jiménez-Vicente, and J. A. Muñoz, Constraints on the abundance of primordial black holes from X-Ray quasar microlensing observations: Substellar to planetary mass range, *Astrophys. J.* **954**, 172 (2023).
- [40] P. Mróz *et al.*, Limits on Planetary-mass primordial black holes from the OGLE high-cadence survey of the magellanic clouds, *Astrophys. J. Lett.* **976**, L19 (2024).
- [41] G. Dvali, A microscopic model of holography: Survival by the burden of memory, *arXiv:1810.02336*.
- [42] G. Dvali, L. Eisemann, M. Michel, and S. Zell, Black hole metamorphosis and stabilization by memory burden, *Phys. Rev. D* **102**, 103523 (2020).
- [43] A. Alexandre, G. Dvali, and E. Koutsangelas, New mass window for primordial black holes as dark matter from the memory burden effect, *Phys. Rev. D* **110**, 036004 (2024).
- [44] B. Barman, S. Jyoti Das, M. R. Haque, and Y. Mambrini, Leptogenesis, primordial gravitational waves, and PBH-induced reheating, *Phys. Rev. D* **110**, 043528 (2024).
- [45] V. Thoss, A. Burkert, and K. Kohri, Breakdown of hawking evaporation opens new mass window for primordial black holes as dark matter candidate, *Mon. Not. R. Astron. Soc.* **532**, 451 (2024).
- [46] M. Chianese, A. Boccia, F. Iocco, G. Miele, and N. Saviano, The light burden of memory: Constraining primordial black holes with high-energy neutrinos, *Phys. Rev. D* **111**, 063036 (2025).
- [47] M. Zantedeschi and L. Visinelli, Ultralight black holes as sources of high-energy particles, *Phys. Dark Universe* **49**, 102034 (2025).
- [48] A. Boccia and F. Iocco, Could the KM3–230213A event be caused by an evaporating primordial black hole?, *Phys. Rev. D* **112**, 063045 (2025).
- [49] R. Calabrese, M. Chianese, and N. Saviano, Impact of memory-burdened primordial black holes on high-scale leptogenesis, *Phys. Rev. D* **111**, 083008 (2025).
- [50] M. Chianese, High-energy gamma-ray emission from memory-burdened primordial black holes, *Phys. Rev. D* **112**, 023043 (2025).
- [51] A. Ambrosone, M. Chianese, and C. Evoli, Exploring memory-burdened primordial black holes with ultra-high-energy cosmic-rays, *arXiv:2603.15827*.

- [52] K. Jedamzik, Primordial black hole formation during the QCD epoch, *Phys. Rev. D* **55**, R5871 (1997).
- [53] K. Jedamzik, Could MACHOS be primordial black holes formed during the QCD epoch?, *Phys. Rep.* **307**, 155 (1998).
- [54] P. Widerin and C. Schmid, Primordial black holes from the QCD transition?, [arXiv:astro-ph/9808142](#).
- [55] C. T. Byrnes, M. Hindmarsh, S. Young, and M. R. S. Hawkins, Primordial black holes with an accurate QCD equation of state, *J. Cosmol. Astropart. Phys.* **08** (2018) 041.
- [56] B. Carr, S. Clesse, and J. García-Bellido, Primordial black holes from the QCD epoch: Linking dark matter, baryogenesis and anthropic selection, *Mon. Not. R. Astron. Soc.* **501**, 1426 (2021).
- [57] P. Conzinu, M. Gasperini, and G. Marozzi, Primordial black holes from pre-big bang inflation, *J. Cosmol. Astropart. Phys.* **08** (2020) 031.
- [58] P. Conzinu and G. Marozzi, Primordial black holes formation in an early matter dominated era from the pre-big-bang scenario, *Phys. Rev. D* **108**, 043533 (2023).
- [59] I. Musco, K. Jedamzik, and S. Young, Primordial black hole formation during the QCD phase transition: Threshold, mass distribution, and abundance, *Phys. Rev. D* **109**, 083506 (2024).
- [60] M. Gonin, O. Ivanytskyi, D. Blaschke, and G. Hasinger, Primordial black holes formation beyond the standard cosmic QCD transition, [arXiv:2604.12581](#).
- [61] X. Pritchard and C. T. Byrnes, Constraining the impact of standard model phase transitions on primordial black holes, *J. Cosmol. Astropart. Phys.* **01** (2024) 076.
- [62] D. Blas, J. W. Foster, Y. Gouttenoire, A. J. Iovino, I. Musco, S. Trifinopoulos, and M. Vanvlasselaer, The dark side of the moon: Listening to scalar-induced gravitational waves, [arXiv:2602.12252](#).
- [63] R. Allahverdi *et al.*, The first three seconds: A review of possible expansion histories of the early universe, *Open J. Astrophys.* **4** (2021).
- [64] T. Harada, C.-M. Yoo, K. Kohri, K.-i. Nakao, and S. Jhingan, Primordial black hole formation in the matter-dominated phase of the universe, *Astrophys. J.* **833**, 61 (2016).
- [65] T. Harada, C.-M. Yoo, K. Kohri, and K.-I. Nakao, Spins of primordial black holes formed in the matter-dominated phase of the universe, *Phys. Rev. D* **96**, 083517 (2017); **99**, 069904(E) (2019).
- [66] T. Kokubu, K. Kyutoku, K. Kohri, and T. Harada, Effect of inhomogeneity on primordial black hole formation in the matter dominated era, *Phys. Rev. D* **98**, 123024 (2018).
- [67] B. Shams Es Haghi, Baryogenesis and primordial black hole dark matter from heavy metastable particles, *Phys. Rev. D* **107**, 083507 (2023).
- [68] T. Harada, K. Kohri, M. Sasaki, T. Terada, and C.-M. Yoo, Threshold of primordial black hole formation against velocity dispersion in matter-dominated era, *J. Cosmol. Astropart. Phys.* **02** (2022) 038.
- [69] H. E. Haber, Introductory low-energy supersymmetry, in *Theoretical Advanced Study Institute (TASI 92): From Black Holes and Strings to Particles* (1993), pp. 589–686, [arXiv:hep-ph/9306207](#).
- [70] H. Baer *et al.*, Low-energy supersymmetry phenomenology [10.2172/72994](#) (1995).
- [71] M. Drees and S. P. Martin, Implications of SUSY model building, in *Electroweak symmetry breaking and new physics at the TeV scale*, edited by T. L. Barklow, S. Dawson, H. E. Haber, and J. L. Siegrist (1995), pp. 146–215, [arXiv:hep-ph/9504324](#).
- [72] C. Csaki, The minimal supersymmetric standard model (MSSM), *Mod. Phys. Lett. A* **11**, 599 (1996).
- [73] A. Escrivá, Y. Tada, and C.-M. Yoo, Primordial black holes and induced gravitational waves from a smooth crossover beyond standard model theories, *Phys. Rev. D* **110**, 063521 (2024).
- [74] X. Pritchard, M. Starbuck, and W. Leung, Beyond standard model equation of state and primordial black holes, *J. Cosmol. Astropart. Phys.* **02** (2025) 071.
- [75] Y. Cui, M. Lewicki, D. E. Morrissey, and J. D. Wells, Probing the pre-BBN universe with gravitational waves from cosmic strings, *J. High Energy Phys.* **01** (2018) 081.
- [76] S. Antusch, K. Hinze, and S. Saad, Explaining PTA results by metastable cosmic strings from SO(10) GUT, *J. Cosmol. Astropart. Phys.* **10** (2024) 007.
- [77] S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, and K. K. Szabo, Full result for the QCD equation of state with $2 + 1$ flavors, *Phys. Lett. B* **730**, 99 (2014).
- [78] A. Bazavov *et al.* (HotQCD Collaboration), Equation of state in $(2 + 1)$ -flavor QCD, *Phys. Rev. D* **90**, 094503 (2014).
- [79] L. Husdal, On effective degrees of freedom in the early universe, *Galaxies* **4**, 78 (2016).
- [80] Z. Berezhiani, M. Chianese, G. Miele, and S. Morisi, Chances for SUSY-GUT in the LHC epoch, *J. High Energy Phys.* **08** (2015) 083.
- [81] S. Dimopoulos, S. Raby, and F. Wilczek, Supersymmetry and the scale of unification, *Phys. Rev. D* **24**, 1681 (1981).
- [82] L. E. Ibanez and G. G. Ross, Low-energy predictions in supersymmetric grand unified theories, *Phys. Lett.* **105B**, 439 (1981).
- [83] M. B. Einhorn and D. R. T. Jones, The weak mixing angle and unification mass in supersymmetric SU(5), *Nucl. Phys.* **B196**, 475 (1982).
- [84] W. J. Marciano and G. Senjanovic, Predictions of supersymmetric grand unified theories, *Phys. Rev. D* **25**, 3092 (1982).
- [85] D. J. Castano, E. J. Piard, and P. Ramond, Renormalization group study of the standard model and its extensions. 2. The minimal supersymmetric standard model, *Phys. Rev. D* **49**, 4882 (1994).
- [86] G. F. Giudice and A. Romanino, Split supersymmetry, *Nucl. Phys.* **B699**, 65 (2004); **B706**, 487(E) (2005).
- [87] N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice, and A. Romanino, Aspects of split supersymmetry, *Nucl. Phys.* **B709**, 3 (2005).
- [88] M. M. Flores and A. Kusenko, New Ideas on the formation and astrophysical detection of primordial black holes, [arXiv:2404.05430](#).
- [89] S. Young, I. Musco, and C. T. Byrnes, Primordial black hole formation and abundance: Contribution from the non-linear relation between the density and curvature perturbation, *J. Cosmol. Astropart. Phys.* **11** (2019) 012.

- [90] G. Franciolini, A. Iovino, Junior., V. Vaskonen, and H. Veermäe, Recent gravitational wave observation by pulsar timing arrays and primordial black holes: The importance of non-Gaussianities, *Phys. Rev. Lett.* **131**, 201401 (2023).
- [91] A. D. Gow, H. Assadullahi, J. H. P. Jackson, K. Koyama, V. Vennin, and D. Wands, Non-perturbative non-Gaussianity and primordial black holes, *Europhys. Lett.* **142**, 49001 (2023).
- [92] A. M. Green, A. R. Liddle, K. A. Malik, and M. Sasaki, A new calculation of the mass fraction of primordial black holes, *Phys. Rev. D* **70**, 041502 (2004).
- [93] I. Musco, V. De Luca, G. Franciolini, and A. Riotto, Threshold for primordial black holes. II. A simple analytic prescription, *Phys. Rev. D* **103**, 063538 (2021).
- [94] I. Musco and T. Papanikolaou, Primordial black hole formation for an anisotropic perfect fluid: Initial conditions and estimation of the threshold, *Phys. Rev. D* **106**, 083017 (2022).
- [95] A. Iannicari, A. J. Iovino, A. Kehagias, D. Perrone, and A. Riotto, The black hole formation—null geodesic correspondence, *Phys. Rev. Lett.* **133**, 081401 (2024).
- [96] A. S. Josan, A. M. Green, and K. A. Malik, Generalised constraints on the curvature perturbation from primordial black holes, *Phys. Rev. D* **79**, 103520 (2009).
- [97] I. Musco, J. C. Miller, and L. Rezzolla, Computations of primordial black hole formation, *Classical Quantum Gravity* **22**, 1405 (2005).
- [98] I. Musco and J. C. Miller, Primordial black hole formation in the early universe: Critical behaviour and self-similarity, *Classical Quantum Gravity* **30**, 145009 (2013).
- [99] I. Musco, Threshold for primordial black holes: Dependence on the shape of the cosmological perturbations, *Phys. Rev. D* **100**, 123524 (2019).
- [100] A. Escrivà and C.-M. Yoo, Nonspherical effects on the mass function of primordial black holes, *Phys. Rev. D* **112**, L081304 (2025).
- [101] M. W. Choptuik, Universality and scaling in gravitational collapse of a massless scalar field, *Phys. Rev. Lett.* **70**, 9 (1993).
- [102] J. C. Niemeyer and K. Jedamzik, Near-critical gravitational collapse and the initial mass function of primordial black holes, *Phys. Rev. Lett.* **80**, 5481 (1998).
- [103] S. Wang, T. Terada, and K. Kohri, Prospective constraints on the primordial black hole abundance from the stochastic gravitational-wave backgrounds produced by coalescing events and curvature perturbations, *Phys. Rev. D* **99**, 103531 (2019); **101**, 069901(E) (2020).
- [104] T. Nakama, J. Silk, and M. Kamionkowski, Stochastic gravitational waves associated with the formation of primordial black holes, *Phys. Rev. D* **95**, 043511 (2017).
- [105] B. Carr, S. Clesse, J. Garcia-Bellido, M. Hawkins, and F. Kuhnel, Observational evidence for primordial black holes: A positivist perspective, *Phys. Rep.* **1054**, 1 (2024).
- [106] S. Young, C. T. Byrnes, and M. Sasaki, Calculating the mass fraction of primordial black holes, *J. Cosmol. Astropart. Phys.* **07** (2014) 045.
- [107] J. S. Bullock and J. R. Primack, NonGaussian fluctuations and primordial black holes from inflation, *Phys. Rev. D* **55**, 7423 (1997).
- [108] P. Ivanov, Nonlinear metric perturbations and production of primordial black holes, *Phys. Rev. D* **57**, 7145 (1998).
- [109] P. Pina Avelino, Primordial black hole constraints on non-Gaussian inflation models, *Phys. Rev. D* **72**, 124004 (2005).
- [110] C. T. Byrnes, E. J. Copeland, and A. M. Green, Primordial black holes as a tool for constraining non-Gaussianity, *Phys. Rev. D* **86**, 043512 (2012).
- [111] S. Shandera, A. L. Erickcek, P. Scott, and J. Y. Galarza, Number counts and non-Gaussianity, *Phys. Rev. D* **88**, 103506 (2013).
- [112] S. Young and C. T. Byrnes, Primordial black holes in non-Gaussian regimes, *J. Cosmol. Astropart. Phys.* **08** (2013) 052.
- [113] S. Young, D. Regan, and C. T. Byrnes, Influence of large local and non-local bispectra on primordial black hole abundance, *J. Cosmol. Astropart. Phys.* **02** (2015) 029.
- [114] V. De Luca, G. Franciolini, A. Kehagias, M. Peloso, A. Riotto, and C. Ünal, The ineludible non-Gaussianity of the primordial black hole abundance, *J. Cosmol. Astropart. Phys.* **07** (2019) 048.
- [115] S. Allegrini, L. Del Grosso, A. J. Iovino, and A. Urbano, Is the formation of primordial black holes from single-field inflation compatible with standard cosmology?, *Phys. Rev. D* **111**, 123557 (2025).
- [116] Y. Akrami *et al.* (Planck Collaboration), Planck 2018 results. X. Constraints on inflation, *Astron. Astrophys.* **641**, A10 (2020).
- [117] G. Ferrante, G. Franciolini, A. Iovino, Junior., and A. Urbano, Primordial black holes in the curvaton model: Possible connections to pulsar timing arrays and dark matter, *J. Cosmol. Astropart. Phys.* **06** (2023) 057.
- [118] I. Stamou, Mechanisms for producing primordial black holes from inflationary models beyond fine-tuning, *Universe* **10**, 241 (2024).
- [119] F. Crescimbeni, V. Desjacques, G. Franciolini, A. Iannicari, A. J. Iovino, G. Perna, D. Perrone, A. Riotto, and H. Veermäe, The irrelevance of primordial black hole clustering in the LVK mass range, *J. Cosmol. Astropart. Phys.* **05** (2025) 001.
- [120] B. Carr, A. J. Iovino, G. Perna, V. Vaskonen, and H. Veermäe, Primordial black holes: Constraints, potential evidence and prospects, [arXiv:2601.06024](https://arxiv.org/abs/2601.06024).
- [121] B. Carr, M. Raidal, T. Tenkanen, V. Vaskonen, and H. Veermäe, Primordial black hole constraints for extended mass functions, *Phys. Rev. D* **96**, 023514 (2017).
- [122] B. J. Kavanagh, Pbhounds: Repository of primordial black hole constraints (2019).