Primordial Black Holes Formed during Magneto-Hydrodynamic Turbulence in the Early Universe as Dominant Part of Dark Matter

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Primordial black holes (PBHs) offer a compelling candidate for dark matter. The production of PBHs through well-tested and accepted physical processes is highly worthy of investigation. This work highlights the role of turbulences in the very early universe in sustaining intense and persistent fluctuations in energy or mass density, which could provide a natural mechanism for PBH formation in the primordial universe. We analyze the mass range and abundance of PBHs produced in the magnetohydrodynamic turbulence induced by the electroweak phase transition. Remarkably, we find that the mass range of the produced PBHs falls within the most viable "asteroid mass" window from the present-day observations, and within natural parameter regions their abundance can be sufficiently large. These findings suggest that PBHs produced during magnetohydrodynamic turbulence in the very early universe may comprise a dominant part of dark matter.

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1. Introduction. Numerous astrophysical and cosmological observations have provided us with irrefutable evidence that about 85% of the matter in our universe is in the form of cold, nonbaryonic dark matter (DM).[1–6] The physical origin and nature of DM remain one of the most perplexing mysteries in modern cosmology and physics, inspiring a great deal of research. Among the DM candidates, primordial black holes (PBHs) can be considered the most appealing option that satisfies almost all the necessary requirements.

PBHs were proposed by Zel'dovich and Novikov,[7] and Hawking[8,9] as hypothetical relics from the collapse of overdense regions in the very early universe. Supposed to form in the radiation-dominated era before nucleosynthesis, PBHs should naturally be considered as nonbaryonic, and today they can be viewed as the only surviving DM candidate that does not invoke new particles beyond the Standard Model. Though lacking direct and decisive evidence for their existence, PBHs nevertheless have drawn extensive attention in the past fifty years and become one of the most active research fields in astrophysics and cosmology since their existence could have important implications and provide natural explanations for various observational conundrums and challenges, including, most importantly, the DM puzzle. For example,[10,11] it is suggested that the coalescing black hole binaries observed by the LIGO–Virgo–KAGRA collaborations might contain primordial ones; furthermore, the unexpected mass gaps and low spins in these stellar mass black holes might be explained.[12–15] Additionally, very large PBHs could provide seeds for supermassive black holes residing in galactic nuclei with high redshifts.[16]

Since the encouraging results from the MACHO (Massive Compact Halo Object) project in the 1990s suggested that DM might be compact objects with mass $\sim 0.5\,M_\odot$,[17] severe constraints from joint observations and theoretical considerations[18–20] had been imposed on the allowed mass range of PBHs. Today, attention has shifted to the most viable "asteroid mass" window of $10^{17}\mathrm{g} \sim 10^{24}\mathrm{g}$, where PBHs could comprise a dominant part of DM.[18,21] However, producing PBHs within a given mass range generally depends on primordial density fluctuations with enhancements peaked at corresponding small scales, which can be achieved by the fine-tuned background dynamics of primordial quantum fields in the very early universe. Furthermore, to produce enough number of PBHs, such enhanced primordial fluctuations on certain scales must be many orders of magnitude larger than those on cosmological scales, which can be achieved in certain inflation models. This introduces the "beyond the Standard Model" physics for PBH DM proposals, while at the same time also brings new challenges.

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Various alternative mechanisms for PBH formation have been proposed, including sound-speed resonance during inflation,[22] scalar field instabilities,[23] collisions of highly energetic particles,[24] topological defects,[25,26] and modified gravity scenarios.[27,28] Notably, cosmological phase transitions in the early universe provide a rich environment for PBH production through multiple distinct channels. These include the gravitational collapse of false vacuum bubbles nucleated at a critical rate during first-order phase transitions,[29] PBH formation via delayed vacuum decay—where asynchronized phase transitions give rise to overdense regions[30]—and the generation of large curvature perturbations through bubble collisions, which may exceed the threshold for gravitational collapse.[31]

In this work, we emphasize the important role of the turbulent behavior of primordial plasma in the very early universe, particularly itse potential implications for PBH formation. The fluid model can be viewed as the most successful model for macroscopic and continuous matter systems. In nature, situations beyond the ideal fluid model, such as complicated disturbances, nonlinearities, dissipation, and instabilities, are more common; turbulence is a rather prevalent state for fluids of high Reynolds number.[32] On the other hand, it has been noticed that the Reynolds number for high-temperature and extremely (or even fully) relativistic fluids in the very early universe is expected to be very high,[33–35] and turbulence is believed to arise not only in the primordial fluids,[34,36] but also even in the violent dynamical spacetime itself.[37] Here, we focus on the magnetohydrodynamic (MHD) turbulence that persists for a period of many Hubble times (H^{-1}) during and after the first-order electroweak phase transition in the early universe.[34,38,39] The most noteworthy feature of such turbulence here is the enhanced and persistent fluctuations of energy or mass density, as the density fluctuations at certain scales exceed a given threshold, PBHs within a certain mass range could then be formed. This therefore provides us with a natural mechanism based on such well-accepted physical processes, for PBH formation in the very early universe.

In the following, we explain the basic principles of PBH formation from MHD turbulence induced by the electroweak phase transition and give estimations of the PBH mass range and abundance. Remarkably, it turns out that the mass range falls precisely within the most viable open asteroid mass window; and within natural parameter regions of the MHD that match remarkably those from previous and independent studies, the PBHs generated can comprise a dominant fraction of DM. For clarity, $c = 1$ is adopted in the following discussion.

2. MHD Turbulences and Density Fluctuations. For hydrodynamic turbulences, the violent density fluctuations and their implications in astrophysics had been extensively studied,[40,41] for example the small-scale structure of electron density fluctuations[42] and higher order structure functions of interstellar turbulences,[43] topologies of density in interstellar mediums,[44] and so on. Density fluctuations produced by compressible MHD turbulences could also play important roles in star and galaxy formation.[45,46] In the very early universe, indirect evidence and theoretical considerations strongly suggest the existence of turbulent processes.[39,47–55]

Generally, turbulence occurs when a fluid with a large Reynolds number is perturbed. Reynolds number is defined by $\mathrm{Re} = vL/\nu$, where v is fluid velocity, L the characteristic length scale, and ν the kinematic viscosity. For the turbulent fluid induced by the phase transition, the magnitudes of v and L can be estimated according to the dynamics of the corresponding phase transition, see Ref. [47] for details of the first-order electroweak phase transition. As the temperature of the universe decreases, the Higgs field will fall into new ground states driven by thermal fluctuations[56] or via quantum transitions.[57] Such phase transition proceeds via bubble nucleations, where small bubbles or regions in new ground states emerge randomly, then expand, collide and merge, ultimately causing the whole universe to enter a new symmetry breaking phase. During this process, collisions among bubbles will violently stir the primordial and extremely relativistic fluid. The energy released by the phase transition is partly injected and transformed into the MHD turbulent flow; according to previous studies' predictions, the energy density proportion in MHD turbulences $\bar{\rho}_{\mathrm{tur}}$ against the total energy density $\delta_{\mathrm{tur}} = \frac{\bar{\rho}_{\mathrm{tur}}}{\bar{\rho}}$ should be in the range $10^{-4} \sim 10^{-2}$,[34,58–60] where $\bar{\rho}$ denotes the total background energy density.

It is natural to consider the turbulence length-scale as the size of phase bubbles,[47]

$$L = 2v_{\mathrm{w}}/\beta, \tag{1}$$

where β denotes the rate parameter of the electroweak phase transition and v_{w} the bubble wall speed. According to the relationship between v_{w} and the sound speed c_{s} in the primordial plasma, there are three possible relativistic combustion cases: subsonic deflagrations,[61] detonations, and supersonic deflagrations (hybrids).[62–65] In detonations, the velocity of the fluid is equal to the wall speed $v = v_{\mathrm{w}} \sim 0.87$.[34,61] In contrast, in supersonic deflagrations, the maximum velocity of the fluid exceeds the wall speed such that $c_{\mathrm{s}} < v_{\mathrm{w}} < v$,[61] which is applicable for the MHD turbulences considered in this work. The kinematic viscosity for primordial plasma reads $\nu = \eta/(\rho + p)$,[34] with ρ and p standing for the energy density and the pressure respectively, and η being shear viscosity. For high-temperature primordial plasma with gauge interactions, one has the form of shear viscosity $\eta = C\frac{T^3}{g^4 \ln g^{-1}}$,[35] where T is temperature, g is gauge coupling, and C is a constant. After the electroweak phase transition, neutrinos will decouple and cause a change in the kinematic viscosity; thus, one has[34]

$$\nu(T) \approx \begin{cases} 22T^{-1}, & T > 100\,\mathrm{GeV}, \\ 5 \times 10^8\,\mathrm{GeV}^4 T^{-5}, & T < 100\,\mathrm{GeV}, \\ 2 \times 10^9\,\mathrm{MeV}^4 T^{-5}, & T < 100\,\mathrm{MeV}. \end{cases} \tag{2}$$

With the above estimation, the Reynolds number for the primordial plasma after the electroweak phase transition

is about $\mathrm{Re} = 10^{13} \sim 10^{16}$.[33] To summarize, the large Reynolds number and the extremely low viscosity will support MHD turbulence existing for many Hubble times, thereby leading to persistent and violent density fluctuations for the production of PBH DM.

For subsonic flow, the density spectrum of MHD turbulence can be obtained by dimensional analysis. In a relatively strong magnetic field, the spectrum of energy density scales similarly to that of the pressure $\sim k^{-7/3}$ (k is the wave number), given the equation of state $p \sim \rho$.[66] For weakly magnetized MHD turbulence, the density spectrum follows the Kolmogorov law, i.e., $\sim k^{-5/3}$.[67] However, in the supersonic flows under consideration, shock waves would pile up matter within local regions and largely enhance the magnitudes of density fluctuations at certain turbulence scales; therefore, the density fluctuations will no longer be proportional to the pressure fluctuations. Without loss of generality, the fluctuations in MHD turbulence are considered to be independent of spacetime locations. The probability distribution function (PDF) of energy or mass density will satisfy a log-normal distribution,[68,69]

$$P(y)\mathrm{d}y = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{-(y-\mu)^2}{2\sigma^2}\right]\mathrm{d}y, \tag{3}$$

where $y = \ln(\rho_{\mathrm{tur}}/\bar{\rho}_{\mathrm{tur}})$, σ^2 is the variance and $|\mu| = \sigma^2/2$. Numerical simulations have confirmed the validity of this relation in three-dimensional turbulent flows,[41,69] and it is applicable to the primordial plasma in the early universe. The specific form of the PDF could be obtained by solving the detailed dynamics of the corresponding MHD turbulence model. Numerical studies of MHD turbulence have been carried out; please see Refs. [41,69,70] for details. These studies clearly point out that density fluctuations strongly depend on the Mach number for both weakly and strongly magnetized turbulence. For supersonic turbulence, the relation between density variance and Mach number M_{s} has been investigated and fitted based on numerical simulations,[71–73]

$$\sigma_{\rho/\bar{\rho}} = bM_{\mathrm{s}}, \tag{4}$$

where b is the proportionality constant. For the log-normal distribution in Eq. (3), one has

$$\sigma^2 = \ln(1 + b^2 M_{\mathrm{s}}^2). \tag{5}$$

According to Ref. [69], the optimal linear fit gives $b^2 = 0.5$.

3. PBH Production. In the radiation-dominated universe, a highly overdense region could collapse into a PBH under the action of its own gravity. The evolution of overdense regions and the formation of PBHs had been extensively studied both numerically and analytically.[74–79] Multiple distinct mechanisms for PBH formation have been proposed. Beyond the well-studied scenario involving the gravitational collapse of large-amplitude density perturbations upon their re-entry into the cosmological horizon after inflation, the collision of bubbles nucleated during a cosmic phase transition constitutes another significant formation channel.[31,80–82] In this latter mechanism, PBHs form via the compression of matter contained within a region collapsing to a scale less than the Schwarzschild radius, induced by coalescing bubble walls.[31] The formation process driven by supersonic turbulence operates in an analogous fashion. Here, intense compression arising from shock waves associated with turbulent flow can compress the material within a region below the Schwarzschild radius, thereby leading to PBH formation.

We consider a spherical overdensity region characterized by a density $\rho = (1 + \Delta)\bar{\rho}$, where $\Delta := \frac{\rho-\bar{\rho}}{\bar{\rho}}$ is the density contrast. The mass M contained within this region of radius R is given by

$$M = \frac{4\pi}{3}\bar{\rho}R^3(1 + \Delta). \tag{6}$$

The Schwarzschild radius R_{s} is

$$R_{\mathrm{s}} = 2GM. \tag{7}$$

Gravitational collapse into a PBH becomes possible if the radius of the overdense region is smaller than its Schwarzschild radius, $R < R_{\mathrm{s}}$. This necessary condition for PBH formation translates into a requirement on the density contrast,

$$\Delta > \Delta_{\mathrm{c}} = \frac{3}{8\pi G\bar{\rho}R^2} - 1. \tag{8}$$

When considering the critical density $\bar{\rho} = \frac{3H^2}{8\pi G}$ as the average density,

$$\Delta_{\mathrm{c}} = \left(\frac{1}{HR}\right)^2 - 1. \tag{9}$$

When the density perturbation scale $R = \frac{1}{H}$ is comparable to the Hubble horizon, a small perturbation can lead to the formation of a PBH. The threshold for this scenario has been discussed in many studies through analytical or numerical simulations,[83–86] and its typical value is $\Delta_{\mathrm{c}} \sim 0.3$. Crucially, the threshold Δ_{c} exhibits a strong dependence on the scale of the overdensity relative to the horizon. When the overdense region is significantly smaller than the Hubble horizon, we have $\Delta_{\mathrm{c}} \sim \frac{1}{R^2}$. This scaling implies that Δ_{c} increases sharply as the perturbation scale R decreases relative to the horizon size, making PBH formation substantially more difficult for sub-horizon perturbations, in striking contrast to the near-horizon case where the threshold is less prohibitive.

We first give the estimation of the mass spectrum of PBHs from MHD turbulence. Like most of the PBH DM proposals in Ref. [18], we find that the masses of the PBHs generated by MHD turbulence will concentrate in a relatively narrow range. As discussed previously, the characteristic mass of PBH produced is highly related to the characteristic scale at which the fluctuations peak most. The general paradigm of turbulence involves large-scale energy injections accompanied by small-scale dissipation. It is then natural to consider that major energy or mass density fluctuations are concentrated or peaked around a characteristic scale, which is considered to be equal to the characteristic scale L defined in Eq. (1). This was confirmed by previous analytical and numerical studies of the

density spectra of MHD turbulences.[41,87] Here, without loss of generality, we consider the case where energy or mass density fluctuations are concentrated in the scale range L, i.e., $R = L$.

According to recent studies, the bubble nucleation rate $\beta = L/2v_{\rm w}$ is estimated to fall in the range $5H \sim 100H$.[38] Particularly, in Ref. [88], it is shown that the efficiency decreases if the expansion of the background is taken into account for slow phase transitions and that β should be $\mathcal{O}(1)H$. Meanwhile, recent works also point out that the formation of large bubbles is a necessary condition for PBH productions.[31] Therefore, it is natural to consider here the characteristic scale of turbulence and the Hubble radius satisfying the relation

$$LH = 1 \sim 0.1. \tag{10}$$

In the following, we work out, based on numerical calculations, the abundance of the generated PBHs and examine the conditions on the relativistic fluid across different turbulence scales. We find that the PBHs formed through this mechanism could comprise a dominant fraction of DM while the required turbulence energy density is consistent with estimations from previous studies. Thus, for a preliminary exploration of this novel PBH formation channel, the relation in Eq. (10) provides a physically well-motivated and self-consistent ansatz.

As PBHs considered here are supposed to be formed nearly during the same period of MHD turbulence, one can estimate their mass range from the scaling in Eq. (10). The mass of a PBH is usually not greater than the total mass within the Hubble mass $M_{\rm H}$.[18] When the size of an overdense region is comparable to the horizon size ($LH = 1$), the mass of the PBH is

$$M_{\rm PBH} = \gamma M_{\rm H} \approx 2.03\times10^{5}\gamma\Big(\frac{t}{1\,{\rm s}}\Big)M_{\odot} \sim 10^{25}\,{\rm g}, \tag{11}$$

where γ is a correction factor that can be derived analytically as $\gamma \simeq 0.2$.[83] When the characteristic scale $LH = 0.1$ and $\Delta_{\rm c} \sim 30$, the mass of the PBH is

$$M_{\rm PBH} = \epsilon\gamma M_{\rm H} = \frac{\Delta_{\rm c}}{(LH)^3}\gamma M_{\rm H} \sim \frac{3}{100}\gamma M_{\rm H} \sim 10^{23}\,{\rm g}, \tag{12}$$

where ϵ is the mass ratio of small-scale PBHs to PBHs on the Hubble radius scale.

We arrive at the first important conclusion that the mass range of the PBHs generated by MHD turbulence during and after the electroweak phase transition should be

$$10^{23}\,{\rm g} \le M_{\rm PBH} \le 10^{25}\,{\rm g}, \tag{13}$$

which overlaps with the asteroid mass range, indicating that this is the most viable open window for the PBH DM candidate under minimal assumptions regarding PBH physics. The generation of PBHs with a mass of $\sim10^{22}$ g under rather extreme conditions is also included in the following discussions.

Secondly, we come to the estimations of the fraction $f_{\rm PBH}$ of the PBHs compared to the total DM component in the present universe. The abundance parameter of the produced PBHs during the MHD turbulence period against the total energy or mass density in the universe can be defined as

$$\alpha := \frac{\rho_{\rm PBH}}{\bar{\rho}}\bigg|_{\text{at formation}},$$

which relates to the faction parameter $f_{\rm PBH}$ as[89]

$$\alpha \simeq 3.7\times10^{-9}\Big(\frac{\epsilon\gamma}{0.2}\Big)^{-\frac{1}{2}}\Big(\frac{g_{*,\rm form}}{10.75}\Big)^{\frac{1}{4}}\Big(\frac{M_{\rm PBH}}{M_{\odot}}\Big)^{\frac{1}{2}}f_{\rm PBH}, \tag{14}$$

where $g_{*,\rm form} \sim 100$ stands for the total relativistic degrees of freedom at that PBH formation epoch.[89] We consider the case that the mass distribution function of PBH is monochromatic, meaning it is a peak-shaped function centered at a certain $M_{\rm PBH}$ with width $\Delta M \sim M_{\rm PBH}$. Given the PDF of the density fluctuation in Eq. (3), α can be calculated according to the Press–Schechter formalism[90] and it is then interpreted as the probability that the energy or mass density fluctuation is larger than the given threshold,

$$\alpha = \gamma\int_{y_{\rm th}}^{\infty}P(y){\rm d}y, \tag{15}$$

where the integration lower bound is given by $y_{\rm th} = \ln(1+\frac{\Delta_{\rm c}}{\delta_{\rm tur}})$. This is because, as mentioned, only a small fraction of total energy is converted into turbulent fluctuations $\bar{\rho}_{\rm tur} = \bar{\rho}\delta_{\rm tur}$, implying that these overdense regions are sparsely distributed. The turbulence fluctuations exceeding the threshold $y > \ln(\frac{\bar{\rho}\delta_{\rm tur}+\bar{\rho}\Delta_{\rm c}}{\bar{\rho}\delta_{\rm tur}}) = \ln(1+\frac{\Delta_{\rm c}}{\delta_{\rm tur}})$ with respect to the energy density $\rho_{\rm tur}$ are counted in the above equation. With the log-normal distribution of MHD turbulence in Eqs. (3)–(5) and the relation in Eq. (14), we can then access how the fraction $f_{\rm PBH}$ of PBHs in the present universe depends on the related parameters of PBH formation and the MHD turbulence, including peak PBH mass $M_{\rm PBH}$, formation threshold $\Delta_{\rm c}$, proportion of energy density in turbulence $\delta_{\rm tur}$, and Mach number $M_{\rm s}$.

As shown in Fig. 1, for the four representative cases with $LH = 1, \sqrt{\frac{1}{10}}, \frac{1}{10}, \frac{1}{10\sqrt{10}}$, which correspond to the thresholds $\Delta_{\rm c} = 0.3, 3, 30, 300$ and the PBH masses $10^{25}\,{\rm g}$, $10^{24}\,{\rm g}$, $10^{23}\,{\rm g}, 10^{22}\,{\rm g}$, we give the allowable regions in the $M_{\rm s}$–$\delta_{\rm tur}$ parameter spaces respectively for PBH fraction $f_{\rm PBH} = 50\%$–100%, 10%–50%, and 1%–10%. The value $\Delta_{\rm c} = 0.3$ corresponds to a larger characteristic turbulent scale and is associated with the formation of large-scale bubbles. This scenario is dynamically well-motivated with a relatively high probability in the context of strong first-order phase transitions, similar to the conclusion in Ref. [31] that large bubble collisions are essential for efficient PBH production. As such, $\Delta_{\rm c} = 0.3$ represents the primary physical scenario considered in this work. On the other hand, the cases $\Delta_{\rm c} = 3$ and $\Delta_{\rm c} = 30$ correspond to the effective density thresholds defined such that the overdense region collapses within a physical scale smaller than the Hubble radius, where such smaller-scale structures are potentially generated from shock compression in

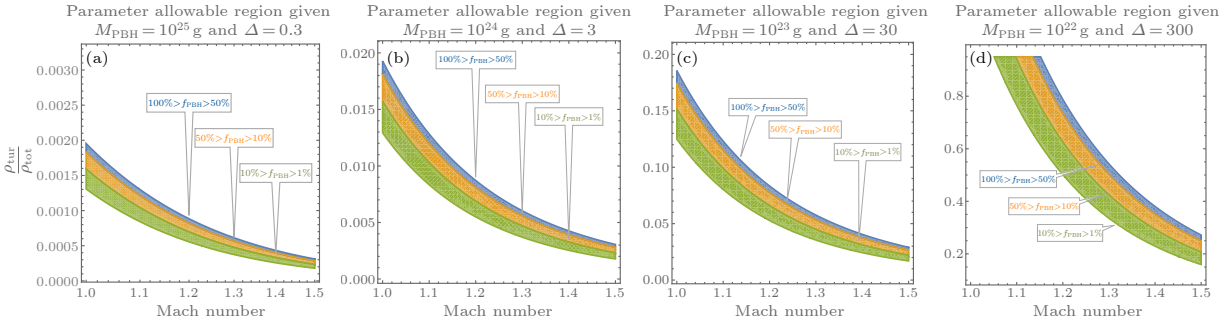

Fig. 1. We consider four representative cases of the turbulence characteristic scale $LH = 1, \sqrt{\frac{1}{10}}, \frac{1}{10}, \frac{1}{10\sqrt{10}}$, which correspond to the thresholds $\Delta_{\rm c} = 0.3$, 3, 30, 300 and the PBH masses 10^{25} g, 10^{24} g, 10^{23} g, 10^{22} g. The allowable regions in the $M_{\rm PBH}$–$\delta_{\rm tur}$ (peak PBH mass–energy density proportion in turbulences) parameter space for PBH formation with the abundance $f_{\rm PBH}$ within 50% ∼ 100%, 10% ∼ 50%, and 1% ∼ 10% are shown.

highly supersonic turbulent flows. Calculations indicate that the high threshold scenarios require prohibitively intense turbulent flows, thereby exhibiting low possibility. These high-threshold cases are included to ensure the completeness of our analysis which may constitute subdominant channels. Here, the Mach number of the supersonic MHD turbulence is considered to take a value near 1, since for the extremely or even fully relativistic primordial MHD turbulence the Mach number could not be much larger than 1.[60] Meanwhile, simulations of relativistic combustion show that the phase transition bubble-wall speed is between $\frac{1}{\sqrt{3}}$c and 0.87c.[47] Therefore, in Fig. 1, the Mach number is set to a typical value of 1–1.5, and within the asteroid mass range one finds that to comprise a dominant part of DM the proportion of energy density in turbulences should fall into the range of 10^{-4}–10^{-2}, which is remarkably in high agreement with the previous and independent studies on how much energy was injected and transformed into MHD turbulent flow during and after the electroweak phase transition.[34,58–60] Figure 1 clearly shows that as the scale of overdense regions diminishes, a greater proportion of turbulent energy and a higher Mach number are needed to form PBH.

Here, we obtain the second important and rather robust conclusion that, without the employment of fine-tuned dynamics of primordial quantum fields and inflation models, the supersonic MHD turbulence that took place during and after the electroweak first-order phase transition in the very early universe can generate PBHs comprising a dominant part of DM. Additionally, the constraint on how much energy was transformed into turbulences matches remarkably well with previous independent studies.

Therefore, the above analysis of the abundance and mass range of PBHs gives us a very strong indication that the important influences and implications of turbulences in the very early universe should not be overlooked, and that the MHD turbulence induced by the electroweak phase transition could provide a natural mechanism to generate the right DM candidate that satisfies the present-day observational constraints. Additionally, in this work we adopt the well-accepted electroweak phase transition energy scale of 100 GeV, corresponding to a cosmic time of $\sim 10^{-12}$ s. If the transition occurred slightly earlier, the horizon mass would decrease, resulting in the formation of lower-mass PBHs. We therefore consider the possibility of forming lighter PBHs, down to 10^{22} g, which could arise on smaller turbulent scales [see Fig. 1(d)]. While this scenario requires significantly enhanced turbulent energy density and represents an extreme case, it remains physically plausible under sufficiently intense MHD turbulence induced by a slightly earlier phase transition. By including this possibility, we demonstrate the flexibility of the formation mechanism across a broad mass spectrum, which may bring the predicted abundance into better agreement with observational constraints.[91,92]

4. Concluding Remarks. PBHs have become an important subject in modern astronomy, cosmology, and fundamental physics, offering a compelling candidate for elucidating the origin and nature of DM. The production of PBHs through well-established and accepted physical mechanisms is highly worthy of in-depth investigations. This work highlights the role of turbulences in the very early universe as a natural state of extremely relativistic fluids subjected to violent disturbances from phase transitions, sustaining intense and persistent fluctuations in energy or mass density. Such turbulent behavior provides a natural mechanism for PBH formation in the primordial universe. Based on previous studies of the electroweak phase transition, we analyze the abundance and mass range of PBHs produced by the MHD turbulence it induces. Remarkably, we find that the mass range of the PBHs falls precisely within the most viable asteroid mass window provided by current joint observations. To form a dominant fraction of asteroid mass PBH DM, an independent but natural constraint $\delta_{\rm tur} = 10^{-4}$–$10^{-2}$ on the energy density proportion of the MHD turbulence is derived. This new constraint on the energy proportion of MHD turbulence closely matches that from previous studies. Such findings suggest that turbulence in the early universe, particularly MHD turbulence induced by the electroweak phase transition, could play a critical role in generating PBHs as a dominant part of DM.

However, our analysis is primarily based on qualitative analysis and order-of-magnitude estimates; future studies will focus on refining the formation mechanisms and dynamical evolution of PBHs to further solidify this compelling scenario. Turbulence in the primordial plasma

may also arise from different nonlinear processes in the early universe, such as those during reheating [93,94] and the quantum chromodynamics (QCD) phase transition. [95] Reheating can drive turbulent thermalization of classical wave fields, initiating relativistic hydrodynamic cascades. During the first-order QCD phase transition, bubble collisions and plasma shocks may generate highly supersonic flows, resulting in high Mach number turbulence. Conversely, PBHs themselves may act as seeds for primordial magnetic fields through mechanisms such as accretion-driven plasma instabilities or anisotropic emission processes. [48,96] Together, these seemingly interrelated processes highlight the early universe as a rich environment for nonlinear hydrodynamical and magnetohydrodynamical phenomena that are closely tied to PBH formation and evolution.

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References

[1] Sahni V 2004 *The Physics of the Early Universe* (Springer Berlin, Heidelberg) p. 141
[2] Bertone G and Hooper D 2018 *Rev. Mod. Phys.* **90** 045002
[3] Efstathiou G, Sutherland W J, and Maddox S 1990 *Nature* **348** 705
[4] Clowe D, Bradač M, Gonzalez A H, Markevitch M, Randall S W, Jones C, and Zaritsky D 2006 *ApJ* **648** L109
[5] Khlopov M Y 2010 *Res. Astron. Astrophys.* **10** 495
[6] Alves J, Bertout C, Alves M I R *et al.* (Planck Collaboration) 2014 *A&A* **571** A1
[7] Zel'Dovich Y B 1967 *Sov. Phys. Uspekhi* **9** 602
[8] Hawking S 1971 *MNRAS* **152** 75
[9] Carr B J and Hawking S W 1974 *MNRAS* **168** 399
[10] Carr B, Clesse S, Garcia-Bellido J, Hawkins M, and Kühnel F 2024 *Phys. Rep.* **1054** 1
[11] Escrivà A, Kühnel F, and Tada Y 2024 *Black Holes in the Era of Gravitational-Wave Astronomy* p. 261
[12] Bird S, Cholis I, Muñoz J B, Ali-Haïmoud Y, Kamionkowski M, Kovetz E D, Raccanelli A, and Riess A G 2016 *Phys. Rev. Lett.* **116** 201301
[13] Sasaki M, Suyama T, Tanaka T, and Yokoyama S 2016 *Phys. Rev. Lett.* **117** 061101
[14] Clesse S and García-Bellido J 2017 *Phys. Dark Universe* **15** 142
[15] Belotsky K M, Dokuchaev V I, Eroshenko Y N, Esipova E A, Khlopov M Y, Khromykh L A, Kirillov A A, Nikulin V V, Rubin S G, and Svadkovsky I V 2019 *Eur. Phys. J. C* **79** 246
[16] Dolgov A D 2023 arXiv:2310.00671 [astro-ph.CO]
[17] Alcock C, Allsman R, Alves D *et al.* 1997 *ApJ* **486** 697
[18] Carr B, Kühnel F, and Sandstad M 2016 *Phys. Rev. D* **94** 083504
[19] Lehoucq R, Casse M, Casandjian J M, and Grenier I 2009 *A&A* **502** 37
[20] Ade P A, Aghanim N, Arnaud M *et al.* (Planck Collaboration) 2016 *A&A* **594** A13
[21] Green A M 2004 *Nucl. Phys. B* **1003** 116494
[22] Cai Y F, Tong X, Wang D G, and Yan S F 2018 *Phys. Rev. Lett.* **121** 081306
[23] Khlopov M Y, Malomed B, and Zeldovich Y B 1985 *MNRAS* **215** 575
[24] Saini A and Stojkovic D 2018 *JCAP* **2018** 071
[25] Hawking S W 1989 *Phys. Lett. B* **231** 237
[26] Polnarev A and Zembowicz R 1991 *Phys. Rev. D* **43** 1106
[27] Barrow J D and Carr B J 1996 *Phys. Rev. D* **54** 3920
[28] Kawai S and Kim J 2021 *Phys. Rev. D* **104** 083545
[29] Hawking S W, Moss I G, and Stewart J M 1982 *Phys. Rev. D* **26** 2681
[30] Liu J, Bian L, Cai R G, Guo Z K, and Wang S J 2022 *Phys. Rev. D* **105** L021303
[31] Jung T H and Okui T 2024 *Phys. Rev. D* **110** 115014
[32] Pope S B 2001 *Meas. Sci. Technol.* **12** 2020
[33] Giovannini M 2012 *Phys. Lett. B* **711** 327
[34] Caprini C, Durrer R, and Servant G 2009 *JCAP* **2009** 024
[35] Arnold P, Moore G D, and Yaffe L G 2000 *JHEP* **2000** 001
[36] Neronov A, Roper Pol A, Caprini C, and Semikoz D 2021 *Phys. Rev. D* **103** L041302
[37] Galtier S and Nazarenko S V 2017 *Phys. Rev. Lett.* **119** 221101
[38] Peter N, Martin S, and Günter S 2018 *Class. Quantum Grav.* **35** 144001
[39] Subramanian K 2016 *Rep. Prog. Phys.* **79** 076901
[40] Kaplan S A and Pikelner S B 1970 *The interstellar medium* (Harvard University Press)
[41] Kowal G, Lazarian A, and Beresnyak A 2007 *ApJ* **658** 423
[42] Armstrong J, Rickett B, and Spangler S 1995 *ApJ* **443** 209
[43] Falgarone E, Hily-Blant P, Pety J, and Pineau Des Forêts G 2005 *IAIP Conf. Proc.* bf 784 299
[44] McKee C F and Ostriker J P 1977 *ApJ* **218** 148
[45] McKee C F and Tan J C 2002 *Nature* **416** 59
[46] Mac Low M M and Klessen R S 2004 *Rev. Mod. Phys.* **76** 125
[47] Hindmarsh M, Lüben M, Lumma J, and Pauly M 2021 *SciPost Phys. Lect. Notes* 24
[48] Papanikolaou T and Gourgouliatos K N 2023 *Phys. Rev. D* **107** 103532
[49] Taylor A, Vovk I, and Neronov A 2011 *A&A* **529** A144
[50] Vachaspati T 1991 *Phys. Lett. B* **265** 258
[51] Baym G, Bödeker D, and McLerran L 1996 *Phys. Rev. D* **53** 662
[52] Kamionkowski M, Kosowsky A, and Turner M S 1994 *Phys. Rev. D* **49** 2837
[53] Roper Pol A, Mandal S, Brandenburg A, Kahniashvili T, and Kosowsky A 2020 *Phys. Rev. D* **102** 083512
[54] Brandenburg A, Enqvist K, and Olesen P 1996 *Phys. Rev. D* **54** 1291
[55] Pen U L and Turok N 2016 *Phys. Rev. Lett.* **117** 131301
[56] Coleman S 1977 *Phys. Rev. D* **15** 2929
[57] Linde A D 1981 *Phys. Lett. B* **100** 37
[58] Kosowsky A, Mack A, and Kahniashvili T 2002 *Phys. Rev. D* **66** 024030
[59] Caprini C and Durrer R 2006 *Phys. Rev. D* **74** 063521
[60] Gogoberidze G, Kahniashvili T, and Kosowsky A 2007 *Phys. Rev. D* **76** 083002
[61] Hindmarsh M and Hijazi M 2019 *JCAP* **2019** 062
[62] Kajantie K and Kurki-Suonio H 1986 *Phys. Rev. D* **34** 1719
[63] Espinosa J R, Konstandin T, No J M, and Servant G 2010 *JCAP* **2010** 028
[64] Giese F, Konstandin T, and van de Vis J 2020 *JCAP* **2020** 057
[65] Kurki-Suonio H and Laine M 1995 *Phys. Rev. D* **51** 5431
[66] Biskamp D 2003 *Magnetohydrodynamic turbulence* (Cambridge University Press)
[67] Montgomery D, Brown M R, and Matthaeus W 1987 *J. Geophys. Res. Space Phys.* **92** 282
[68] Passot T and Vázquez-Semadeni E 1998 *Phys. Rev. E* **58** 4501
[69] Lemaster M N and Stone J M 2008 *ApJ* **682** L97
[70] Sahraoui F, Hadid L, and Huang S 2020 *Rev. Mod. Plasma Phys.* **4** 4

[71] Price D J, Federrath C, and Brunt C M 2010 *ApJL* **727** L21
[72] Federrath C, Klessen R S, and Schmidt W 2008 *ApJ* **688** L79
[73] Federrath C, Glover S C, Klessen R S, and Schmidt W 2008 *Phys. Scr.* **2008** 014025
[74] Niemeyer J C and Jedamzik K 1998 *Phys. Rev. Lett.* **80** 5481
[75] Shibata M and Sasaki M 1999 *Phys. Rev. D* **60** 084002
[76] Musco I, Miller J C, and Rezzolla L 2005 *Class. Quantum Grav.* **22** 1405
[77] Polnarev A G and Musco I 2007 *Class. Quantum Grav.* **24** 1405
[78] Musco I, Miller J C, and Polnarev A G 2009 *Class. Quantum Grav.* **26** 235001
[79] Nakama T, Harada T, Polnarev A, and Yokoyama J 2014 *JCAP* **2014** 037
[80] Khlopov M Y, Konoplich R, Rubin S, and Sakharov A S 1999 arXiv:hep-ph/9912422
[81] Lewicki M, Toczek P, and Vaskonen V 2023 *JHEP* **2023** 92
[82] Baker M J, Breitbach M, Kopp J, and Mittnacht L 2021 arXiv:2105.07481 [astro-ph.CO]
[83] Carr B J 1975 *ApJ* **201** 1
[84] Sasaki M, Suyama T, Tanaka T, and Yokoyama S 2018 *Class. Quantum Grav.* **35** 063001
[85] Nadezhin D, Novikov I, and Polnarev A 1978 *Astron. Zh.* **55** 216
[86] Bicknell G and Henriksen R 1979 *ApJ* **232** 670
[87] Molina F, Glover S C, Federrath C, and Klessen R S 2012 *MNRAS* **423** 2680
[88] Cai R G and Wang S J 2018 *Sci. China Phys. Mech. Astron.* **61** 080411
[89] Carr B, Kohri K, Sendouda Y, and Yokoyama J 2010 *Phys. Rev. D* **81** 104019
[90] Press W H and Schechter P 1974 *ApJ* **187** 425
[91] Carr B, Kohri K, Sendouda Y, and Yokoyama J 2021 *Rep. Prog. Phys.* **84** 116902
[92] Niikura H, Takada M, Yasuda N *et al.* 2019 *Nat. Astron.* **3** 524
[93] Micha R and Tkachev I I 2003 *Phys. Rev. Lett.* **90** 121301
[94] Micha R and Tkachev I I 2004 *Phys. Rev. D* **70** 043538
[95] Khachatryan V 2008 *Nucl. Phys. A* **810** 109
[96] Safarzadeh M 2018 *MNRAS* **479** 315