Signatures of a High Temperature QCD Transition in the Early Universe

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Beyond-Standard-Model extensions of QCD could result in quark and gluon confinement occurring well above at temperature around the GeV scale. These models can also alter the order of the QCD phase transition. Therefore, the enhanced production of primordial black holes (PBHs) that can accompany the change in relativistic degrees of freedom at the QCD transition could favor the production of PBHs with mass scales smaller than the Standard Model QCD horizon scale. Consequently, and unlike PBHs associated with a standard GeV-scale QCD transition, such PBHs can account for all the dark matter abundance in the unconstrained asteroid-mass window. This links beyond-Standard-Model modifications of QCD physics over a broad range of unexplored temperature regimes (around $10-10^3$ TeV) with microlensing surveys searching for PBHs. Additionally, we discuss implications of these models for gravitational wave experiments. We show that a first-order QCD phase transition at around 7 TeV is consistent with the Subaru Hyper-Suprime Cam candidate event, while a transition of around 70 GeV is consistent with OGLE candidate events and could also account for the claimed NANOGrav gravitational wave signal.

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With tremendous predictive success and extensive experimental testing, the Standard Model (SM) is a central pillar of modern science. The interaction of quarks and gluons as described by SM quantum chromodynamics (QCD) predicts that those particles will be in a quark-gluon plasma at early Universe temperatures sufficiently above the QCD energy scale $\Lambda_{\rm QCD} \sim 160$ MeV. As the universe expands and the temperature drops below $\Lambda_{\rm QCD}$, chiral symmetry will be broken, and the quarks and gluons will be confined in color singlets (e.g., mesons, nucleons, etc.). This is the QCD transition. Lattice calculations that employ the high entropy believed to characterize the early universe show that the SM QCD transition is simply a cross-over and not a first-order phase transition [1]. However, despite significant progress, lattice methods remain limited and cover only part of the parameter space of the QCD phase diagram.

Astrophysical environments can offer probes of QCD that are complementary to laboratory experiments like relativistic heavy ion collisions. For example, neutron star mergers provide tests of strong interaction physics at extreme densities [2] and low entropy per baryon. The early universe with its high temperatures and low net baryon density (high entropy-per-baryon $s \sim 10^{10}$ Boltzmann's constant per baryon) provides a potentially unique probe of QCD. This regime of temperature and entropy is unexplored in laboratory experiments. Current observations only constrain the physics of the early universe that affects neutrino decoupling and primordial nucleosynthesis. These occur at a temperature scale of $T \lesssim 5$ MeV [3–5]. The cosmological QCD phase transition has been shown to affect primordial nucleosynthesis [6], but these effects are most important when the transition is first order and the distribution of entropy is inhomogeneous. However, new physics beyond the SM could significantly alter the history of the early Universe.

A QCD phase transition in the early Universe occurring in the SM at $T \sim 160$ MeV significantly affects the equation-of-state (EOS) governing behavior of the cosmological fluid. The dimensionless parameter $w = p/\rho$, where p is the pressure and ρ is the density, is significantly decreased compared to radiation-dominated environments with $w = 1/3$. Since the pressure balancing gravity becomes weaker at QCD transitions, inhomogeneities associated with cosmological perturbations reentering the horizon collapse with an enhanced rate and can naturally lead to primordial black holes with masses peaked in the range associated with these scales [7–14]. Interestingly, since the horizon mass at the transition temperature is $\mathcal{O}(1)M_\odot$, the resulting solar-mass PBHs have been associated with some of the recent gravitational wave (GW) events of LIGO-Virgo-KAGRA (LVK) (e.g., Ref. [15]). Stellar-mass PBHs formed prior to galaxies and stars (e.g., Refs. [16–30]) have been directly linked with LVK GW events more generally (e.g., Refs. [31–41]). In the mass range associated with the SM QCD transition, PBHs are already constrained from a variety of observations and cannot constitute all of the dark matter (DM) abundance (e.g., Refs. [27–29]).

In this Letter, we show that by utilizing PBHs as proxies, a variety of telescope surveys can probe the cosmological QCD transition over unexplored regimes covering orders of magnitude in temperature higher than that of the SM $\Lambda_{\rm QCD} \sim 160$ MeV. Unlike the SM, such a QCD transition could be first order, which would further enhance PBH production due to reduced sound speed and pressure of the cosmological fluid. First-order QCD transitions are generally expected from effective field theory if the number of light quarks $N_f \geq 3$ [42]. For example, an ultralight scalar field and additional massless quarks at the QCD transition allow for a first-order transition at lower temperatures $\Lambda_{\rm QCD}$, below around 100 MeV, resulting in PBHs in the LVK mass window [43]. We note that while the PBH formation we discuss can also be associated with hidden dark sector gauge dynamics (e.g., Ref. [44]), it is particularly intriguing to explore formation within the context of a high temperature QCD transition because of a significant change in relativistic degrees of freedom in a QCD transition. Additionally, there remains a large unexplored parameter space of one of the most fundamental forces we know.

A high temperature first-order QCD transition can readily appear in classes of models where strong coupling becomes a dynamical quantity [45–47]. Here, QCD confined at a high temperature scale can dynamically transition at lower temperatures to SM QCD with standard parameters. A minimal realization of this is based on a SM gauge singlet scalar S coupling to the gluon field with strength $G^{\mu\nu}$. This could appear in scenarios with radion or dilaton fields, in models based on extra dimensions (e.g., Ref. [48]), or with an extra scalar coupled to gluons via vectorlike fields charged under $SU(3)$. Here, we consider the SM gluon kinetic term

$$\mathcal{L} \supset -\frac{1}{4}\left(\frac{1}{g_{s0}^2} + \frac{S}{M}\right) G^a_{\mu\nu} G_a^{\mu\nu} + \ldots, \tag{1}$$

where g_{s0} is the $SU(3)$ gauge coupling when $\langle S \rangle = 0$, and M is the scale characterizing nonrenormalizable scalar-gluon interactions.

In this scenario, when S acquires a vacuum expectation value (VEV) $\langle S \rangle \neq 0$, the effective modified strong coupling in Eq. (1) can be realized. Following renormalization running of the coupling g_{s0} at one loop and considering that QCD confinement occurs when the strong coupling constant is $\alpha_s^{-1} \sim 0$, the confinement scale Λ is given by [45]

$$\Lambda(\langle S \rangle) = \Lambda_0 \mathrm{Exp}\left[\frac{24\pi^2}{2N_f - 33} \frac{\langle S \rangle}{M}\right]. \tag{2}$$

Taking $N_f = 6$ massless quarks and the energy scale $\Lambda_0 \sim$ GeV, which determines g_{s0} in the ultraviolet limit, $\langle S \rangle / M = -0.81$ gives a resulting QCD confinement scale of $\Lambda \sim 10$ TeV. A full model potential $V(S)$—which, in generality, could include, at zero temperature, distinct S^n terms (with $n = 1, 2, 3, 4$)—could readily yield the desired $\langle S \rangle$ for a choice of couplings. Further, we assume that the possible mixing terms between S and the Higgs are small, consistent with Large Hadron Collider results [49].

The implication of a QCD phase transition at extreme temperatures, above the electroweak scale, is largely unexplored. To gain insight, we first model it using effective Polyakov-loop enhanced Nambu–Jona-Lasinio (PNJL) theory [50] following Refs. [51,52]. This treatment can model the SM QCD transition [51]. We reproduce the PNJL results for SM QCD as confirmed by lattice calculations. We then calculate the EOS behavior when the critical temperature T_c associated with the phase transition is set to 1 TeV. This scale is beyond that of electroweak phase transitions, but other phenomenological parameters that describe the PNJL model are set to those of SM QCD. We further consider several possible distinct phenomenological behaviors of the EOS in this model. We find that the resulting EOS behavior can be similar to that of the SM QCD transition, albeit centered around a higher critical temperature.

We now discuss PBH production associated with a high temperature first-order QCD transition, focusing on the regime above the electroweak scale. Consider that inflation generically results in a broad, flat, primordial curvature (scalar) power spectrum that could arise in a broad class of models [53–56],

$$\mathcal{P}_\zeta(k) = A_s \Theta(k_{\max} - k)\Theta(k - k_{\min}), \tag{3}$$

where $k_{\max}$ is the cutoff scale, with $k_{\max} \gg k_{\min}$; Θ is the Heaviside step function; and A_s is the amplitude. From $\mathcal{P}_\zeta(k)$, we can obtain the power spectrum of density perturbations $\mathcal{P}_\delta(k)$.

When a sufficiently large density fluctuation enters the Hubble horizon, PBHs can efficiently form from an overdense region. The total mass–energy in the causal horizon is (e.g., Refs. [27,28])

$$M_H \simeq 12 M_\odot \left(\frac{k_*}{10^6\ \mathrm{Mpc}^{-1}}\right)^{-2}\left(\frac{g_*}{106.75}\right)^{-1/6}$$
$$\simeq 4.8\times 10^{-10} M_\odot \left(\frac{T}{10\ \mathrm{TeV}}\right)^{-2}\left(\frac{g_*}{106.75}\right)^{-1/2}, \qquad (4)$$

where k_* is the comoving wave number corresponding to the horizon length scale at the epoch of black hole formation in the radiation-dominated era at temperature T, and g_* accounts for the relativistic degrees of freedom in the primordial plasma. In the second line of Eq. (4), we have also shown M_H in terms of energy contained within the horizon during the radiation-dominated era. This indicates that typical masses of PBHs associated with high QCD transition temperatures $T \gtrsim$ TeV could be well below the solar mass range associated with PBH formation at the SM QCD transition.

The fraction of energy density collapsing to PBHs at formation can be found using Press-Schechter formalism [27],

$$\beta = 2\int_{\delta_c}^{\infty} d\delta \frac{M_{\mathrm{PBH}}}{M_H} P(\delta,\sigma), \qquad (5)$$

where δ_c is the critical density contrast for collapse. The critical density δ_c depends on the EOS parameter w [57]. Here, $P(\delta,\sigma)$ is the probability distribution of density fluctuations entering the horizon, and it is assumed to be Gaussian, $P(\delta,\sigma) = (1/\sigma)\sqrt{2/\pi}\exp[-\delta^2/2\sigma^2]$, with variance

$$\sigma^2 = \int_0^\infty \mathcal{P}_\delta(k) W(kR)^2 \mathcal{T}^2(k,\eta)\frac{dk}{k}, \qquad (6)$$

where $W(kR) = \exp(-(kR)^2/4)$ is the Fourier transform of the window smoothing function over the horizon scale [58], with $R \sim 1/k_*$ being the length scale of mode k_* when it enters the horizon. The transfer function is a function of the conformal time η,

$$\mathcal{T}(k,\eta) = 3\frac{\sin(k\eta/\sqrt{3}) - (k\eta/\sqrt{3})\cos(k\eta/\sqrt{3})}{(k\eta/\sqrt{3})^3}. \qquad (7)$$

We can employ Eq. (5) for the critical collapse method. First, we solve for the density contrast δ' at a given PBH mass and temperature,

$$\delta'(T) = \delta_c(T) + \left(\frac{M_{\mathrm{PBH}}}{K M_H(T)}\right)^{1/\gamma(T)}, \qquad (8)$$

where γ is the critical exponent that determines the scaling behavior of PBH mass and depends on $w(T)$, for which we follow the simulation results of Ref. [57]. We can invert this to find $T(\delta')$ at a given PBH mass. Since PBH with mass M_{PBH} can be produced at multiple temperatures, we integrate over T and impose a Dirac delta function $\delta[T - T(\delta')]$,

$$\beta(M) = 2\int_0^{T_{\max}} dT \int_{\delta_c(T)}^{\infty} d\delta \frac{M}{M_H(T)} P(\delta)\delta[T - T(\delta')]$$
$$= 4\int_0^{T_{\max}} \frac{dT}{T}\frac{M}{M_H(T)} P[\delta'(T)][\delta'(T) - \delta_c(T)]. \qquad (9)$$

Here, $T_{\max}$ is the temperature at which $M_{\mathrm{PBH}} = M_H(T)$. In the second line, we have swapped the order of integration and changed the Dirac delta variable from T to δ. From this modified β function, the PBH fraction of DM is calculated as

$$f_{\mathrm{PBH}} = \int \left(\frac{M}{M_{\mathrm{eq}}}\right)^{-1/2} \frac{\beta(M)}{\Omega_{\mathrm{DM}}}\frac{dM}{M}, \qquad (10)$$

where $M_{\mathrm{eq}} = 3\times 10^{17} M_\odot$ is the horizon mass at matter-radiation equality and Ω_{DM} is the dark matter contribution to closure.

In Fig. 1, we display results for our models A–C, with descriptions of a high temperature QCD transition scenario (see Table I for details). The PBH mass spectra peak at the mass corresponding to the horizon mass $M_H(k)$ of Eq. (4) when the shortest wavelength, around $1/k_{\max}$, reenters the horizon and has a tail of about $M^{-1/2}$, characteristic of the broad power spectrum of Eq. (3) [59]. On the other hand, a high temperature QCD transition results in a significantly pronounced peak at $M_{\mathrm{PBH,peak}}$ in the PBH mass distribution associated with the horizon mass $M_H(T)$ of Eq. (4) around the transition temperature T_o (see Table I for model parameters). In the Supplemental Material [60], we discuss how the PBH DM spectrum would look for a PNJL model, as well as for other phenomenological approaches we consider. Intriguingly, we find that a QCD transition at temperatures $T \sim 200$ TeV could yield PBHs with masses that account for all of the DM, given current constraints. In contrast, PBHs formed in a SM QCD scenario could constitute a subdominant DM component. PBHs in this mass range are known to result in a variety of intriguing observational signatures when they interact with neutron stars (e.g., Refs. [38–40,63–65]). We establish that optical telescopes conducting microlensing surveys, which have been shown to be excellent probes of PBHs (e.g., Refs. [26,66–68]), could explore untested strong-force regimes spanning decades in QCD transition temperatures above the electroweak scale.

The HSC microlensing survey of the Andromeda galaxy (M31) reported a candidate event consistent with a PBH at $f_{\mathrm{PBH}}(M \sim 10^{-9} M_\odot) \sim 10^{-2}$ [68]. We note that this detected HSC event is consistent with PBHs produced at a first-order QCD transition around $T \sim 7$ TeV, as exemplified by model B in Table I and Fig. 1. Intriguingly, the detected HSC event was obtained with only 7 hours of data. For reference, we also display model C in Fig. 1, where the QCD transition

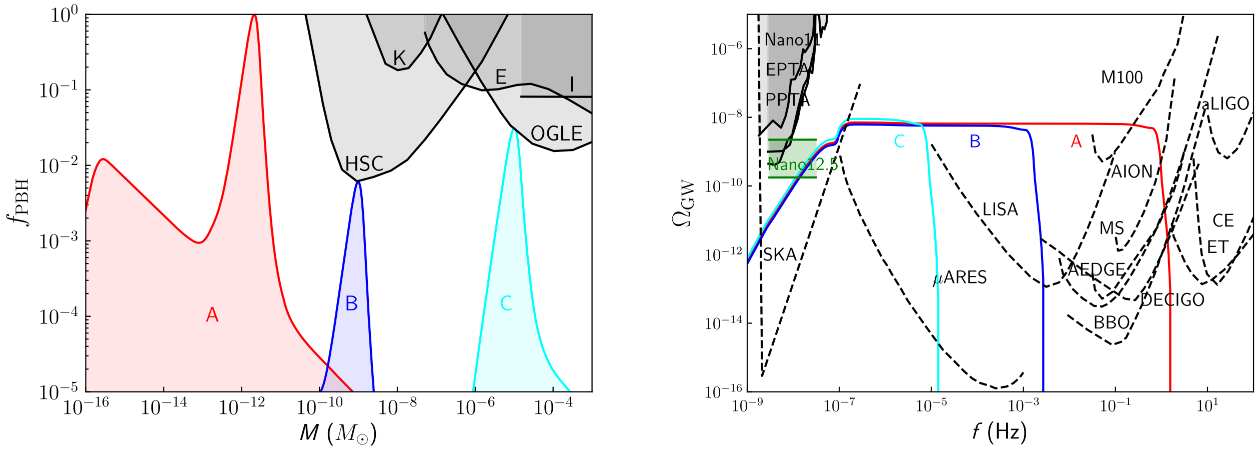

FIG. 1. Left panel: PBH fractional contribution to DM, $f_{\rm PBH}$, for PBHs of mass M in solar masses, in models of a first-order QCD transition at high temperature scales. Shown are existing PBH parameter constraints from Subaru Hyper-Suprime Cam (HSC) [68,69], MACHO/EROS (E) [70,71], OGLE [72], Icarus (I) [73], and Kepler data (K) [74]. Models A, B, and C correspond to those in Table I. Right panel: induced GW spectrum as a function of GW frequency f, along with current constraints of EPTA [75], PPTA [76], and NANOGrav 11-yr [77,78], as well as projections for SKA [79], LISA [80], DECIGO/BBO [81], Cosmic Explorer (CE) [82], Einstein Telescope (ET) [83,84], μ-Ares [85], Magis-100 (M100)/Magis-Space (MS) [86], AEDGE [87], AION [88], and aLIGO [89].

occurs below the electroweak transition. While a detailed discussion of such a scenario is beyond the scope of this Letter, it exemplifies that a QCD transition around $T \sim 70$ GeV is consistent with the six Earth-mass candidate events detected in the 5-year survey of the Galactic bulge by the Optical Gravitational Lensing Experiment (OGLE) [72]. Future longer surveys could produce stronger constraints on PBH masses and contributions to closure, and our work shows that these could have implications for beyond-the-SM extensions of QCD. In the Supplemental Material [60], we demonstrate that the resulting abundance of PBHs $f_{\rm PBH}$ sensitively depends on the amplitude A_s of the primordial power spectrum from Eq. (3). Since induced GWs, as is clear in Eq. (11), depend on around A_s^2, these signatures are also sensitive to variations in A_s.

Curvature perturbations resulting in PBHs could also lead to generation of induced gravitational waves at second order [90–94]. These could give a stochastic GW background (SGWB) at present, with a closure contribution

$$\Omega_{\rm GW} = \frac{c_g \Omega_{r,0}}{972} \int_0^\infty dx \int_{|1-x|}^{1+x} dy \frac{x^2}{y^2} \left[1 - \frac{(1+x^2-y^2)^2}{4x^2}\right]^2 \times \mathcal{P}_\zeta(kx)\mathcal{P}_\zeta(ky)\mathcal{I}^2(x,y), \tag{11}$$

where $k = 2\pi f$ and f is the GW frequency, c_g describes the change in the number of radiation degrees of freedom over the evolution of the universe from the GW generation epoch to the present, $\Omega_{r,0}$ is the radiation contribution to closure today, and $\mathcal{I}(x,y)$ is the kernel function employed in the analytic solution obtained by Ref. [93]. In Fig. 1, we display our resulting GW signatures and relevant observational limits. We note that GWs from models A–C for PBHs produced from high temperature QCD phase transitions can account for the recently claimed signal from the 12.5-year analysis of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) Collaboration [95]. These results will be tested with upcoming observations of LISA [80] and the proposed μ-Ares experiment [85]. References [67,96] give a different context for the connection of the perturbation spectrum in Eq. (3) with NANOGRav signatures. Since PBH formation is exponentially sensitive to a small variation of the EOS, while the induced GWs are only linearly sensitive to it, we do not expect that effects from changes in the EOS parameter w stemming from the QCD phase transition will significantly affect our results (see also Ref. [97]).

In addition to induced GW signals, first-order phase transitions are expected to also generate GW signatures

TABLE I. Input parameters for QCD transition models A and B. Parameters include the PNJL transition critical temperature T_0, momentum cutoff $\Lambda_{\rm p}$, and number of massless quarks, N_f, as well as the curvature power spectrum amplitude A_s, and cutoff scales $k_{\rm max}$ and $k_{\rm min}$, which describe the range of masses of the resulting PBH distribution associated with the corresponding horizon mass.

Model	T_0	$\Lambda_{\rm p}$	N_f	A_s	$k_{\rm max}$	$k_{\rm min}$	$f_{\rm PBH}$	$M_{\rm PBH,peak}$
A	150 TeV	450 TeV	6	0.0153	5.6×10^{14} Mpc^{-1}	5×10^7 Mpc^{-1}	1	$10^{-12}M_\odot$
B	7 TeV	21 TeV	6	0.0143	10^{12} Mpc^{-1}	5×10^7 Mpc^{-1}	$5 * 10^{-3}$	$10^{-9}M_\odot$
C	70 GeV	210 GeV	5	0.0173	5×10^9 Mpc^{-1}	5×10^7 Mpc^{-1}	$2 * 10^{-2}$	$10^{-5}M_\odot$

(e.g., Ref. [98]). GWs of comoving frequency f could result from a first-order QCD transition at corresponding horizon mass $M_H \simeq 5.7 \times 10^{-10} M_\odot (10^{-4}\ \ \mathrm{Hz}/f)^2$. Hence, formation of asteroid-mass PBHs near the microlensing and open DM window could be associated with observational signatures in upcoming GW observatories such as LISA [80], μ-Ares [85], and DECIGO [99]. This allows for an additional possibility of probing the considerations discussed here. Since production of such GWs strongly depends on complicated details of transition dynamics, we leave the analysis of such GW production coincident with PBH formation associated with high temperature QCD transition for future work.

In addition to the PBHs and GWs discussed above, further possible signatures could point to a high temperature QCD transition. These include potential high energy collider signals from a scalar S coupled to gluons and deviations from the standard Higgs couplings if that field mixes with the Higgs boson. Dynamics that restore the QCD transition to a conventional one occurring at low scales could manifest in, e.g., heavy ion collisions. A detailed discussion of these possibilities is beyond the scope of this Letter.

The novel connection between beyond-SM QCD extensions, PBHs, and GWs is intriguing. It represents a promising connection between exciting particle physics possibilities and upcoming observations.

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