Could MACHOS be Primordial Black Holes formed during the QCD Epoch?

Karsten Jedamzik [a,1]

[a] *Max-Planck-Institut für Astrophysik, 85740 Garching bei München, Germany*

Observations by the MACHO collaboration indicate that a significant fraction of the galactic halo dark matter may be in form of compact objects with masses $M \sim 0.5 M_\odot$. Identification of these objects as red or white dwarfs is problematic due to stringent observational upper limits on such dwarf populations. Primordial black hole (PBH) formation from preexisting density fluctuations is facilitated during the cosmic QCD transition due to a significant decrease in pressure forces. For generic initial density perturbation spectra this implies that essentially all PBHs may form with masses close to the QCD-horizon scale, $M_h^{\rm QCD} \sim 1 M_\odot$. It is possible that such QCD PBHs contribute significantly to the closure density today. I discuss the status of theoretical predictions for the properties of QCD PBH dark matter. Observational signatures of and constraints on a cosmic solar mass PBH population are also discussed.

1 PBH Formation during the QCD Epoch

It is long known that only moderate deviations from homogeneity in the early universe may lead to abundant production of PBH's from radiation [1]. For a radiation equation of state (i.e. $p = \rho/3$, where p is pressure and ρ is energy density) there is approximate equality between the cosmic Jeans-, M_J, and horizon-, M_h, masses. The ultimate fate of an initially super-horizon density fluctuation, upon horizon crossing, is therefore determined by a competition between dispersing pressure forces and the fluctuation's self-gravity. For fluctuation overdensities exceeding a critical threshold at horizon crossing $(\delta\rho/\rho)_{hc} \geq \delta_c^{\rm RD} \approx 0.7$ [2] formation of a PBH with mass $M_{pbh} \sim M_h$ results.

[1] Corresponding author. E-mail: jedamzik@mpa-garching.mpg.de

The universe must have passed through a color-confinement quantum chromodynamics (QCD) transition at cosmic temperature $T \approx 100\mathrm{MeV}$. Recent lattice gauge simulations indicate that the transition between a high-temperature quark-gluon phase and a low-temperature hadron phase may be of first order [3], even though such simulations are still plagued by limited resolution and problems to account for finite strange quark mass. A first order phase transition is characterized by coexistence of high- and low-temperature phase at coexistence temperature T_c. Both phases may exist in pressure equilibrium, $p_c^{qg} = p_c^h$ but with different and constant (at T_c) energy densities, $\rho_c^{qg} - \rho_c^h = L$, where L is the latent heat. During phase coexistence adiabatic expansion of the universe causes a continuous growth of the volume fraction occupied by hadron phase $(1-f_{qg})$, on the expense of quark-gluon phase, such that through the release of latent heat the universe is kept at T_c. The transition is completed when all space is occupied by hadron phase.

Consider a volume element of mixed quark-gluon- and hadron phase- during phase coexistence. Provided a typical length scale of the volume element is much larger than the mean separation between quark-gluon and hadron phase (i.e. the mean hadron- or quark-gluon- bubble separation, l_s) one may regard the volume element as approximately homogeneous. The average energy density of the volume element is $\langle\rho\rangle = \rho_c^h + f_{qg}L$ and continuously varies with the change of f_{qg}, whereas pressure remains constant, $p = p_c^h$. Upon adiabatic compression of mixed quark-gluon/hadron phase there is therefore no pressure response, $v_s^{eff} = \sqrt{(\partial p/\partial\langle\rho\rangle)_s} = 0$ [4]. Of course, the pressure response may only vanish if thermodynamic equilibrium is maintained. For rapid compression time scales or small compression amplitudes this may not be the case, whereas it is anticipated that approximate thermodynamic equilibrium applies over a Hubble time and order unity compression factors. During phase coexistence the universe is effectively unstable to gravitational collapse for all scales exceeding l_s. Note that a vanishing of v_s^{eff}, which was independently discovered by [5], may also have interesting non-gravitational effects on density perturbations.

These considerations have led me [4] to propose PBHs formed during the QCD epoch from pre-existing initially superhorizon density fluctuations, such as leftover from an early inflationary period of the universe, as a candidate for non-baryonic dark matter. Fluctuations crossing into the horizon during the QCD epoch experience a significant reduction of pressure forces over that regime of the fluctuation which exists in mixed phase. Since the PBH formation process is a competition between self-gravity and pressure forces, and $v_s = 1/\sqrt{3}$ is constant during most other radiation dominated epochs, the threshold for PBH formation should be smaller during the QCD epoch than during other early eras, $\delta_c^{\mathrm{QCD}} < \delta_c^{\mathrm{RD}}$. Only a slight favor for PBH formation during the QCD epoch may effectively lead to the production of PBH on only approximately the QCD horizon mass scale $M_h^{\mathrm{QCD}} \approx 2M_\odot(T_c/100\mathrm{MeV})^{-2}$.

This holds true for strongly declining probability distribution functions for the pre-existing fluctuation overdensities. For example, assuming Gaussian statistics, PBH formation is dominated for $\delta\rho/\rho$ in the range δ_c and $\delta_c + \sigma^2/\delta_c$, where σ is the variance of the Gaussian distribution. This range is very small, $\sigma^2/\delta_c \lesssim 10^{-2}$, if PBH mass density is not to exceed the present closure density, $\Omega_{pbh} \lesssim 1$. For $\Omega_{pbh} \approx 1$ PBH formation during the QCD epoch is also a very rare event with only a fraction $\sim 10^{-8}$ of horizon volumes collapsing to black holes.

The possible production of PBH during the QCD epoch is not a completely new suggestion. In fact, in the mid seventies it was believed that a QCD era was characterized by an ever-increasing production of massive hadronic resonances. Such a " soft "(i.e. almost pressure-less) Hagedorn era was argued to be suspect since overproduction of primordial black holes seemed likely [6]. In the eighties it was argued that the long-range color force could lead to the generation of subhorizon density fluctuations which in turn could collapse to planetary sized PBHs [7]. Nevertheless, the simple properties of mixed phase during a cosmic first-order transition and their possible implications for PBH formation on the QCD horizon mass scale have so far been overlooked.

Currently there are two groups attempting to simulate the PBH formation process during a QCD transition with aid of a general-relativistic hydrodynamics code [8,9]. Preliminary results by [9] verify the reduction of PBH formation threshold during the QCD epoch. Assuming a bag equation of state and phase transition parameter, $L/\rho_c^h = 2$, we have found a PBH formation threshold reduction, $\delta_c^{\rm QCD}/\delta_c^{\rm RD} \approx 0.77$, for fluctuations entering the horizon approximately during the middle of the phase transition. Note that a canonical bag model with total statistical weights of $g_{qg} = 51.25$ and $g_h = 17.25$ for quark-gluon- and hadron- phases [10], respectively, predicts even larger $L/\rho_c^h = 2.63$, whereas lattice simulations may favor smaller L [11]. For fluctuations entering the horizon during the QCD epoch one typically finds the evolution of the fluctuation into two different spatial regimes. An inner part of the fluctuation exists in pure guark-gluon phase $\rho > \rho_c^{qg}$ surrounded by an outer part existing in pure hadron-phase $\rho < \rho_c^h$. The enhanced density in the inner part of the fluctuation assists the collapse to a PBH. This is in contrast to PBH formation during simple radiation dominated eras, where the fluctuation's density distribution is continuous. It has also been attempted to derive approximate analytic estimates of the threshold reduction and PBH masses for PBH formation during the QCD epoch [12]. The model predicts that $\delta_c^{\rm QCD}$ is minimized for fluctuations entering the horizon well before the transition resulting into PBH masses considerably smaller than the QCD horizon.

2 Theoretical Predictions for QCD PBH Scenarios

It is valuable to advance the initial suggestion of possible abundant production of PBH during the QCD epoch to a complete and predictive scenario. I outline here to which degree this may be accomplished and briefly describe the theoretical issues in QCD PBH scenarios.

Threshold reduction: The bias for forming PBHs almost exclusively on the QCD scale is dependent on the PBH formation threshold reduction, $\delta_c^{\rm QCD} < \delta_c^{\rm RD}$. Within the context of a bag model equation of state for a first order transition preliminary results of numerical simulations confirm the proposed threshold reduction. For higher order QCD transitions threshold reduction could still occur but would have to be verified by using accurate $\rho(T)$, $p(T)$, and $v_s(T)$ determined from lattice gauge simulations. Due to the duration of the QCD transition, $L/\rho_c^h \sim 1$, threshold reduction will be of order unity. A very accurate determination of $\delta_c^{\rm QCD}$ is only necessary if PBH formation is efficient over a range in $\delta\rho/\rho$ which is also of order unity. This is not the case for Gaussian statistics of the pre-existing density fluctuations but may apply for non-Gaussian statistics.

Mass function: A crucial prediction of a QCD PBH dark matter scenario is the average QCD PBH mass. There is seemingly rough agreement of the QCD horizon mass scale $M_h^{\rm QCD} \approx 2M_\odot(T_c/100{\rm MeV})^{-2}$ and the inferred masses of compact objects in the galactic halo by the MACHO collaboration, $M \sim 0.5M_\odot$. Nevertheless, currently there are large uncertainties in the prediction for average QCD PBH mass, $\langle M_{\rm pbh}^{\rm QCD}\rangle$. Even incorrectly assuming $M_h^{\rm QCD} = \langle M_{\rm pbh}^{\rm QCD}\rangle$, there is a factor eight uncertainty in $M_{\rm pbh}^{\rm QCD}$ depending on if the horizon length is taken as radius or diameter of a spherical horizon volume. The QCD equation of state, order of the transition, and transition temperature are as yet not precisely determined. The transition temperature may fall somewhere in the range $200\,{\rm MeV} \gtrsim T_c \gtrsim 50\,{\rm MeV}$ implying a factor sixteen uncertainty in $M_h^{\rm QCD}$, and probably equal uncertainty in $\langle M_{\rm pbh}^{\rm QCD}\rangle$. Assuming a first order transition, $\langle M_{\rm pbh}^{\rm QCD}\rangle$ may also depend on L and the equation of states above, and below, the transition point. An accurate determination of $\langle M_{\rm pbh}^{\rm QCD}\rangle$ requires detailed and reliable lattice gauge simulation data. Approximate trends may be obtained by using a bag equation of state. A PBH mass function, as well as $\langle M_{\rm pbh}^{\rm QCD}\rangle$, is obtained by convolving the distribution function for density contrast of the pre-existing density perturbations, $\delta\rho/\rho$, with a scaling relation associating final PBH mass with density contrast [13]. The average PBH mass is thus also dependent on the statistics of the density perturbations. Further, it has been shown that resulting PBH masses are dependent on the fluctuation shape [14]. These uncertainties are particularly difficult to remove since they require knowledge about the underlying physics creating density perturbations, presumably occurring at a scale not accessible to particle accelerators.

Contribution to $\Omega_{\mathbf{pbh}}$: The contribution of QCD PBHs to the closure density at the present epoch is dependent on the fraction of space which is overdense by more than $\delta_c^{\rm QCD}$. COBE normalized, exactly scale-invariant ($n = 1$) Gaussian power spectra, imply negligible PBH production. Gaussian blue spectra with $1.37 \leq n \leq 1.42$ predict Ω_{pbh} in QCD PBHs in the range 10^{-5} to 10^3 [12]. Such spectral indices are consistent with cosmic microwave background observations [15]. Nevertheless, blue spectra resulting from inflationary epochs have been shown to generically be non-Gaussian, skew-negative [16]. Density perturbations with an exactly scale-invariant, COBE normalized power spectrum, but with a non-Gaussian, skew-positive distribution tail, may yield $\Omega_{pbh} \sim 1$. One argument against QCD PBH dark matter is the degree of fine-tuning involved for obtaining $\Omega_{pbh} \sim 1$.

Accretion around recombination: It is long known that black holes may efficiently accrete after the epoch of recombination [17]. Whereas accretion does not appreciably change the black hole masses, conversion of accreted baryon rest mass energy into radiation may produce substantial radiation backgrounds. The presently observed X-ray and/or UV backgrounds may be incompatible with a population of PBHs with mass $M_{pbh} > 10^4 M_\odot$ and $\Omega_{pbh} > 0.1$ [17]. A population of $M_{pbh} \sim 1 M_\odot$ PBHs with large Ω_{pbh} is consistent with the observed X-ray and/or UV backgrounds. Accretion of baryons on PBH shortly before the epoch of recombination may produce distortions in the blackbody of the cosmic microwave background radiation. PBHs with $M_{pbh} \sim 1 M_\odot$ would accrete at the Bondi rate, with Thomson drag inefficient. Tidal interactions between the accreting gas and neighboring PBHs would lead to the transfer of angular momentum and the formation of disks around the PBH. Preliminary results of an investigation of PBH accretion before recombination indicate that the resulting blackbody distortions would be below the current FIRAS limit.

PBH formation during other epochs: Efficient PBH formation during the QCD era may, in principle, imply formation of PBHs during other epochs as well. For example, during the e^+e^--annihilation there is a decrease in the speed of sound which may result in a bias to form PBHs on the approximate horizon scale of this era. Further, for power spectra of the underlying density distribution characterized by $n > 1$ QCD PBH formation may be accompanied by PBH formation at earlier times on mass scales $M \ll M_h^{\rm QCD}$. It is important to verify that such PBHs do not violate observational constraints [18].

3 Observational Signatures of QCD PBH Dark Matter

Ultimately, only by observational technique the existence of a population of QCD PBH may be established. It is therefore important to establish the observational signatures of QCD PBH dark matter. Particular emphasis is laid on observations which may be performed in the not-to-distant future.

Galactic halo microlensing searches: The recent results of microlensing searches for compact, galactic halo dark matter by the MACHO collaboration [19] provide some motivation for QCD PBH dark matter. Low event statistics as well as uncertainties about the halo model which is to be adopted result in fairly large ranges for the average MACHO mass, $0.1M_{\odot} \lesssim M \lesssim 1M_{\odot}$, and halo dark matter fraction provided by MACHOs, $f_M \gtrsim 0.2$. The error bars may be reduced by increasing the number of observed microlensing events and observing towards several line-of-sights (e.g. towards the Large and Small Magellanic Clouds). Nevertheless, it will not be possible by only the observational MACHO project to determine an accurate mass function. Only in combination with follow-up observations, such as by a space interferometry sattelite, degeneracy between MACHO lens mass, distance, and projected velocity may be lifted and a mass function may be determined.

Alternative interpretations of the MACHO results: The inferred masses of MACHOs are close to those of stars, stellar remnants, or brown dwarfs. The most straightforward interpretation of the observations by the MACHO collaboration are that baryonic objects have been detected. However, one has to resort to fairly extreme galactic models in order for a characteristic MACHO mass of $M \lesssim 0.1M_{\odot}$ to be consistent with the observations and for brown dwarfs to remain a viable interpretation for the lenses. A significant contribution to the halo dark matter by red dwarfs seems ruled out by observations of the Hubble deep field [20]. Halo white dwarfs with halo dark matter fractions exceeding $f_M \gtrsim 0.1$ seem also in conflict with observations of the Hubble deep field, even though this constraint is dependent on somewhat uncertain white dwarf ages and cooling curves [21]. In addition, it has been argued that the light which would be emitted by the progenitors of abundant halo white dwarf populations has not been observed in deep galaxy surveys [22]. It has been suggested that the lenses responsible for the observed microlensing are not within the halo, but within a warped or thick galactic disk. Such scenarios may possibly be rejected by microlensing observations on more than one line of sight. There are other more, or less, radical interpretations of the results of the MACHO collaboration. It is important, not only for the viability of QCD PBH dark matter, to establish, or rule out, these alternative interpretations.

Quasar microlensing: The optical depth for microlensing of distant quasars by a cosmic component of compact, solar mass objects with $\Omega_c \sim 1$ is remarkably large. In fact, a constraint of $\Omega_c \lesssim 0.2$ for a population of compact objects with masses $M_c \sim 1M_{\odot}$ has been derived from observations of broad line radiation- to continuum radiation- flux ratios of ~ 100 quasars [23]. This limit relies on the assumption that most continuum radiation is emitted from within a compact $\lesssim 0.1$pc region in the center of the quasar, whereas the broad line radiation emerges from a much more extended region around the quasar. The limit is independent of the clustering properties of the compact objects. There is as yet no conclusive model for quasar variability. It has thus been proposed that quasar variability is due to microlensing of an $\Omega_c \sim 1$ component of compact objects with $M_c \sim 10^{-3}M_{\odot}$ [24]. QCD PBH dark matter may therefore be constrained by large, homogeneous samples of quasar observations, such as expected to result from the Sloan Digital Sky Survey, hopefully accompanied by an improved understanding of the physics of quasars.

Gravitational wave detection from PBH binaries: It has been shown that a fraction $10^{-2} - 10^{-1}$ of QCD PBHs may form in PBH binaries [25]. This values is in rough agreement with the fraction of binaries observed by the MACHO collaboration. Gravitational waves emitted during PBH-PBH mergers are above the expected detection threshold for the LIGO/VIRGO interferometers when occurring within a distance of ~ 15Mpc. For galactic halos consisting exclusively of QCD PBH dark matter with $M_{pbh} \sim 0.5M_{\odot}$ this implies that up to a few mergers per year may be detected by the next generation gravitational wave interferometers [25]. It is particularly encouraging that the gravitational wave signal is sensitive to the masses of PBH within the binary. One may hopefully also distinguish between neutron star and black hole binaries. Establishing the existence of black holes with masses well below the upper mass limit for neutron stars may strongly argue in favor of primordial black holes.

Galactic disk accretion: Limits may be placed on galactic halo PBH number densities by the accretion induced radiation which may be observed when a halo PBH passes through the galactic disk in the solar vicinity [26]. Nevertheless, even the $\sim 10^8$ objects which will be observed within the Sloan Digital Sky Survey will not provide sufficient statistics to establish, or rule out, an all QCD PBH halo with masses as small as $\sim 1M_{\odot}$.

4 Conclusion

QCD PBHs may be an attractive dark matter candidate. I have outlined here to which degree accurate predictions for the properties of QCD PBH dark matter may be made. Most uncertain is the contribution to Ω of such objects since it relies on knowledge about the underlying density perturbations on mass scales not accessible to cosmic microwave background radiation observations. Predicting QCD PBH mass functions beyond the approximate equality between MACHO masses and the QCD horizon mass may improve with detailed numerical simulations of the PBH formation process and future results of lattice gauge simulations for the QCD equation of state. A combination of observational techniques, such as galactic microlensing searches, quasar microlensing searches, and gravitational wave interferometry may point towards the abundant existence of such objects. Ultimately, the unambiguous detection of a black hole well below the maximum mass for neutron stars may argue strongly for its primordial nature.

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