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Formation of the seed black holes: a role of quark nuggets?

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Abstract. Strange quark nuggets (SQNs) could be the relics of the cosmological QCD phase transition, and they could very likely be the candidate of cold quark matter if survived the cooling of the later Universe, although the formation and evolution of these SQNs depend on the physical state of the hot QGP (quark-gluon plasma) phase and the state of cold quark matter. We reconsider the possibility of SQNs as cold dark matter, and find that the formation of black holes in primordial halos could be significantly different from the standard scenario. In a primordial halo, the collision between gas and SQNs could be frequent enough, and thus the viscosity acting on each SQN would decrease its angular momentum and make it to sink into the center of the halo, as well as heat the gas. The SQNs with baryon numbers less than 10^{35} could assemble in the center of the halo before the formation of primordial stars. A black hole could form by merger of these SQNs, and then its mass could quickly become about 10^3 $M_\odot$ or higher, by accreting the surrounding SQNs or gas. The black holes formed in this way could be the seeds for the supermassive black holes at redshift as high as $z \sim 6$.

Contents

1 Introduction

QCD (quantum chromo-dynamics) is believed to describe the strong interactions between quarks and gluons, and is characteristic by asymptotic freedom at high energy scale and color confinement at low energy scale. The scale of QCD is $\Lambda_{QCD} = \mathcal{O}(100\,\text{MeV})$, below which quarks and gluons are confined into hadrons. Because the early Universe was in a hot and dense phase, in its cooling precess, cosmological QCD phase transition took place, when quarks and gluons confined into hadrons. If the cosmological QCD phase transition is of first order, there could be dramatic consequences on astrophysics. Witten [1] suggested a separation of phases during the QCD phase transition, and suggested that most of the deconfined quarks would be concentrated in the dense and invisible strange quark nuggets (SQNs for short, which are composed of up, down and strange quarks). Moreover, the ratio of mass density of SQNs to that of hadrons could be approximately the ratio of mass density of dark matter to that of ordinary matter.

It depends on the physical state of QGP (quark-gluon plasma) and strange quark matter to determine the formation and evolution of SQNs. Unfortunately, there is no experimental result or theoretical method which can give clear answers. The order of cosmological QCD phase transition is still uncertain, which could be of first order, second order or crossover. Lattice QCD calculations predict that the QCD phase transition is a simple crossover [2]; however, it can be of first order if the neutrino chemical potentials are sufficiently large [3]. Here we take the assumption of first order transition and study the consequences; after all, in the other two cases, there would be no formation of SQNs, and all of the free quarks would be confined into hadrons.

Another important process is that in the hot universe, an SQN would lose its baryons, depending on the state of quark matter. This issue has been studied, in the framework of MIT bag model [4, 5], the chromoelectric flux tube model [6], the color superconductivity model [7] and so on. However, the state of quark matter could be more complex, just as

showed in the experiments of relativistic heavy ion collisions (RHIC), which indicated a strongly coupled QGP (sQGP) [8]. After the formation, the temperature of each SQN would decrease due to the cooling by neutrinos, thus the interaction between quarks could be much stronger than that in the case of hot QGP. As we will discuss in this paper, the survived SQNs would have interesting astrophysical consequences. If the astrophysical observations could give some constraints on the baryon number of SQNs, we can get some hits as to the state of quark matter at low energy scales, complementary to the terrestrial experiments.

As a dark matter candidate, SQNs are different from the conventional version of dark matter. First, SQNs is a special kind of baryons with large baryon number, so they are still in the standard model of particle physics; whereas the conventional dark matter is of new physics. Second, the mass scales are different. The largest SQNs are macroscopic particles with mass $M \sim 10^{-9} M_\odot$ and length of ~ 1000 cm; however, for conventional dark matter particles, the largest mass is usually $100\,\text{GeV}$, and they are always been treated as mass points.

On the other hand, although SQNs are baryon matter, they have the characteristics of dark matter. First of all, because of the very low electric charges per baryon ($\sim 10^{-5}$) [9], the electric charge-to-mass ratio is very small even if they are completely ionized. This means that the gravitational force dominates the interaction between SQNs. Secondly, unlike the ordinary atoms, the electrons of an SQN is in the continuous states, thus an SQN cannot radiate via the electron transitions between different energy levels, which means they are "dark". In addition, it is hard for an SQN to absorb protons and ordinary atoms because of the Coulomb barrier on its surface [9], so we do not have to worry about the absorption of ordinary matter by SQNs. Because SQNs were non-relativistic particles at the time they formed, they manifestly like the cold quark matter (CDM). In this case, the overall picture of structure formation in the standard cosmology with cold dark matter (ΛCDM) could not change significantly, although this has not been tested by numerical simulations.

SQNs as dark matter could not lead to conflicts with observations. In the early Universe they would absorb neutrons and repel protons, thus reducing primordial helium production. Madsen [10] found that if the dark matter is completely composed of SQNs, the consistency between prediction of Big Bag Nucleosynthesis (BBN) and observational result for the helium abundance would not be affected as long as their radius exceed 10^{-6} cm. We revisit the issue using the more reasonable cosmology and more accurate observational result of the helium abundance, and find that the constraint for the radius is $R \geq 2 \times 10^{-5}$ cm, a little more severe than before. On the other hand, SQNs in our galaxy could have been depleted by the SNe acceleration, so it is hard for us to detect them.

SQNs as dark matter could not significantly affect the overall scenario of structure formation in the standard ΛCDM model. However, they may affect the formation of black holes in primordial halos. Because the SQNs are macroscopic particles, inside a primordial halo, in the region where the gas density is high enough, the SQNs could feel the viscosity due to their collisions with gas. This would decrease their angular momentum and make them to sink into the center of the halo before the formation of primordial stars (Pop III stars) in the halo, if their baryon number A satisfies $A \leq 10^{35}$. At the same time, the gas would be heated and thus collapse more slowly. The collision and merger of these SQNs that assemble in the center of the halo could lead to a formation of a stellar-mass black hole. The rest of SQNs will sink into the black hole through viscosity too, and if their total mass is higher than $10^3\ M_\odot$, then a black hole with mass higher than $10^3\ M_\odot$ would quickly form. On the other hand, before the formation of Pop III stars, the gas has not been polluted by metals, so it would be difficult to cool and fragment. Consequently, the black hole would also increase

its mass by accreting the surrounding unionized gas quickly with nearly spherical accretion rate. In both cases a black hole with mass higher than $10^3 \, M_\odot$ would form in a short enough time, which could be the seed of the supermassive black holes ($M \sim 10^9 M_\odot$) at high redshifts ($z \sim 6$). We assume that dark matter is completely composed of SQNs, but even if they only make up a fraction of dark matter, the results could almost be the same qualitatively.

This paper is arranged as follows. To illustrate why SQNs could be a candidate of dark matter, we show a brief review of their formation and evolution in section 2. The constrains from BBN and our present galaxy are discussed in section 3. In section 4, we show the implications for the formation of supermassive black holes at high redshifts. We make conclusions and discussions in section 5.

2 Formation and evolution of SQNs

2.1 Formation

SQNs formed in the first-order QCD phase transition in the early Universe [1, 11]. The baryon number inside the Hubble volume (with radius about 10 km) is

$$A_{\max} = 10^{48} \left(\frac{170 \text{ MeV}}{T_{\mathrm{c}}} \right)^2 , \tag{2.1}$$

which is the maximum baryon number of SQNs, corresponding to maximum mass of $M_{\max} \sim 10^{-9} M_\odot$. Here $T_{\mathrm{c}} \simeq 170 \, \mathrm{MeV}$ is the critical temperature of the phase transition. The age of the Universe is $t \sim 10^{-6}$ s. Before the phase transition, the particles in the Universe are quarks (u, d, and s quarks), gluons, leptons and photons. When the temperature of the Universe reaches T_{c}, hadron drops nucleate by a small amount of supercooling. The hadron bubbles grow and release latent heat to keep the temperature of Universe at T_{c}, and quarks outside of the hadron bubbles are still in QGP phase. Once hadron bubbles occupy roughly half of the total volume, they begin to collide and merge, leaving the Universe with shrinking bubbles of QGP immersed in a hadron matter medium. The QGP phase could keep the temperature and pressure equilibriums with hadron phase by the release of neutrinos, which is efficient because the neutrinos have long mean-free path. In this way, the QGP bubbles shrink without losing baryons (baryons and antibaryons annihilated into neutrinos), and the baryon number density increases. The coexistence of the two phases can maintain until the baryon number density of QGP phase is large enough (about 3 to 5 times of nuclear matter densities), when the QGP bubbles condense into SQNs.

If we assume that at the epoch of transition, QGP phase is composed of massless and free quarks and hadron phase is composed of non-relativistic hadrons, we can get the baryon number density for each phase [1]. In the condition of equilibrium of the two phases, the ratio of baryon number density in hadron phase to that in the QGP phase is $\epsilon \simeq 0.003$ to 0.27, if $T_{\mathrm{c}} = 100 \, \mathrm{MeV}$ to $200 \, \mathrm{MeV}$. The ratio of mass density of ordinary matter to that of dark matter is in this range, which is one of the reasons to take SQNs as a candidate of dark matter.

An SQN is composed of nearly equal numbers of up, down and strange quarks, with a few electrons to maintain it electrically neutral. Strange quark matter could be more stable than the ordinary nucleus [1, 12], since the existence of strange quarks could make the energy per baryon to be lower than that in ordinary nucleus under reasonable QCD parameters [9]. Strange quark stars as another kind of strange quark matter in our Universe has attracted a lot of attention since 1970's [13].

It is important for us to get the initial mass-spectrum of SQNs, which depends on the properties of QGP. Although some results were derived by Bhattacharyya et al [14], the results were model depended. They treated the quark phase by MIT bag model and found that the initial baryon numbers were between 10^{38} and 10^{47}, depending on the models for the rate of hadron nucleation. It is conventional to apply MIT bag model to describe the quark phase; however, recent results of Relativistic Heavy Ion Collisions (RHIC) experiments show some evidences that the interaction between quarks is very strong, i.e., the strongly coupled quark-gluon plasma [8]. This means that QGP is composed of strongly interacting quarks, and the perturbative QCD is inadequate to describe it. If this is the real case, QGP will be more complex than we imagine [15], and the calculation of the initial baryon number distribution of the quark nuggets will become more involved. Moreover, the ratio of baryon number density of hadron phase to that of QGP phase ϵ should be recalculated.

Derivation of the initial mass-spectrum of SQNs is out of the range of our discussion in this paper, although it is important for studying the cosmological QCD phase transition. In addition, different initial mass-spectrum would not lead to much differences in the final mass-spectrum after the evaporation process. Therefore, at this stage, we do not put constrains on the initial baryon number of SQNs.

2.2 Evolution

Strange quark matter could be more stable than the ordinary nucleus. However, in the environment of the hot early Universe SQNs suffer the losing of baryons from their surfaces, just like liquid water drops will evaporate. Alcock and Farhi [4] found that even the largest SQNs formed in the cosmological QCD phase transition (with baryon number $A \simeq 10^{48}$) could not survive the evaporation of hadrons in the cooling of the Universe. Madsen [5] then pointed out that the absorption of the nucleons dominates over evaporation when the temperature decreases to between 10 and 20 MeV. He also took into account the increases of the effective binding energy on the surface of a nugget, and found that at it is possible for SQNs with baryon number $A \geq 10^{45}$ to survive. Further work applied chromoelectric flux tube model and considered the effects of strong coupling constant α_s [6], and found that a nugget having baryon number $A \geq 10^{39}$ could survive evaporation. All of the above work treated the quark phase in the framework of MIT bag model. Recently, a color-superconductivity (CS) phase and a color-flavor locked (CFL) phase have been suggested in quark matter, in which cases the quarks pairing could form because of the weak interaction between quarks. Horvath [7] studied the evaporation of SQNs taking into account the QCD pairing and found that a nugget as small as $A \sim 10^{42}$ could survive evaporation.

The evaporation process depends on the state of strange quark matter, which is difficult for us to derive theoretically or experimentally. The temperature inside an SQN will decrease after its formation due to the cooling by neutrinos, so if QGP is strongly coupled at the transition temperature, the interaction between quarks could be stronger inside SQNs during the evaporation process. At zero temperature, in quark nuggets with baryon density about 3 to 5 times of nuclear matter densities, quark clustering could occur because of such strong interaction [16, 17]. Although the evaporation process last until the temperature of the Universe drops at about 10 MeV, the temperature inside SQNs is much lower than the chemical potential of quarks, which means that the finite temperature effect is not important. The interaction between quarks or quark-clusters could decrease the evaporation rate, and make the nuggets easier to survive. The detailed calculation should involve non-perturbative QCD, so it is a difficult task. In this paper, we try to get some constrains from astrophysics

on the baryon numbers of the survived SQNs. Because the evaporation process of SQNs depends on the state of quark matter, the constrains to the baryon numbers of the survived SQNs could give us some hints as to the properties of low energy QCD.

3   SQNs as dark matter in the early and present Universe

An SQN is composed of nearly equal numbers of u, d and s quarks, with a few electrons to maintain it electrically neutral. This is because the number of s quark is less than u and d quarks, due to the larger mass of s quarks. The binding energy of the outermost electrons is very small ($\sim 1\,\mathrm{eV}$ if we describe the distribution of electrons in an SQN by the Thomas-Fermi-Dirac model), so they were easy to be ionized in the early Universe and in the present galaxies.

3.1   Constrains from BBN

The influences of charged dark matter on BBN have been discussed by some authors (e.g, in [18, 19]), but they only considered the dark matter particles with negative charges, which could form bound states with ordinary nucleus. SQNs are positively charged, so they can only combine with electrons, and they would influence BBN in a different way.

Under the MIT bag model, the electrostatic potential at the surface of quark matter is of order $10\,\mathrm{MeV}$ [9]. Therefore, when the temperature of the Universe is under $10\,\mathrm{MeV}$, SQNs repel protons. However, they absorb neutrons. At temperature $T \gg 1\,\mathrm{MeV}$, the weak interaction is in equilibrium, so even though SQNs are absorbing neutrons, the weak interaction can keep the neutron-to-proton ratio at the equilibrium value. The electroweak freeze-out take place at $T_\mathrm{F} \sim 1\,\mathrm{MeV}$. From then on, the absorption of neutrons by SQNs will affect the neutron-to-proton ratio, and consequently affect the process of BBN which begins at the temperature $T_\mathrm{N} \sim 0.1\,\mathrm{MeV}$. The standard theory of BBN has been tested very well by the observations of CMB (Cosmic Microwave Background) and the light element abundances. As a candidate of dark matter, the absorption of neutrons by SQNs should not change this consistency. This issue was first studied by Madsen [10].

For simplicity, we suppose that all SQNs have the same radius R. The absorption rate per neutron by SQNs is

$$r = \sigma_\mathrm{n} v_\mathrm{n} n_\mathrm{Q}, \tag{3.1}$$

where $\sigma_\mathrm{n} = \pi R^2$ is the cross section for the absorption, $v_\mathrm{n} = (8kT/\pi m_\mathrm{n})^{1/2}$ is the velocity of neutrons of mass m_n at temperature T, and n_Q is the number density of SQNs. n_Q can be written as

$$n_\mathrm{Q} = \Omega_\mathrm{Q} \rho_{\mathrm{crit},0} \left(\frac{T}{T_0}\right)^3 / m, \tag{3.2}$$

where $m = 10^{15}$ g/cm^3 is the mass of each SQN, Ω_Q is the present contribution of SQNs to the density in units of the present critical density $\rho_{\mathrm{crit},0} = 1.88 \times 10^{-29} h^2$ g/cm^3 ($100h$ kms^{-1}Mpc^{-1} is the present value of the Hubble parameter), and T_0 is the present temperature. Collecting all the above terms, we get

$$r \simeq 1.7 \times 10^{-4}\ \mathrm{s}^{-1} \left(\frac{T}{1\ \mathrm{MeV}}\right)^{\frac{7}{2}} \left(\frac{10^{-2}\mathrm{cm}}{R}\right) \left(\frac{\Omega_\mathrm{Q} h^2}{0.3}\right) \left(\frac{3\mathrm{K}}{T_0}\right)^3 a^{-1}, \tag{3.3}$$

where a is a parameter of order unity giving the relation between mass and radius of an SQN, $m = a(10^{15}\mathrm{g/cm}^3)R^3$.

Let n_n and n_p denote the neutron and proton abundances at the beginning of BBN, and x' and x denote the neutron-to-proton ratio at the beginning of BBN in the presence of SQNs and the standard case respectively. The relation between x' and x is

$$\frac{x'}{x} = \frac{(n_n/n_p)_{\text{SQN}}}{(n_n/n_p)_{\text{standard}}} = \exp\left(-\int_{t_F}^{t_N} r\, dt \right), \tag{3.4}$$

where t_N and t_F are the time at the beginning of BBN and electroweak freeze-out respectively. Using the relation between time t and temperature T,

$$t \simeq \left(\frac{1\ \text{MeV}}{T} \right)^2 s, \tag{3.5}$$

we get

$$\int_{t_F}^{t_N} r\, dt \simeq 1.8 \times 10^{-4} \left(\frac{T_F}{1\ \text{MeV}} \right)^{\frac{3}{2}} \left(\frac{10^{-2}\text{cm}}{R} \right) \left(\frac{\Omega_Q h^2}{0.3} \right) \left(\frac{3\text{K}}{T_0} \right)^3 a^{-1}, \tag{3.6}$$

The abundance of ^{4}He is denoted by Y_p, $Y_p = 2x/(1+x)$. Combining with the CMB observation and BBN theory, ^{4}He is predicted to be [20]

$$Y_p = 0.2484^{+0.0004}_{-0.0005}, \tag{3.7}$$

while the observational result for Y_p is [21]

$$Y_p = 0.238 \pm 0.002 \pm 0.005. \tag{3.8}$$

If the presence of SQNs do not spoil the consistence of the prediction and observation, we should let

$$\frac{2x'/(1+x')}{2x/(1+x)} \geq \frac{0.2310}{0.2488}, \tag{3.9}$$

which means that

$$R \geq 2 \times 10^{-5}\ \text{cm}\ \left(\frac{T_F}{1\ \text{MeV}} \right)^{\frac{3}{2}} \left(\frac{\Omega_Q h^2}{0.3} \right) \left(\frac{3\text{K}}{T_0} \right)^3 a^{-1}. \tag{3.10}$$

If dark matter is composed of SQN, then $\Omega_Q h^2 \simeq 0.3$, therefore the lower limit for the radius of SQNs is about 2×10^{-5} cm. If R is larger, x' is closer to x, which means that the influence of SQNs on standard BBN (at least for ^{4}He) is less significant. An SQN with radius of about 2×10^{-5} cm has baryon number $A \sim 10^{25}$ and mass ~ 10 g. Here we assume that all of the SQNs have the same radius for simplicity, but it is certainly not the real case. As long as most of the SQNs have radii larger than 2×10^{-5} cm, then the abundance of ^{4}He is still in consistence with the observations. The productions of D, ^{3}He and ^{7}Li are sensitive to the ratio of baryons to photons at the epoch of BBN η_{bbn}, and in our case that dark matter is composed of SQNs, the value of η_{bbn} would not be different from the standard case (without SQNs). If the abundance of ^{4}He is consistent with the observations, then the abundances of other light elements such as D, ^{3}He and ^{7}Li could also be consistent with the observations, as long as the other conditions of the Universe (such as η, Ω and so on) are the same as in the standard case. Although a more detailed demonstration is required, this is out of the range of discussion in this paper.[1]

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[1] It is worth mentioning the presence of SQNs could lead to inhomogeneous BBN due to the inhomogeneous distribution of baryons [22, 23], which could provide explanations to the inconsistent between the observed D abundance and ^{4}H and ^{7}Li measurements combining with CMB measurements.

3.2 SQNs in present galaxies

As a candidate of dark matter, SQNs have similar properties with charged massive particles (CHAMPs) which are essentially predicted in physics models beyond Standard Model. Chuzhoy & Kolb revisited the possibility of CHAMPs as charged dark matter in our Milky Way, and they got some constrains on the charge-to-mass ratio based on the fact that no such particles has been detected yet on our earth [24]. In their demonstration, the critical velocity v_c beyond which the charged particles can escape the galaxy by gaining more energy from SNe than losing in Coulomb scatterings depends on the mass m_X and the electric charges q_X of one CHAMP, $v_c \propto m_X^{-1/3} q_X^{2/3}$. The mass of each SQN is larger than protons by many orders of magnitude, so even it has multi-charges, its critical velocity could be much smaller than that have been derived in the case of CHAMPs. This means that it is very easy for SQNs to escape our galaxy, and that could be the reason why we have not detected them yet. Moreover, because the extremely large mass of each SQN, the number density of SQNs could be much smaller than that of the conventional dark matter particles, so even SQNs cannot escape the galaxy, it could be still very hard for us to detect them.

We suppose that at least a fraction of dark matter is composed of SQNs, and it is also worth mentioning that the constrains on the fraction of dark matter in CHAMPs has been derived recently by Sanchez-Salcedo et al [25]. They find that the fraction of the mass of galactic halo in CHAMPs should be less than about 1%, otherwise they cannot in pressure equilibrium in the presence of magnetic field in the galactic disk. Because all of the SQNs in the galaxy could have depleted due to the very low critical velocity, we need not to put the pressure equilibrium condition, and the constrains on the fraction of dark matter in SQNs could be released.

4 The implications for supermassive black holes at high redshifts

If dark matter is composed of SQNs, the overall picture of structure formation could not be quite different from the standard ΛCDM model. This kind of dark matter particles were non-relativistic particles and decoupled from the cosmological radiative background when they formed. Because of their extremely low electric charge-to-mass ratio, even if they are completely ionized, the electromagnetic force acting on each other is negligible compared to the gravitational force. Despite that the standard picture of structure formation could not be affected significantly, there are interesting implications for formation of supermassive black holes at high redshifts.

The supermassive black holes form by accretion and merging of seed black holes which are the end products of the primordial stars (Pop III stars). Recombination occurs at $z \sim 1200$ when the "dark ages" of the Universe begin. The residual ionization of the cosmic gas keeps its temperature locked to the CMB temperature down to a redshift of $z \sim 160$ [26, 27]. Until this point the cosmological Jeans mass (gas plus dark matter) is $M_J \sim 10^5 M_\odot$, which is independent of z. At lower redshifts, gas cool adiabatically and $M_J \propto (1 + z)^{3/2}$ [28, 29]. The Pop III stars form at $z \sim 20$, with mass on the order of $10^2 M_\odot$, which reionize the Universe. A Pop III star evolves quickly and end up with a black hole which will increase its mass by accreting the surrounding gas, but the accretion rate is constrained by Eddington rate. Moreover, the ionizing radiation produced by the Pop III star can photo-evaporates the surrounding gas, leaving little gas available to be accreted by the black hole [30]. Therefore, even if the mass of the black hole could be of the order 100 $M_\odot$, its growth rate is limited.

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The discovery of the quasar at high redshifts ($z \sim 6$) [31] indicates that supermassive black holes with $M_{\mathrm{BH}} \simeq 10^9 M_\odot$ had already formed by that time. This rapid growth of black holes is still unexplained, although their formation could be possible under some mechanisms, e.g., the direct collapse in pre-galactic haloes [32]. The formation of primordial black holes during inflation with spectrum covering a wide range of masses could also be possible to lead to the supermassive black holes at high redshifts [33]. Another promising way is to get more massive seed black holes, e.g., the direct collapse into black holes by supernova explosion under the photodisintegration pair instability if Pop III stars are massive enough [34]. However, a detailed calculation of trapping of Lyman-α photons shows that the cooling of gas in primordial gas cloud is efficient, which means that the formation of massive primordial stars could be difficult [35]. In the following we propose another possible mechanism that could lead to the formation of seed black holes which are more massive than that as the end products of Pop III stars.

4.1 Assembling of SQNs in the center of a primordial halo

Dark matter virialize into gravitational bound objects through the violent relaxation, and the density distribution could be described by the isothermal sphere. In the period from $z \simeq 160$ to $z \simeq 30$, baryons have decoupled from radiation, and they collapse into structure in the gravitational potential of the dark matter halo which formed earlier. Before the cooling effect become dominant, the density distribution of gas could also be approximately described by

$$\rho_{\mathrm{h}}(r) = \frac{v^2}{4\pi G r^2}, \tag{4.1}$$

where the circular velocity is v. The total mass of gas inside radius r where the mass density of gas is ρ_{h} can be written as

$$M = \int_0^r 4\pi r'^2 \rho_{\mathrm{h}} dr' \simeq 6 \times 10^3 \ M_\odot \ \left(\frac{v}{1 \ \mathrm{km/s}}\right)^3 \left(\frac{1 \ \mathrm{cm}^{-3}}{n_{\mathrm{h}}}\right)^{\frac{1}{2}}, \tag{4.2}$$

and the radius where the gas number density is $1 \ \mathrm{cm}^{-3}$ is about 30 pc. Gas are more concentrated than dark matter particles, but the average mass density of dark matter is much more than gas, so we could estimate the total mass of dark matter inside this radius $r \sim 30$ pc to be approximately $10^2 - 10^4 \ M_\odot$.

SQNs are macroscopic particles, so they can collide with gas. The time scale for an SQNs with radius R and baryon number A to collide with gas with number density n_{h} is[2]

$$t_{\mathrm{collide}} = \frac{1}{n_{\mathrm{h}} \pi R^2 v} \simeq 10^{-3} \ \mathrm{s} \ \left(\frac{1 \ \mathrm{cm}^{-3}}{n_{\mathrm{h}}}\right) \left(\frac{10^{35}}{A}\right)^{\frac{2}{3}} \left(\frac{1 \ \mathrm{km/s}}{v}\right), \tag{4.3}$$

If $n_{\mathrm{h}} \geq 1 \ \mathrm{cm}^{-3}$, the collision between these two components could be frequent. Under such circumstance, the velocity of each SQN will decrease due to viscosity. The viscosity coefficient

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[2]The temperature in the problem we are discussing is less than 10^4 K, so SQNs are neutral and we need not to consider the Coulomb interaction of SQNs. On the other hand, the gravitational accretion of gas onto SQNs can also be neglected: the gravitational accretion radius of one SQN with mass M and velocity v is $R_{\mathrm{a}} \approx GM/v^2$, and then the ratio of the radius of one SQN R (its baryon number is A) to R_{a} is $R/R_{\mathrm{a}} \simeq 2 \times (A/10^{42})^{-2/3}$, which is lager than one in the situation we will consider in the following. Consequently, we use the geometric cross section of one SQN as the its colliding cross section with gas.

of gas cloud with temperature T is

$$\mu = \frac{1}{3}\rho_{\rm h}v_{\rm s}\lambda_{\rm h} = \frac{1}{3\pi R_0^2}\sqrt{3kTm_{\rm h}}, \tag{4.4}$$

where $\lambda_{\rm h}$ is the mean free path of gas molecules, $v_{\rm s}$ is the sound velocity, $m_{\rm h}$ and R_0 are mass and Bohr radius of hydrogen ($v_{\rm s} = \sqrt{3kT/m_{\rm h}}$, $\lambda_{\rm h} = 1/\pi R_0^2 n_{\rm h}$). We can see that μ is independent of number density of gas $n_{\rm h}$. The viscosity force acting on each SQN with radius R and velocity v is

$$F = -6\pi\mu v R, \tag{4.5}$$

which implies

$$\frac{dJ}{dt} = -\frac{6\pi\mu R}{M}J, \tag{4.6}$$

where J is the angular momentum of one SQN.

In the primordial halo with mass of about $10^5\ M_\odot$, the virial temperature is about 100 K [29], so we can estimate the time scale for one SQN with baryon number A to sink into the center of the halo from initial angular momentum $J_{\rm i}$ to finial angular momentum $J_{\rm f}$ as

$$\tau_{\rm sink} = \frac{M}{6\pi\mu R}\lg(J_{\rm i}/J_{\rm f}) = \frac{AR_0^2}{2R}\sqrt{\frac{m_{\rm h}}{3kT}}\lg(J_{\rm i}/J_{\rm f})$$

$$\simeq 1.6\times10^{15}\ {\rm s}\ \left(\frac{A}{10^{35}}\right)^{\frac{2}{3}}\left(\frac{100\ {\rm K}}{T}\right)^{\frac{1}{2}}\left(\frac{\lg(J_{\rm i}/J_{\rm f})}{10}\right). \tag{4.7}$$

We can see that before redshift $z\sim30$ when the age of the universe is about 3×10^{15} s, the angular momentum of an SQN has decreased by over ten orders of magnitude. On the other hand, the interaction between gas and SQNs transfers energy from SQNs to gas, and thus gas would be heated. The collapse of the gas would then become more slowly, although it is difficult to estimate what temperature of the gas would become under this heating mechanism. As a result, the collapse of SQNs could be faster than the collapse of gas, then there could be enough SQNs which would sink into the center of the halo. Because $\tau_{\rm sink}$ is independent of $\rho_{\rm h}$ as long as the viscosity force acting on each SQNs can be described by eq. (4.5), then even the density distribution of gas evolves dramatically after the cooling of hydrogens becomes important, the value of $\tau_{\rm sink}$ will not be affected.[3]

4.2 Formation of a stellar-mass black hole

Due to the viscosity, the orbital radius of each SQN will decrease as the decreasing of its angular momentum. Consequently the number density of SQNs will become higher and higher in the center of the halo, and then it is inevitable that they will collide with each other and merge into a larger SQN. The total mass of SQNs which suffer the viscosity and assemble in the center of the halo could be as high as about $10^2 - 10^4 M_\odot$, then it is possible that a large SQN with mass of the order of $M_\odot$ can form, which is like a quark star. If

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[3] The Reynolds number $\mathscr{R}$ is

$$\mathscr{R} = \frac{2Rn_{\rm h}m_{\rm h}v}{\mu} \simeq 0.2\left(\frac{A}{10^{35}}\right)^{\frac{1}{3}}\left(\frac{100\ {\rm K}}{T}\right)^{\frac{1}{2}}\left(\frac{n_{\rm h}}{10^{16}\ {\rm cm}^{-3}}\right)\left(\frac{v}{1\ {\rm km/s}}\right), \tag{4.8}$$

so as long as SQNs are not near the central of gas cloud, the Reynolds numbers are safely smaller than one, then the viscosity force acting on each SQN can be written in the Stokes form as in eq. (4.5).

the mass the large SQN becomes higher than about 3 $M_\odot$, then it will suffer gravitational instability and become a black hole.[4] To estimate the time for SQNs to assemble within some radius, we can take the trajectory of each SQN to be approximately helical curves with quasi-Keplerian motion. Note that the angular momentum of one SQN with circular orbital radius r is $J = M\sqrt{GM_t(r)r}$, where M_t is the total mass within the sphere of radius r, so we can directly transform the time scale derived in eq. (4.7) to be a function of r. Assuming that the merger of SQNs with total mass $\sim 3\ M_\odot$ is quick enough if they have assembled within radius about 30 km (the radius of innermost stable circular orbit of 3 $M_\odot$ black hole), we can estimate the time scale for the formation of this black hole, if the total mass $M_t(r)$ inside the orbital radius r of each SQNs in its sinking process will not significantly change,

$$\tau_{\rm bh} \simeq 5 \times 10^{15}\ {\rm s}\ \left(\frac{A}{10^{35}}\right)^{\frac{2}{3}} \left(\frac{100\ {\rm K}}{T}\right)^{\frac{1}{2}} \left({\rm lg}\,\frac{r_i/30\ {\rm pc}}{r_f/30\ {\rm km}}\right), \tag{4.9}$$

where r_i and r_f are the initial and finial orbital radius of the SQN.

The age of Universe at $z \sim 20$, when Pop III stars form in the gas cloud in the primordial halo, is about 5×10^{15} s, so if the baryon number A of each SQN is less than 10^{35}, then a black hole would form before the formation of Pop III stars. The energy released during the collapse of 3 $M_\odot$ quark star into a black hole would not be large enough to blew away the surrounding gas, for the following reasons. During the collapse, the rest of the quark star would be heated due to the released gravitational energy from a growing black hole inside it. To get a upper limit of the released energy which can be deposited into the surrounding gas, we take the quark star to be a black-body with radius R_Q of about 12 km and temperature T of about 1 MeV (a higher temperature would lead to effective neutrino emission which would take away most of the energy). The time for the quark star to become a black hole could be estimated as $(R_Q - R_s)/c$, where $R_s \sim 0.9$ km is its Schwarzschild radius, and c is the velocity of light, and then we can estimate the energy released by black-body radiation during this process as $E_{\rm bb} = \sigma T^4 R_Q^2 (R_Q - R_s)/c \sim 10^{43}$ erg, where σ is the Stefan-Boltzmann constant. This energy is much lower than the gravitational binding energy of the gas cloud in most cases. On the other hand, because of the low electric charges per baryon of SQNs, the impact of the radiation on motion of the surrounding SQNs would be negligible.

4.3 Growth to a high-mass black hole

The surrounding SQNs can sink into the black hole through losing angular momentum too. In this process, the initial orbital radius r_i is much smaller than 30 pc, and the final orbital radius r_f is larger than 30 km as the mass of the black hole is increasing, so the time for one SQN to sink into the black hole should be smaller than 10^{15} s. Moreover, because of the extremely low electric charges per baryon of each SQN, the feed-back effect of radiation on accreted mass could be negligible. This means that all of the surrounding SQNs can sink into the black hole in a short enough time. If the total mass of the surrounding SQNs is higher than $10^3\ M_\odot$, then a black hole with mass higher than $10^3\ M_\odot$ can form.

The surrounding gas can also be accreted into the black hole. This process is different from the standard scenario where the black holes as the end products of Pop III stars can also accrete gas. In our picture, the black hole forms before the formation of Pop III stars, as we have mentioned in the last subsection, so the surrounding gas has not been polluted

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[4]Although the exact value of the maximum mass of quark stars depends on the equation of state of quark matter and is still uncertain, it could be safely smaller than about 3 $M_\odot$ [37, 38].

by metals which are produced by nucleosynthesis inside stars and can be ejected into the surrounding media by supernovae in the standard evolution scenario of Pop III stars. The lack of metals would make the surrounding gas to cool less efficiently. Additionally, in the absence of Pop III stars, the gas has not been ionized. The accretion of the *hot and unionized* gas into the black hole can be approximated to be spherical accretion, and the mass accretion rate can be estimated as [39]

$$\dot{M} = 4\pi\rho_{\rm h}r^2 v_{\rm s} \sim \frac{v_{\rm s}^3}{G}, \tag{4.10}$$

where $v_{\rm s}$ is the sound velocity of the gas cloud. For temperature $T \sim 10^3$ K, we can get $\dot{M} \sim 10^{-3}$ $M_\odot$ yr^{-1}, so the total gas with mass of 10^3 $M_\odot$ could be accreted into the central black hole in about 10^6 yr. The lack of efficient cooling mechanism in the metal-free gas could make the possible fragment of the hot gas to be difficult, so the total mass of the gas which can be accreted into the black hole could be high.

Therefore, the black hole with mass of about 3 $M_\odot$ that forms before the formation of Pop III stars could become a black hole with mass higher than 10^3 $M_\odot$ in a short enough time, by either eating the surrounding SQNs or accreting the surrounding gas. On the other hand, if the total mass of SQNs that can assemble in the center of the halo by viscosity is much less than 100 $M_\odot$, and in addition the surrounding gas cloud is not massive enough, then it is difficult for the black hole to form (in the way we have discussed) before the formation of Pop III stars. In this case, the evolution of the halo could be nearly the same as in the standard scenario (without SQNs).

If most of the SQNs that formed in the early Universe and then survived the evaporation process have baryon numbers $A \le 10^{35}$, the evolution of primordial halos could be different, which could lead to the formation of black holes with mass higher than 10^3 $M_\odot$. These black holes could seed the supermassive black hole ($M \sim 10^9$ $M_\odot$) at high redshifts ($z \sim 6$). Although minimum baryon number A of SQNs that can survive the evaporation process have not been derived in reasonable models, the picture we describe here in which the black holes with mass higher than 10^3 $M_\odot$ could form quickly can be seem as a possible explanation to the formation of the high redshift supermassive black holes.

5 Conclusions & discussions

We reconsider the probability of strange quark matter being the candidate of dark matter and suggest a possible astrophysical consequence. If the cosmological QCD phase transition is of first order, SQNs could form. The strong interaction between quarks may favor the survival of SQNs during the evaporation process. The ratio of mass density of SQNs to that of hadrons could be approximately the ratio of mass density of dark matter to that of the ordinary matter. Although they have a few electrons to maintain electrically neutral, the extremely low charge-to-mass ratio leads to the domination of gravity over the electromagnetic force, as well as low radiative efficiency. In addition, it is hard for them to radiate because their degenerate electrons are in continuous states, unlike that in the ordinary atoms. If they survive after the evaporation of baryons, SQNs could provide a candidate of dark matter, and the standard BBN and the structure formation of standard ΛCDM model could not be affected significantly. Certainly, future numerical simulations are necessary to study their influences in the structure formation, which are not included in this paper. Although having only roughly done some estimations, we can see that there could be interesting astrophysical

consequences if SQNs did form in the early Universe and are stable throughout the life-time of the Universe.

One of the interesting consequences is that these dark matter particles could influence the formation of black holes in the primordial halos, as long as the baryon number of each SQN A satisfies $A \leq 10^{35}$. Inside a primordial halo, the collision between gas and SQNs could be frequent enough, and thus the viscosity acting on SQNs would decrease their angular momentum, making them to sink into the center of the halo and heat the gas. The collisions and mergers of these SQNs that assemble in the center of the halo could lead to a formation of a stellar-mass black hole. If the rest SQNs that surround the black hole have total mass higher than 10^3 $M_\odot$, then a black hole with mass higher than 10^3 $M_\odot$ could form after the sinking of all of the rest SQNs, which can be very quickly. Even if the surrounding SQNs are not enough, the black hole could also increase its mass to be higher than 10^3 $M_\odot$ by accreting the surrounding gas. In both cases, before the formation of Pop III stars, a black hole with high enough mass could form, which can be the seed of the supermassive black holes ($M \sim 10^9 M_\odot$) at high redshifts ($z \sim 6$). Although the more detailed calculations and numerical simulations are required to get a more precise result, the rough estimates we make here could be meaningful. In a word, if dark matter is (partly) composed of SQNs, it could not only have all of the properties that the conventional dark matter has, but also help us to understand some unexplained phenomenons.

The collision between gas and SQNs can transfer energy from SQNs to gas and heat the gas in the primordial halo, as mentioned in section 4.1. This could lead to an inefficient star-formation in the primordial hole. Because Pop III stars, which emit ionizing photons, play an important role in the reionization of hydrogen in the Universe, the reionizing efficiency would be lower than that in the standard scenario of Pop III stars. Consequently, the reionization would proceed more slowly and end at a later time. Moreover, in this case, during the reionization process there would be more discrete HII regions. Quasar spectra indicate that hydrogen in the intergalactic medium (IGM) had not been completely ionized at a redshift of $z \sim 6.3$, and the IGM surrounding these quasars had a neutral hydrogen fraction of about ten percent [40]. The usefulness of quasar spectra to probe reionization has been assessed, finding that the previous claims of a significant neutral hydrogen fraction at $z \approx 6$ could be strengthened [41]. The HII regions could imprint features on the power spectrum that allowed us to separate ionization histories with discrete bubbles from those with partial uniform ionization [42]. Although the reionization process is very complex, it is hopeful that the future advanced and detailed observations, for example the low-frequency radio telescopes, could give more constrains to the ionization history and to test the picture we have described in this paper.

On the other hand, some more fundamental questions related to the formation, the mass-spectrum, the evolution and the electromagnetic properties of SQNs are still uncertain. Is the cosmological QCD phase transition is really of first order? What is the state of matter for QGP at the critical temperature? At lower temperature, what is the state of matter for strange quark matter whose density is several times of the nuclear matter densities? Theoretically, these questions involve the non-perturbative properties of strong interaction, thus are difficult for us now to answer. Experimentally, getting clear evidences that show the properties of QGP at the critical temperature has not yet been achieved with certainty. It is also worth mentioning that, being a candidate of dark matter, we can get constrains to the properties of SQNs from the astrophysical observations, such as the influences to the CMB, the formation of primordial stars and the masses of seed black holes.

Acknowledgments

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