Cosmological Consequences of QCD Phase Transition(s) in Early Universe

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Abstract

We discuss the cosmological consequences of QCD phase transition(s) on the early universe. We argue that our recent knowledge about the transport properties of quark-gluon plasma (QGP) should throw additional lights on the actual time evolution of our universe. Understanding the nature of QCD phase transition(s), which can be studied in lattice gauge theory and verified in heavy ion experiments, provides an explanation for cosmological phenomenon stem from early universe.

1 introduction

Our knowledge about the early and present universe is based on two successful models; the standard model for elementary particles and the one for cosmology. The main ideas about the early universe cosmology seem to be confirmed from various cosmological data, like the temperature anisotropy in cosmic microwave background radiation (CMB), the light element abundances, etc. Although we have a solid description for phase transitions in almost all epochs in the early universe, their confirmations still indirect processes. The observation of cosmological 'exotic' phenomenon and the fruitful results from heavy ion experiments are promising tools to confirm these theoretical predictions.

In this work, we limit our discussion to QCD epoch, i.e. to energy scale of $\Delta_{QCD} \approx 200 \text{ MeV}$, $t \approx 10^{-5} - 10^{-6}$ second after the begin and when the universe has the Hubble radius of about $d_H \approx 10 \text{ Km}$ corresponding to scales of about 1 pc or about 3 light years today. At high energy the coupling between quarks and gluons likely becomes weaker. This coupling diverges at $\Delta_{QCD} = 200 \text{ MeV}$. From this property, QCD is known as asymptotically free theory.

As the energy decreases, i.e. the universe expands and cools down, the quarks and gluons underwent to confined state, to hadrons (deconfinement-confinment phase transition) and the chiral symmetry almost simultaneously breaks down, i.e., orientation of right- and left-handed quarks. The latter likely leads to production of Goldstone bosons. The three pions are the lightest Goldstone bosons. Dynamical fluctuations on these particles and/or disoriented chiral condensates (DCC) would manifest this transition.

In this talk, we discuss the cosmological consequences of nature and order of the QCD phase transition(s) on early universe.

2 Ideal and non-ideal Quark Gluon Plasma

A theoretical framework for dynamics of phase transition(s) from quark-gluon plasma (QGP) to hadrons still fails. In heavy ion collisions, we can detect produced particles at final state,
i.e. after chemical and thermal freeze-out. Consequently, there is no smoking-gun signal for occurrence of equilibration processes while the energy density $\epsilon$ decreases. Same statement is also valid for the degrees of freedom (d.o.f.). It is known that the thermal (statistical) models, like hadron resonance gas, work very well in final state. These models presume a charge-conserved hadronic phase, but they have no access to the phase transition itself.

Although the energy density $\epsilon$ available to heavy ion experiments at CERN-SPS, BNL-RHIC and recently to CERN-LHC exceeds the critical value calculated in lattice QCD ($\epsilon_c \approx 2$ GeV/fm$^{-3}$ for physical quark masses and vanishing net baryon number density), there is no unambiguous QGP-signature. For example, $\epsilon$ achieved at RHIC $\sim 5.5$ GeV/fm$^3$ for proper time $\tau_0 \sim 1$ fm/c. If $T_c \approx T_{fo}$, where $T_c$ is the critical temperature and $T_{fo}$ is the freeze out temperature, holds at small or vanishing net baryon number density, as we used to assume for ideal QGP, the phenomenological signals characterizing the phase transition(s) have to remain measurable at final state, at least the ones which are not sensitive to strong interaction or to the medium, such as photons, leptons or color screening as $J/\Psi$ dissociation into two leptons. According to recent lattice QCD results with almost physical quark masses, $T_c \approx 200$ MeV. This value exceeds $T_{fo}$ with at least $\sim 30$ MeV. During the relaxation time, within which the system (universe) loses $\sim 30$ MeV most of dynamical fluctuations might be moderated. According to \cite{7}, the inelastic scattering rate should have steep $T$-dependence. The plasma, like QGP, is a state in which the charges are screened due to the existence of other mobile charges. This will modify the Coulomb’s law. Lattice QCD results in that the $J/\Psi$ bound state would survive up to $2T_c$, where $T_c \approx 270$ MeV. The RHIC results suggested to include viscous corrections to the hydrodynamic evolution, so that the plasma state turns to be a fluid rather than an ideal gas of massless components (quarks and gluons) and negligible correlations (free interactions).

Taking into consideration shear viscosity in QGP fluid leads to slower hydrodynamic evolution relative to QGP with zero viscosity. The transverse expansion in viscous QGP fluid turns to be stronger than the one in an ideal QGP fluid. Also the particle production might considerably be enhanced in viscous QGP fluid. That QGP turns to be viscous fluid, apparently, modifies our ideas even about the time evolution of early universe.

3 QCD Phase Transition(s) and Chemical Freeze out

The QCD predicts that the asymptotically free quarks and gluons are weakly correlated. QCD has been extensively studied on lattice for the last thirty years; QCD Lagrangian has to be discretized. Then we put everything on a finite a space-time lattice. It has been shown that a rapid change in various thermodynamic quantities undoubtedly takes place at sufficiently high energies \cite{10}. The degrees of freedom markedly decreases in a relative narrow region of temperatures.

First order phase transition at $T_c \sim 270$ MeV is evidenced in lattice QCD without dynamical quarks (quenched) \cite{11,12}. Including the dynamical quarks makes the order of phase transition and the value of $T_c$ depending on the mass and number of quark flavors.

For two massless light quarks ($m_u = m_d = 0$) and infinity heavy strange quark ($m_s \to \infty$) at vanishing net baryon number (chemical potential $\mu_\text{q}$), which is appropriate to the early universe, where $\mu_\text{q}/T \sim 10^{-8}$, the phase transition is of second order and $T_c \sim 175$ MeV. If the light quarks get small masses, the critical behavior of phase transition moves to smooth cross over. For degenerate quarks ($m_u = m_d = m_s = 0$), the phase transition is again first order but with $T_c \sim 155$ MeV. For light up and down quarks and massive strange quark, the transition is cross over and $T_c \sim 170$ MeV again. Therefore, we would expect an upper value for the quark mass to secure first order phase transition. Above this values the order of phase transition seems to be cross over or weak second order.
It has been observed that the chiral symmetry is restored at the same critical temperature \( T_c \approx 154 - 174 \) MeV (depending on the quark flavors) as that of the deconfinement phase transition. The restoration of chiral symmetry means that the effective mass of quarks forming the confined hadronic states becomes zero. Another important consequence of chiral symmetry breaking restoration is the disappearance of mass degeneracy of hadronic states having same spin but different parity quantum numbers.

We find that the bulk thermodynamic quantities at very high temperatures of \( 4 - 5T_c \) remains below the Boltzmann limit [15, 14]: \( \epsilon_{SB} \approx g\pi^2 T^4/30 \). This behavior would indicate that thermodynamic quantities may remain constant at much higher temperatures. This means that the deconfined matter might remain strongly correlated. That QGP at \( 4 - 5T_c \) turns to be strongly correlated, would have consequences on its hydrodynamic evolution, production of confined hadrons and might delay the freeze out processes.

The chemical freeze out is characterized by \( s/T^3 = 7 \) for three quark flavors [1]. \( s \) is the entropy density. This condition characterizes a stage at which annihilation and production processes are in chemical equilibrium. As shown earlier, the consequence that \( T_{fo} \) is below \( T_c \), would lead to steep \( T \)-dependence of the inelastic scattering rate.

### 4 Cosmological Consequences

#### 4.1 Nature and Order of QCD Phase Transition(s)

At temperatures higher than the QCD critical temperature, \( T_c \), the matter are mainly formed in quarks, gluons, leptons and photons. In QCD epoch, the energy scale (\( \Lambda_{QCD} \sim 200 \) MeV) is much larger than the physical masses of these components, we therefore can approximate their masses to be almost vanishing. As given above, the universe in this epoch has a radius of \( \sim 10 \) km, which leads to mass content of \( \sim 4\pi R_H^3 \epsilon(T_c)/3 \sim 1.25 M_\odot \). \( \epsilon(T_c) \) is the energy density at the critical temperature \( T_c \). Its value is taken from lattice QCD simulations [14]. Under these circumstances the matter can be treated as a radiation.

The relaxation time scale of particle interaction at QCD energy scale (\( \Gamma_q \sim \alpha_s^2 T \) and \( \Gamma_q \sim -\alpha_s T \ln g \), where \( \Gamma = t^{-1} \). \( g \) and \( \alpha_a \) being gauge and strong coupling constant, respectively) is much shorter than the Hubble radius \( H \), thus the different phases of the matter; QGP, hadron gas, leptons and photons, are likely in thermal and chemical equilibrium. Therefore this matter is much similar to radiation fluid and the effective d.o.f are the baryon quantum numbers. Under these conditions, the baryon number density can be calculated from

\[
n_B(T_c) = \eta \cdot s(T_c) \left. \frac{n_\gamma}{s_{BBN}} \right|_{BBN} \quad (1)
\]

where \( n_\gamma \) is the photon density at Big Bang Nucleosynthesis (BBN). \( \eta \) is the celebrated ratio of baryon density asymmetry \( (n_B - n_{\bar{B}}) \) to photon density. According to recent WAMP data [16], \( \eta \) reads

\[
4 \times 10^{-10} < \eta < 7 \times 10^{-10} \quad (2)
\]

Using recent lattice QCD results [6] for \( T_c \) and \( s \), we can calculate the physical units of baryon number density \( n_B(T_c) \) for three dynamical quark flavors at physical masses in QCD epoch

\[
n_B(T_c) = 8.1 \times 10^{-11} \quad s(T_c) = 5.5 \times 10^{-3} \quad MeV^3 \quad (3)
\]

To get this value, we assume that no annihilation process is effective. The number of baryons filling out the Hubble volume up to the causal horizon at the QCD phase transition reads

\[
N_B(T_c)|_H \approx 3 \times 10^{48} \quad (4)
\]
Obviously, this number strongly depends on nature and order of QCD phase transition as $s$ and $T_c$ do (review Sec. 3). When the universe loses $\sim 30$ MeV temperature, i.e. at the chemical equilibrium freeze out [1], $N_B(T_c)$ consequently decreases to one half or one third of this value.

In first order phase transition, the two phase co-exist and bubbles "dirt objects" in form of mixed phase of QGP and hadron gas are quite likely expected. To keep the temperature constant, bubbles slowly dominate the system. Since the two phases have different entropy densities, the bubbles release latent heat and accordingly the energy density $\epsilon$ decreases [10] until the transition is completed. Released latent heat can reheat the matter (universe) to tiny fraction. Candidates for such "cosmic" bubbles would be primordial monopoles, cosmic strings, black holes, etc. As there is so far no verification for any of these objects, we have to look for other consequences, like primordial temperature fluctuations [17] and inhomogeneities forming dark matter clumps, etc.

At QCD phase transition, neutrinos move freely with mean free path $\lambda_{free} \approx 10^{-6} R_H \approx 1$ cm and the fluctuations on their diffusion scale might be washed out during QCD phase transition, $\lambda_{diff} \approx 10^{-4} R_H \approx 1$ m. These scales determine whether the temperature fluctuations (inhomogeneities) have to be neglected and the bubble hadronization proceeds in a homogeneous rate or the bubble hadronization is indeed inhomogeneous. According to [17], the second scenario can be fulfilled, if the rms temperature fluctuations $> 10^{-5}$. In that case, the scale of inhomogeneity in baryon distribution [18] can be related to the scale of inhomogeneity in radiation fluid after the QCD phase transition. This might modify the neutron to proton ratio and thus explain the initial conditions for BBN. BBN is an important tool to verify our ideas about the early universe. Inhomogeneities would lead to formation of cold dark matter clumps in connection with the Hubble scale as given above.

The scale separation between bubble hadronization and hadron diffusion is about two orders of magnitude. This scale difference has been calculated for first order phase transition. It depends on released latent heat and free energy difference between the two phases (QGP and hadron gas).

Once again, in the first order phase transition, both phases exist at one critical pressure and therefore the speed of sound $c_s^2 = \partial p/\partial \epsilon$ vanishes throughout the whole transition. During the time of transition, the density perturbation within visible horizon ($\lambda < R_H$) falls freely, i.e. radiation fluid velocity remains constant. At $T > T_c$, the density perturbation modes causes acoustic oscillations. They entirely vanish, when $c_s$ vanishes. At very high energies, $c_s = 1/\sqrt{3}$ in radiation-dominant matter (universe) [19]. At very high temperatures, $p/\epsilon$ can be related to $c_s$ at very high temperatures, i.e., in an ideal gas. We notice that $p/\epsilon$ reaches 0.14 at the critical point.

The production of sterile neutrinos occurs through collisions between active neutrino gas and plasma of weakly interacting particles. The production in cold, warm and hot dark matter scenarios [20] is maximum around $\sim 130$ MeV. Intuitively, one can think about a close relation between sterile neutrinos and QCD phase transition. According to [21], first order phase transition significantly enhance sterile neutrino relic densities relative to crossover one.

QCD predicts another phase transition at almost same $T_c$ of confinement-deconfinement phase transition; the restoration of chiral breaking symmetry, i.e., anisotropic rotation of right and left handed quarks. The breaking chiral symmetry results in the pions as the lightest Goldstone bosons. Therefore, strong fluctuations on the pion fields known as DCC, *disordered chiral condensates* [22], are quite likely through the transition. If chiral phase transition takes place through an out-of-equilibrium process, it would provide a crucial tool to explain the primordial magnetic fields [23]. The origin of the primordial magnetic fields shall be studied by the Square Kilometer Array (SKA) [24]. The particle production can be studied in hadron resonance gas (below $T_c$). Left panel of Fig. 2 shows ratios of various particles as a function of $\sqrt{s}$ [25].

The dynamical fluctuations associated with strong first order of phase transition are likely
very large. The continues second order or cross over phase transition might wish out large part of dynamical fluctuations in the final state and do not provide out-of-equilibrium. On the other hand, the dynamical fluctuations are conjectured to slow down near the second order phase transition. This has been confirmed in classical systems, solid state physics. In quantum field theory, the long-wavelength (spinodal) modes will be quenched through the second order phase transition [26].

In right panel of Fig. 2, we notice that the dynamical fluctuations smoothly increase with the center-of-mass energy $\sqrt{s}$. This agrees with lattice simulations for $n_\sigma$ fluctuations [27] and might support the conclusions that any anomalous phenomenon associated with non-equilibrium phase change likely would be washed out, if the phase change is smooth and does not cause out-of-equilibrium.

In second order phase transition, the correlation length $\zeta$ likely diverges at the critical point. This divergence can be characterized by a critical exponent $\nu$. $\nu$ has a universal value, $\sim 2/3$. It does not depend on the microscopic details of the system in transition. It only depends on the universality class.

\[
\zeta(T) = \zeta(T_c) \left( \frac{T_c - T}{T_c} \right)^{-\nu} \tag{5}
\]

The relaxation time $\tau$ also diverges at the critical point. $\tau$ gives the time needed for a small perturbation to be in-equilibrium.

\[
\tau = \tau_0 \left( \frac{T_c - T}{T_c} \right)^{-\mu} \tag{6}
\]

Assuming that the system cools down with a constant rate so that

\[
T(t) = T_c \left( 1 - \frac{t}{\tau_Q} \right) \tag{7}
\]

Fig. 1: It shows the results from a hadron resonance gas [10] below $T_c$. Open symbols give $p/\epsilon$ as a function of $\epsilon^{1/4}$ in physical units $\text{[GeV/fm}^3]^{1/4}$. Solid symbols show normalized $s/n$. The continues second order or cross over phase transition might wish out large part of dynamical fluctuations in the final state and do not provide out-of-equilibrium. On the other hand, the dynamical fluctuations are conjectured to slow down near the second order phase transition. This has been confirmed in classical systems, solid state physics. In quantum field theory, the long-wavelength (spinodal) modes will be quenched through the second order phase transition [26].

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\]
Fig. 2: Left panel: ratios of different particles as functions of $\sqrt{s}$ \cite{25}. The largest $\sqrt{s}$ is related to early universe, where the net baryon number is almost zero. Right panel: the dynamical fluctuations of $K/\pi$ particle ratios $\sqrt{s}$ \cite{28}. The points give the experimental data from various heavy ion collisions. The curves show the results from a hadron resonance gas \cite{10}.

where $\tau_Q$ is the quench time. From Eq. (5), (6) and (7), the correlation length and relaxation time can be related to $t/t_Q$

$$\zeta(t) = \zeta_0 \left( \frac{t}{\tau_Q} \right)^{-\nu} \quad (8)$$

$$\tau(t) = \tau_0 \left( \frac{t}{\tau_Q} \right)^{-\mu} \quad (9)$$

The fluctuations that survive the phase transition are depending on the freeze out time. The fluctuations are characterizing these fluctuations. The freeze out time can be obtained by solving the equation $\tau(t) = \hat{t}$

$$\hat{t} = -\left( \tau_0 \frac{\tau_T}{\tau_Q} \right)^{1/(1+\mu)} \quad (10)$$

As shown above, the hydrodynamic evolution of viscous QGP fluid is slower than the ideal QGP, i.e. $\tau(t) > t$ or any out-of-equilibrium process is slow and therefore can survive the phase transition. That we do not observe dynamical fluctuations would indicate that the phase transition is continuous (cross over), Fig. 2.

4.2 Chemical freeze out

At chemical equilibrium, $s/T^3 = 7$ for three quark flavors and the freeze out temperature $T_{fo} \approx 174$ MeV. $s/T^3 = 7$ is a universal condition describing all experimental data from heavy ion collisions at a wide range on incident energies \cite{1}. Then the entropy in QCD epoch reads

$$S = V \cdot T^3 \approx 2.05 \cdot 10^{58} \quad (11)$$

This number reflects that about ten orders of magnitude an increase in produced particles as a reason of QCD phase transition are expected. The multiplicities of produced particles in heavy ion collisions should manifest this increase. Should we take into consideration that the Universe meanwhile expands this number becomes larger.
4.3 Non-ideal QGP (strongly correlated QGP)

According to [29], the hydrodynamic evolution of QGP fluid with dissipation due to shear viscosity has a slower rate than the ideal QGP fluid. The transverse expansion in the viscous fluid is stronger and faster than the one in an ideal fluid. The pion production is considerably enhanced in viscous fluid, so that larger viscosity straightforwardly leads to more pions. The particle production increases when the freeze out surface is extended and the distribution function become non-equilibrium. The freeze out surface [30] can be parameterized and fitted to the experimental data. With extension we mean change. The conditions deriving the freeze out as a function of the incident energies are discussed in [1].

The dissipation has another crucial consequence. It might modify the elliptic flow. The elliptic flow reduces with the viscosity. The reduction tends to reach a saturated value at high energies (large transverse momentum). The ideal fluid shows almost opposite behavior. The elliptic flow increases with the transverse momentum.

5 Summary and Conclusion

Lattice QCD calculations with dynamical quarks and physical masses show that the phase transition at very small net baryon density, which is related to early universe is likely cross over or very weak second order. Phenomenological indications for such a continuous transition is quite likely an ambiguous task. As discussed earlier, the order and critical temperature of deconfinement-confinement phase transition(s) calculated in lattice QCD strongly depend on the number and masses of quark flavors. The order varies from strong first order to very weak second order or cross over. Consequently, the critical temperature takes values between 150 MeV and 200 MeV. The cosmological consequences strongly depend on the QCD phase transition(s).

We used to assume that QGP can be treated as a free ideal gas. The recent RHIC results suggested that QGP is a fluid rather than an ideal gas. Also recent lattice QCD simulations support such a conclusion. Taking into consideration that quark-gluon plasma is strongly correlated (sQGP) and has shear viscosity would lead to the consequence that its hydrodynamic evolution is slower relative to QGP with zero viscosity. Also the transverse expansion in such a fluid is much stronger than the one in an ideal QGP fluid. Phenomenologically, the particle production is considerably enhanced in sQGP. All these results would to some extent modify our ideas about the time evolution in early universe, for example.

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