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Quantum Chromodynamics in the Early Universe: The Color Glass Condensate

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Quantum chromodynamics (QCD), the basic theory of strong interactions between the quarks and gluons is expected to play an important role in the early universe. We discuss the scenario when the fast cooling of QCD matter leads to the creation of a saturated phase with an enormous number of possible configurations. Using an analogy with the classical glasses we predict that this glassy form of matter – the Glasma – existing at temperatures above a few GeV has dominated properties of the universe in the period preceding the formation of quark-gluon plasma (QGP). We examine the possibility that the properties of this high-temperature color-glass condensate (CGC) filling the universe in the very hot QCD and EW eras, and beyond were close to the stiff matter.

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1. Saturated QCD matter in high-energy particle collisions

In perturbative QCD the density of its basic degrees of freedom (DoF) – partons (quarks and gluons) evolves along two different paths (see e.g. the standard textbooks [1, 2] and references therein). The first corresponds to the development of a partonic cascade in variable Q – the momentum transferred between the partons during their interaction, the second follows the evolution in variable $x = k^+/P^+$, a fraction of the light cone momentum P^+ of the parent parton, which has radiated a parton emerging with the light-cone momentum k^+ [2].

While the evolution in variable $\ln(Q^2/\Lambda^2_{\rm QCD})$, where $\Lambda_{\rm QCD} \simeq 200$ MeV is the characteristic QCD scale, is described by the DGLAP equations, the evolution in variable $Y = \ln(1/x)$ at fixed Q is described by the BFKL equations [1, 2]. The increase of Q leads to the dilution of the density of partons that occupy a transverse area $1/Q^2$, the increase of Y leads to its growth. In the latter case, the radiated quanta (mostly, soft partons with $x \ll 1$, i.e. with $Y \gg 1$) are typically of the same size. The repulsive interactions among them ensure that their occupation number N (the number of gluons $xG_A(x, Q_s^2)$ with a given x times the area each gluon fills up divided by the transverse size of the object R_A^2 they occupy such as nucleus) saturates at [2–4]

$$N \equiv \frac{xG_A(x, Q_s^2)}{2(N_c^2 - 1)\pi R_A^2 Q_s^2} = \frac{1}{\alpha_S(Q_s)}\,, \qquad Q_s = Q_s(x)\,. \tag{1}$$

Here $N_c = 3$ is the number of QCD colors, $\alpha_S(Q_s) \ll 1$ is the QCD running coupling constant, determining the strength of the interaction amongst the quanta at $Q_s \gg \Lambda_{\rm QCD}$ – the emergent "close packing" scale arising from the parton recombinantion.

The saturation of the particle density is a very generic behavior – the same density scaling as the inverse interaction strength α^{-1} is characteristic of several condensation phenomena such as the Higgs condensate, superconductivity or a long-lived graviton condensate forming a black hole [5]. In QCD, the soft gluons form a highly coherent configuration called color-glass condensate (CGC) [4], or Glasma which due to its high occupation number N represents the classical limit of QCD (see Ref. [11] and references therein).

The word "glass" appearing in the acronym CGC is used in condensed matter physics to describe a non-equilibrium, disordered state of matter acting like solids on short time scales but liquids on long time scales, see e.g. [6]. Glasses are formed when liquids are cooled too fast to form the crystalline equilibrium state. The fast cooling leads to an enormous number of possible configurations $N_{\rm gl}(T)$ into which they can freeze and consequently to their large entropy $S(N_{\rm gl})$ not vanishing even at zero temperatures. Similarly to this phenomenon, the saturated QCD matter acquires a large number of gapless modes corresponding to a specific micro-state entropy S [5] with an upper bound $S_{\max} = N = \alpha^{-1}(Q_s)$ imposed by the unitarity, see Eq. (1).

2. Saturated QCD matter in the early universe

To describe the evolution of energy density $\epsilon(T)$ and entropy density $s(T)$ of hot and dense matter filling the early universe, it is customary to normalize both quantities to their values $\epsilon_0(T)$ and $s_0(T)$ corresponding to an ideal massless Bose gas with a single DoF at temperature T

$$g_{\rm eff}(T) \equiv \frac{\epsilon(T)}{\epsilon_0(T)}\,, \quad \epsilon_0(T) = \frac{\pi^2}{30}T^4\,; \quad h_{\rm eff}(T) \equiv \frac{s(T)}{s_0(T)}\,, \quad s_0(T) = \frac{2\pi^2}{45}T^3\,, \tag{2}$$

where $g_{\rm eff}(T)$ and $h_{\rm eff}(T)$ are the effective numbers of DoFs in energy and entropy, respectively. For non-interacting gas consisting of $N_{\rm F}$ Dirac fermions, $N_{\rm V}$ massive vectors, $N_{\rm V0}$ massless vectors and $N_{\rm S}$ neutral scalars, the two functions are identical and read

$$g^{(0)}_{\rm eff}(T) = \ h^{(0)}_{\rm eff}(T) = 4\cdot\frac{7}{8}N_{\rm F} + 3N_{\rm V} + 2N_{\rm V0} + N_{\rm S}\,, \tag{3}$$

where the prefactors account for the DoF of each of the considered particle species. In terms of the pressure $p = sT - \epsilon$ and using Eq. (2) the EoS of the fluid can be written as

$$p = w\epsilon\,, \quad w(T) = \frac{sT}{\epsilon} - 1 = \frac{4h_{\rm eff}(T)}{3g_{\rm eff}(T)} - 1\,. \tag{4}$$

The causality condition $c_s^2 = dp/d\epsilon = w(T) \leq 1$, where c_s is the speed of the sound in the medium, induces the inequality $2h_{\rm eff}(T) \leq 3g_{\rm eff}(T)$ with an upper bound corresponding to absolutely stiff fluid [8]. The latter has therefore the largest number of DoF in entropy $h_{\rm eff}(T)$ among all other forms of matter with the same effective number of DoF in energy $g_{\rm eff}(T)$.

In complete analogy with the glass in condensed matter physics, we propose the following cosmological scenario. Immediately after the end of the reheating phase of the Big Bang, the QCD matter expanding with the speed of light underwent a fast cooling process. In (Q, Y)-plane this corresponds to a rapid decrease of Q at fixed $Y \gg 1$. In this regime, the QCD mater has acquired a substantial excess in $h^{\rm QCD}_{\rm eff}$ over $g^{\rm QCD}_{\rm eff}$ leading to the increase of the EoS parameter well above $w = 1/3$; see Eq. (4). Eventually, this glassy form of QCD matter was transformed into a hot stiff fluid[1] with $w = 1$ and the evolution of the scale factor has slowed from $a(t) \sim t^{1/2}$ to $a(t) \sim t^{1/3}$.

Compared to collisions of ultra-relativistic nuclei (see e.g. [7]), where Glasma represents the initial state of matter consisting of small-x weakly interacting partons which thermalize only after the collision of two nuclei, the hot and super-dense rapidly expanding medium filling the early universe appears to be in local thermal equilibrium characterized by a fixed temperature $T = Q/2\pi$, where Q is the average momentum transfer among its constituents. Thus in the period preceding the formation of QGP covering the very hot QCD era, EW era, and beyond when $T \gtrsim T_s \gg \Lambda_{\rm QCD}/(2\pi)$, where $T_s = Q_s/(2\pi)$ is the saturation temperature and Q_s the corresponding close packing scale, the universe was dominated by the fully saturated QCD matter. The value of the saturation temperature is set by the condition $Q_s \gg \Lambda_{\rm QCD}$. Taking, for instance, $Q_s \approx 5 \div 25$ GeV corresponding to $\alpha_S(Q_s) \approx 0.2 \div 0.15$, we obtain $T_s \approx 1 \div 4$ GeV.

In thermal QCD the breakdown of scale invariance is frequently accomplished by including the power-like correction $O(T^2)$ to the perturbative high-temperature behavior of the EoS [11–13]

$$\epsilon(T) = \sigma T^4 - CT^2 + \mathcal{B}\,, \qquad p(T) = \frac{\sigma}{3}T^4 - DT^2 - \mathcal{B}\,, \qquad \Theta = \frac{\epsilon - 3p}{T^4} = \frac{4\mathcal{B}}{T^4} + \frac{A}{T^2}\,, \tag{5}$$

where $\sigma = (\pi^2/30)g^{(0)}_{\rm eff}$, $\mathcal{B}$ is the confining part of the interaction, so-called bag constant, Θ is the trace anomaly, C and D are some constants and $A = 3D - C$. The introduction of quadratic terms leads to the softening of the EoS $w(T) < 1/3$ close to the critical temperature T_c of the QGP-hadron phase transition [13]. Using the same ansatz for saturated matter existing at temperatures

[1]This is to be contrasted with the models in which the very early universe contains the stiff matter made of a cold gas of baryons [9] or of dark matter made of relativistic self-gravitating Bose-Einstein condensates [10].

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$T \geq T_s \gg T_c \simeq \Lambda_{\mathrm{QCD}}$ with $w(T) \lesssim 1$ we can safely neglect $\mathcal{B}$ in Eq. (5) to obtain for the stiff fluid at saturation temperature T_s

$$\epsilon_s = \sigma T_s^4 - C T_s^2 = \phi(z) \cdot \sigma T_s^4, \quad s_s = \frac{2\epsilon_s}{T_s} = \frac{3}{2}\phi(z) \cdot \frac{4}{3}\sigma T_s^3, \qquad z = -\frac{A}{C}, \quad \phi(z) = \frac{z}{z+2}. \tag{6}$$

In this case, the effective number of DoF in energy is always smaller: $g_{\mathrm{eff}}/g_{\mathrm{eff}}^{(0)} = \phi(z) < 1$. For the effective number of DoF in entropy h_{eff} this happens only for $0 < z < 4$ and for $z \geq 4$ we have $h_{\mathrm{eff}}/h_{\mathrm{eff}}^{(0)} \geq 1$. Note that the increase in entropy density s_s is solely due to temperature-dependent gluon condensate $\langle G^2 \rangle_T$ [12]: $p_s + \epsilon_s = 2\epsilon_s \simeq \langle G^2 \rangle_{T_s}$.

The QCD stiff matter – lumpy configuration of gauge fields has a typical correlation length $R_s \sim 1/Q_s$ [5]. For expansion times $R_s \alpha_S^{-1} < t < R_s \alpha_S^{-3/2}$ the semiclassical picture of the Glasma as a high occupancy state with $N \sim \alpha_S^{-1}$ gluons with momenta $p \sim Q_s$ breaks down due to their rescattering. In (Q, Y)-plane this corresponds to a decrease of Y at nearly constant Q. This is followed by the quantum kinetic $2 \to 3$ process among liberated gluons at the time scales of $\sim R_s \alpha_S^{13/5}$ which leads to bottom-up thermalization [14] and the emergence of a strongly interacting QGP [7, 11]. The cosmological expansion is restored to $a(t) \sim t^{1/2}$.

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References

[1] B. L. Ioffe, V. S. Fadin and L. N. Lipatov, Quantum Chromodynamics, CUP, 2010.
[2] Y. V. Kovchegov and E. Levin, Quantum Chromodynamics at High Energy, CUP, 2013.
[3] L. V. Gribov, E. M. Levin and M. G. Ryskin, Phys. Rept. **100**, 1-150 (1983).
[4] L. D. McLerran and R. Venugopalan, Phys. Rev. D **49**, 2233-2241 (1994).
[5] G. Dvali and R. Venugopalan, Phys. Rev. D **105**, no.5, 056026 (2022).
[6] J. P. Sethna, Statistical Mechanics: Entropy, Order Parameters, and Complexity, OUP, 2006.
[7] R. Pasechnik and M. Šumbera, Universe **3**, no.1, 7 (2017).
[8] Ya. B. Zel'dovich, JETP **41**, 1609 (1961).
[9] Ya. B. Zel'dovich, Mon. Not. R. Astron. Soc. **160**, 1 (1972).
[10] P. H. Chavanis, Eur. Phys. J. Plus **130** (2015), 181.
[11] A. Addazi *et al.*, Universe **8**, no.9, 451 (2022).
[12] R. A. Schneider and W. Weise, Phys. Rev. C **64**, 055201 (2001).
[13] R. D. Pisarski, Prog. Theor. Phys. Suppl. **168**, 276-284 (2007).
[14] R. Baier, A. H. Mueller, D. Schiff and D. T. Son, Phys. Lett. B **502**, 51-58 (2001).