Bose-Einstein Condensation in "the very hot"

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In relativistic heavy ion collisions, a highly occupied gluonic matter is created shortly after initial impact, which is in a non-thermal state and often referred to as the glasma. How the glasma evolves quickly toward an emergent hydrodynamic behavior remains a significant challenge for theory as well as phenomenology. Recently there has been important progress in understanding the pre-equilibrium evolution using the kinetic theory description, in a highly overpopulated regime[1–3)] where the system is weakly coupled yet strongly interacting with the possibility of a transient BEC during the course of thermalization.

Inspired by the Color Glass Condensate description of the initial conditions, the gluon distribution in the glasma is schematically given by $f(p \leq Q_s) = f_0$, $f(p > Q_s) = 0$ with Q_s the saturation scale. One may introduce the overpopulation parameter $n\epsilon^{-3/4}$ which is directly related to the ratio between inter-particle distance d and typical de Broglie wavelength λ, i.e. $n\epsilon^{-3/4} \sim (\lambda/d)^\alpha$ thus measuring the degrees of quantum coherence: when $n\epsilon^{-3/4} \to \hat{o}(1)$ then $\lambda \to d$ and one expects BEC to occur. In the glasma distribution $n_0\epsilon_0^{-3/4} = f_0^{1/4}\,\frac{2^{5/4}}{3\,\pi^{1/2}}$ and, compared with thermal case $n\,\epsilon^{-3/4}|_{SB} = \frac{30^{3/4}\,\zeta(3)}{\pi^{7/2}} \approx 0.28$, the system becomes *overpopulated* when $f_0 > f_0^c \approx 0.154$. One thus see in the glasma with $f_0 = 1/\alpha_s$, even with rather modest weak coupling $\alpha_s \simeq 0.3$ the system is highly overpopulated and will develop Bose condensate.

So how does the thermalization proceed in such a overpopulated glasma? Numerical solutions reported in [2)] suggest two generic features. First, two cascades in momentum space will quickly develop: a particle cascade toward the IR momentum region that quickly populates the soft momentum modes to high occupation, and a energy cascade toward the UV momentum region that spreads the energy out. As a consequence a high occupation number at IR is quickly achieved, leading to the second interesting feature: an almost instantaneous local "equilibrium" form for the distribution near the origin $\vec{p} \to 0$: $f^*(p \to 0) = \frac{1}{e^{(p-\mu^*)/T^*}-1}$. In the overpopulated case the IR cascade persists to drive the local thermal distribution near $p = 0$ to increase rapidly in a self-similar form (see Fig.1 upper). The associated negative local "chemical potential" is driven to approach zero, i.e. $(-\mu^*) \to 0^+$ and ultimately vanishes in a finite time, marking the onset of the condensation. The approaching toward onset is well described by a scaling behavior: $|\mu^*| = C(\tau_c - \tau)^\eta$ with a universal exponent $\eta \approx 1$ for varied values of $f_0 > f_0^c$. Such general link from initial overpopulation to the onset of BEC *in a finite time* with a scaling behavior appears to be very robust against different choices of initial distribution shapes and possible initial anisotropy, including longitudinal expansion, as well as adding finite medium-generated mass.

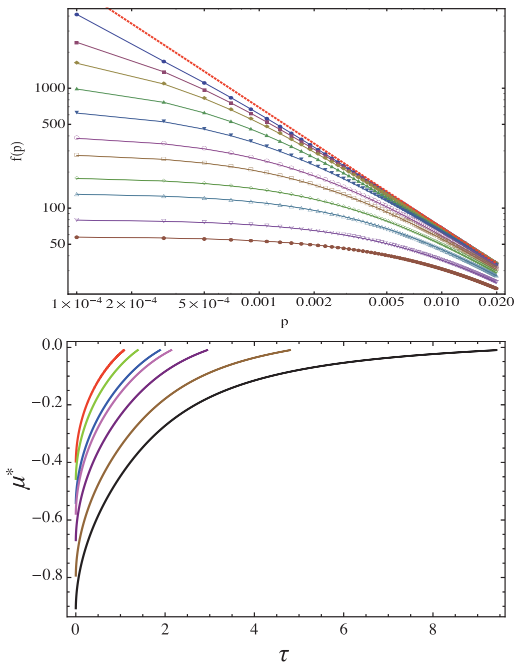

Fig. 1. Local thermal form (upper) of $f(p \to 0)$ and the vanishing of local chemical potential $\mu^* \to 0$ (lower).

There is one particularly important issue related to the role of inelastic processes. One may even wonder if such onset (manifested as the development of an infrared singularity in the kinetic evolution) would happen anymore. To answer this, one needs to study the kinetic evolution including both processes: a first attempt has been done, recently in [3)]. Contrary to usual expectation, it is found that the inelastic process has two effects: globally changing (mostly reducing) the total particle number, while locally at small p always filling up the infrared regime extremely quickly. This latter effect is found to significantly speed up the emergence of local thermal form with vanishing local "chemical potential" and catalyzes the onset of Bose condensation to occur faster (as compared with the purely elastic case) in the overpopulated glasma.

References

1) J. -P. Blaizot, F. Gelis, J. -F. Liao, L. McLerran and R. Venugopalan, Nucl. Phys. A **873**, 68 (2012).
2) J. -P. Blaizot, J. Liao and L. McLerran, Nucl. Phys. A **920**, 58 (2013).
3) X. -G. Huang and J. Liao, arXiv:1303.7214 [nucl-th].

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